Dissertation Title: Design of Novel Wideband Electromagnetic Band Gap Metamaterials and Antenna Elements Utilizing Oriented Cobalt-Substituted Z-Type Barium Hexaferrites

Author: Andrew Daigle

Department: Electrical and Computer Engineering

Approved for Dissertation Requirement of the Degree of Doctor of Philosophy

Dissertation Advisor: Prof. Vincent G Harris

Dissertation Committee: Prof. Carmine Vittoria

Dissertation Committee: Dr. Anton Geiler

Dissertation Committee: Dr. Yajie Chen

Department Chair: Prof. Ali. Abur

Graduate School Notified of Acceptance:

Director of the Graduate School: Prof. Yaman Yener
DESIGN OF NOVEL WIDEBAND ELECTROMAGNETIC BAND GAP METAMATERIALS AND ANTENNA ELEMENTS UTILIZING ORIENTED COBALT SUBSTITUTED Z-TYPE BARIUM HEXAFERRITES

A Dissertation Presented

by

Andrew Daigle

to

The Department of Electrical and Computer Engineering

in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

in

Electrical Engineering

in the field of

Electromagnetics, Plasma, and Optics

Northeastern University
Boston, Massachusetts
May 2011
ACKNOWLEDGEMENT

I would like to thank my advising Professor, Professor Vincent G. Harris for his constant help and support during the time spent working on this project. His novel approach to the problems I encountered was invaluable to my experience. I would also like to thank him for allowing me to do my research in his group "The Center for Microwaves, Magnetic Materials and Integrated Circuits", at Northeastern University. Without the friendly help from the lab personnel, and the scholarly and constructive work environment within the center, this process would have taken much longer. In particular I would like to thank Dr. Anton Geiler, Dr. Yajie Chen, and Professor Carmine Vittoria for their invaluable help with all of my questions and ideas. They have been priceless resources in ferrite production, antenna design, and creative problem solving along the way.

Many thanks also go out to the friends that I have made over the years here at Northeastern and in Boston. Thank you for listening to me talk about antennas and simulations all the time, and for putting up for me while I studied for exams and wrote my dissertation.

Finally a special thanks goes out to my friends and family, who have always been behind me whatever my goal at the time happened to be. Their love and support has helped me to achieve my goals, and I will forever appreciate it.
ABSTRACT

In order to achieve a significant reduction in volume over standard dielectric $\lambda_{\text{sub}}/4$ cavity slot antenna designs, while concurrently maintaining usable gains >2-3 dB, realizable high permeability oriented cobalt-substituted Z-Type barium hexaferrite materials have been introduced through a modified aqueous synthesis technique both as magnetic substrates and as electromagnetic band gap (EBG) metamaterial ground planes. Significant volumetric reduction of antenna elements (92%) due to magnetic and dielectric loading has been achieved via tailoring the permittivity and permeability of the ferrite material through an orientation process over standard $\lambda_0/4$ cavity designs. Further reduction (94% of $\lambda_0/4$ cavity designs) is achieved via combining a realizable high permeability Co$_2$Z hexaferrite ($\varepsilon_r=16, \mu_r=14$) with a periodic array of metallic Sivenpiper Structures to create an EBG metamaterial. The thickness of the investigated EBG metamaterial is $<\lambda_0/125$ at the lowest operation frequency. The bandwidth of these metamaterials is investigated in terms of realizable fabrication techniques, and is determined while biased from the phase of a reflected plane wave, as is common in literature, to be >50-75% of the L-Band. Unbiased designs with >50% bandwidth have also been reported. Gains of -2.5 to 2.5 dB have been achieved for both magnetic substrates and EBG ground planes, with a voltage standing wave ratio (VSWR) <2 indicating that these designs are practical for commercial and defense applications which call for low profile miniaturized antenna designs which do not suffer from reduced gain. Furthermore, these designs have been applied to conformal surfaces increasing the potential applications of these technologies.
# Table of Contents

ACKNOWLEDGEMENT .................................................................................................................. 1

ABSTRACT..................................................................................................................................... 2

LIST OF FIGURES .................................................................................................................... 11

LIST OF TABLES .................................................................................................................. 30

Chapter 1: *Introduction* ............................................................................................................. 31

1.0 Reason for Study ................................................................. 31

1.1 Dissertation Overview ................................................................. 33

1.2 References ......................................................................................... 40

Chapter 2: *High Permittivity Dielectric Materials* ............................................................ 43

2.0 Common Antenna Miniaturization Techniques ............................................................ 43

2.0.1 Introduction ......................................................................................... 43

2.0.2 Effective Dielectric Constant ................................................................. 44

2.0.3 Superstrate Designs ......................................................................................... 49

2.0.4 Conclusions ................................................................................................. 53

2.1 High Permittivity Dielectrics Developed as Antenna Substrates ............................................. 54

2.1.1 Background ................................................................................................. 54

2.1.2 Potential Materials for Antenna Substrate Designs ................................................. 55

2.1.3 Development of Practical Substrate Materials ................................................. 58
3.6 Conclusions

3.7 References

Chapter 4: Aqueous $\text{Co}_2\text{Y}$ Hexaferrite Nanoparticle Formation

4.0 Introduction to $\text{Co}_2\text{Y}$ Hexaferrites

4.0.1 Crystal Structure and Theory

4.1 Aqueous Hexaferrite Formation [12]

4.1.1 Cobalt Substituted Barium Y-Type Hexaferrite Material

4.1.2 Magnetic Properties and Crystallography

4.1.3 Conclusions on the Co-precipitation Method

4.2 Orientation Provided by the Rotational Magnet Setup

4.2.1 Introduction/Reason for Study

4.2.2 Orientation Effect Viewed Through Vibrating Sample Magnetometry

4.2.3 Orientation Effect Viewed Through X-Ray Diffraction

4.3 Discussion of Operational Ranges for Device Design

4.3.1 Optimization of Permeability

4.3.2 Optimization of Magnetic Losses

4.4 Conclusions

4.5 References

Chapter 5: Aqueous $\text{Z}$-Type Hexaferrite Nanoparticle Formation
6.4 Conclusions ........................................................................................................... 186

6.5 References .......................................................................................................... 187

Chapter 7: Ferrites in Antenna Design ................................................................. 190

7.1 Chapter Goals/Previous Works ........................................................................ 190

7.2 Ferrite Substrates .............................................................................................. 193

7.2.1 Planar Approach SSSA Design ..................................................................... 193

7.2.2 Conformal Approach .................................................................................... 200

7.3 Ferrite Absorbers .............................................................................................. 202

7.3.1 Previous Works ............................................................................................. 202

7.3.2 Novel Absorber Designs .............................................................................. 204

7.4 Conclusions on Ferrite Designs ........................................................................ 209

7.5 References ......................................................................................................... 210

Chapter 8: Phased Array Design .......................................................................... 212

8.1 Introduction to Dielectric Phased Arrays ......................................................... 212

8.1.1 Theory of Phased Arrays ............................................................................. 212

8.1.2 Dielectric Element used in Array Study ...................................................... 214

8.1.3 Effect of Increasing the Number of Elements .............................................. 215

8.1.4 Array Patterns and Pencil Beams ............................................................... 221

8.2 Introduction to Magnetic Phased Arrays ......................................................... 223
8.2.1 SSSA Array .......................................................... 223
8.2.2 SSSA Scanning Angle Study ................................. 225
8.2.3 ASA Array ............................................................ 226
8.2.4 ASA Scanning Angle Study ................................. 228
8.2.5 Beam Width Study ................................................ 229
8.3 Conclusions ............................................................ 230
8.4 References ............................................................. 231

Chapter 9: EBG Design .................................................. 233
9.0 Introduction to EBG Metamaterials ......................... 233
9.0.1 Goal of Chapter .................................................. 233
9.0.2 Background ........................................................ 233

9.1 Bandwidth of EBG Metamaterials ........................ 236
9.1.1 Dispersion Curves to Designate Bandwidth ............. 236
9.1.2 Reflected Wave Phase to Designate Bandwidth ....... 241

9.2 Optimizing EBG Bandwidth ................................. 243
9.2.1 Effect of ε and μ of Substrate ............................... 243
9.2.2 Effect of Patch Height and Spacing ....................... 246
9.2.3 Effect of Varying Incident Angle ......................... 249

9.3 Discussion of Co-Site Interference ......................... 251
Chapter 9: Design of EBG Metamaterials

9.4 Design of Dielectric Material EBGs

9.4.1 Standard Dielectric Material EBG Design

9.5 Design of Magnetic Material EBGs

9.5.1 Introducing \( \mu \) in EBG Metamaterial Design

9.5.2 Spinel Ferrites

9.5.3 Hexaferrites

9.6 Conclusions

9.7 References

Chapter 10: EBG Metamaterials in Antenna Design

10.1 Introduction to Previous Works

10.2 Dielectric EBG Substrates in Antenna Designs

10.2.1 Introduction to a Dielectric EBG SSSA Design

10.2.2 Effect of Dielectric EBG on Spiral Performance

10.3 Ferrite EBG Substrates

10.3.1 Low Frequency SSSA Element

10.3.2 Conformal Antenna Designs

10.3.3 Realistic Antenna Fabrication

10.4 Conclusions on EBG Designs

10.5 References
Chapter 11: Thesis Conclusions
LIST OF FIGURES

Figure 1: Depiction of a standard patch antenna designed on a dielectric substrate ($\varepsilon_r$) [3]. ................................................................. 45

Figure 2: Depiction of the effective permittivity ($\varepsilon_{\text{eff}}$) as a function of frequency, used in order to determine the effective electrical length of a patch antenna, and through this value its lowest operating frequency [3]. ....................................................... 47

Figure 3: Effect of changing the substrate permittivity on patch antenna operating frequency, one of the more common antenna miniaturization techniques. ........ 48

Figure 4: Effect of superstrates of varying dielectric constants on the broad side gain of a spiral antenna [10]................................................................. 50

Figure 5: Effect of changing superstrate permittivity on patch antenna operating frequency, one of the most common antenna miniaturization techniques.......... 51

Figure 6: Effect of tapering the superstrate on the low frequency gain of a slot radiating element [10]. ................................................................. 52

Figure 7: Dielectric constant of ($\text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3$) for x varying from 0.45 to 0.60 [15]. ..... 57

Figure 8: Loss tangents of ($\text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3$) ceramics doped with common oxides [16]..... 58

Figure 9: Previous work on high permittivity dielectrics designed for Navy shipboard applications, (a) demonstrates the stability of the permittivity with applied voltage. (b) Demonstrates the temperature stability of the permittivity, varying ~10% over the desired operating region. (c) Demonstrates the phase purity of the ceramic dielectric composites with varying MgO weight compositions.......... 60
Figure 10: Design of a 50 Ω coaxial fed GPS antenna utilizing high permittivity materials ($\varepsilon_r > 90$). Simulated utilizing FEM software on an infinite ground plane. 62

Figure 11: Simulated return loss of a 50 Ω coaxial fed GPS antenna utilizing high permittivity materials ($\varepsilon_r > 90$). Simulated utilizing FEM software on an infinite ground plane. 63

Figure 12: Simulated impedance matching of a 50 Ω coaxial fed GPS antenna utilizing FEM software on an infinite ground plane. The red curve is the real impedance, and the blue curve is the imaginary impedance. 64

Figure 13: Simulated electric field on the radiating patch of a 50 Ω coaxial fed GPS antenna utilizing high permittivity materials ($\varepsilon_r > 90$). Simulated utilizing FEM software on a circular ground plane. 65

Figure 14: Simulated radiation pattern at the center frequency of 1.575 GHz of a 50 Ω coaxial fed GPS antenna utilizing high permittivity materials ($\varepsilon_r > 90$). Simulated utilizing FEM software on a circular ground plane. 66

Figure 15: Depiction of cubic spinel crystal structure, showing where the octahedral and tetrahedral sites reside [4]. 70

Figure 16: Comparison of magnetic properties of spinel ferrites formed via different polyol co-precipitation routes [1]. 74

Figure 17: Magnetic Moment vs Mg concentration in $\text{Mg}_x\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ spinel ferrites for $x$ varying between 0 and 1 by increments of .2 [1]. 75

Figure 18: X-ray diffraction spectra of $\text{Mg}_x\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ ferrites ($x = 0.5$) produced using diethylene glycol (DEG) compared to those produced using tetraethylene glycol.
(TEG) (a). X-ray diffraction spectra of $\text{Mg}_{x}\text{Zn}_{1-x}\text{Fe}_2\text{O}_4$ ferrites produced using diethylene glycol (DEG) as a function of Mg content ($0 \leq x \leq 1$) (b) [1]. .......... 77

Figure 19: XRD spectra of $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ spinel ferrites, plotted as intensity vs. $\theta-2\theta$ (degrees) indicating high phase purity. ............................................................... 78

Figure 20: Comparison of magnetic properties of $\text{Ni}_{0.35}\text{Zn}_{0.65}\text{Fe}_2\text{O}_4$ [19] and $\text{Mg}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ spinel ferrites are plotted with respect to particle size [1]. ........................................... 79

Figure 21: XRD spectra of $\text{CoFe}_2\text{O}_4$ spinel ferrites are plotted as intensity vs. $\theta-2\theta$ (degree) indicating high phase purity. ................................................................. 80

Figure 22: Scanning electron microscopy images of $\text{CoFe}_2\text{O}_4$ spinel ferrites produced via the co-precipitation of elements method in polyol (TEG). ................................................. 81

Figure 23: Depiction of particle size vs. glycol type for $\text{Mg}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ spinel ferrites where; (a) shows SEM and TEM images of ferrites with a particle size of 8-10 nm produced utilizing TEG. (b) Depicts particles produced with particle size on the order of 20-30 nm produced utilizing DEG. (c) Shows particles produced with particle size on the order of 100-130 nm produced via an aqueous method. (d) Depicts the grain size as a function of Mg concentration (x), calculated via Sheerer analysis [1]....................................................................................................................... 83

Figure 24: XRD spectra of $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ and $\text{Mg}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ spinel ferrites are plotted as intensity vs. $\theta-2\theta$ (degrees) indicating high phase purity for both materials [1]. 85

Figure 25: XRD spectra and VSM data of $\text{Mn}_{0.68}\text{Zn}_{0.26}\text{Fe}_{2.06}\text{O}_4$ produced via a modified aqueous co-precipitation method. ................................................................. 88

Figure 26: SEM images of $\text{Mn}_{0.68}\text{Zn}_{0.26}\text{Fe}_{2.06}\text{O}_4$ produced via a modified aqueous co-precipitation method showing clear spinel cubic structures. ........................................... 88
Figure 27: XRD spectra and VSM data of NiZnFe$_2$O$_4$ spinel ferrites produced via a modified aqueous co-precipitation method.......................................................... 90

Figure 28: SEM images of NiZnFe$_2$O$_4$ produced via a modified aqueous co-precipitation method showing clear spinel cubic structures. ................................................. 91

Figure 29: XRD spectra and VSM data of CoFe$_2$O$_4$ produced via a modified aqueous co-precipitation method. ............................................................................................ 93

Figure 30: SEM images of CoFe$_2$O$_4$ produced via a modified aqueous co-precipitation method................................................................................................................ 93

Figure 31: X-ray diffraction data of FeCo nanoparticles formed via a modified co-precipitation method in polyol. Also shown is the VSM data of the produced powders................................................................. 95

Figure 32: Images of FeCo powders at high magnification achieved through scanning electron microscopy which depict the surfactants of these particles as a function of PVP addition.............................................................................................. 96

Figure 33: Depicts the magnetic moment of each of these samples as a function of PVP addition. ................................................................................................................ 97

Figure 34: Permeability spectra of various spinel ferrites produced via the aqueous method. Co doping shows an increase in the resonant frequency. ....................... 98

Figure 35: The (110) cross-section shows examples of M-type [(Ba,Sr)Fe$_{12}$O$_{19}$] (a), Y-type [(Ba,Sr)$_2$Met$_2$Fe$_{12}$O$_{22}$], (b) and Z-type [(Ba,Sr)$_3$Met$_2$Fe$_{24}$O$_{41}$] (c) hexaferrites. All compounds are made up of R, S and T layers, or minor modifications of them [1]............................................................................................................. 105
Figure 36: Energy dispersive X-ray spectroscopy measurements, indicating the successful removal of Na and Cl from the filtration process described in 4.1.1................. 108

Figure 37: (a) X-ray diffraction (XRD) intensity as square root for the sample processed at 900°C. (b) Simulated pure phase curve from peak locations given in literature [16] (a.u. designates arbitrary units) (4).......................... 109

Figure 38: (a) Vibrating sample magnetometer (VSM) measurements of ferrites after removal from beaker (dotted line) and subsequent sinter at 900°C (solid line). (b) Comparison of magnetic properties for different sintering temperatures at 800°C (dotted line), 900°C (short dashed line), 1000°C (long dashed line), 1100°C (dash dot dash line), and 1200°C (solid line). (c) Saturation magnetization ($M_s$) changes with sintering temperature as well as coercive field ($H_c$), changes with sintering temperature. All measurements performed at room temperature (4)................. 109

Figure 39: (a) X-ray diffraction patterns (SQRT) for ferrite powders produced at different sintering temperatures (a.u. designates arbitrary units). (b) Logarithm scale of X-ray intensity versus $2\theta$ with symbols denoting phases, where closed circles denote Y-type ferrite peaks, open squares denote M-type ferrite peaks (BaFe$_{12}$O$_{19}$), open circles denote spinel phases (CoFe$_2$O$_4$ and Fe$_3$O$_4$), and open triangles denote as prepared precursor phases (BaCO$_3$) and oxides. (c) Lattice parameters of ferrite powders produced at different sintering temperatures plotted against bulk values (denoted by dashed lines) (4)................................................................. 111

Figure 40: Scanning electron microscope measurements of Y-type ferrites with different sintering temperatures: (a) as prepared sample, (b) 800°C, (c) 900°C, and (d) 1000°C (4).............................................................................................................. 115
Figure 41: Permeability spectra of non oriented Co$_2$Y hexaferrite toroid material produced via a modified aqueous chemical processing technique. .......................... 116

Figure 42: Permittivity spectra of non oriented Co$_2$Y hexaferrite toroid material produced via a modified aqueous chemical processing technique. ........................................ 116

Figure 43: Scanning electron microscopy image of Co$_2$Y hexaferrite powder which has been reduced to single domain size 0.5-2 µm through ball milling. In (a), a 2.20x10$^3$ magnification of particles, and in (b) a 9.00x10$^3$ magnification of particles is shown. ........................................................................................................ 119

Figure 44: SEM image of Co$_2$Y particles produced via the aqueous co-precipitation route (a). Magnetic hysteresis loops of a textured Co$_2$Y compact with magnetic field applied parallel (par) and perpendicular (perp) to the compact surface (b). Depiction of rotating magnetic field orientation and compaction apparatus (c). 120

Figure 45: Depiction of the orientation effect of the rotational magnet setup through in plane and out of plane hysteresis loops produced via vibrating sample magnetometry comparing oriented ($\alpha_3$) and non oriented samples ($\alpha_4$). .......... 122

Figure 46: Depiction of the orientation effect of the rotational magnet setup through in plane and out of plane hysteresis loops produced via vibrating sample magnetometry for various rotation speeds. ................................................................. 123

Figure 47: Depiction of the orientation effect of the rotational magnet setup through in plane and out of plane hysteresis loops produced via vibrating sample magnetometry for pre and post sintered compacts. ............................................. 124
Figure 48: Depiction of X-ray diffraction data for oriented and non oriented compacts of Co$_2$Y hexaferrite materials. Significant reduction in out of plane refraction peaks is observed. ................................................................. 125

Figure 49: Initial permeability and magnetic loss tangents of oriented and non-oriented samples of Co$_2$Y hexaferrites................................................................. 127

Figure 50: Effect of orientation on initial permeability and magnetic loss tangents of oriented and non-oriented samples of Co$_2$Y hexaferrites. ......................... 128

Figure 51: Optimized permeability of Y-type hexaferrite green body compacts sintered at a variety of different temperatures to see the effect of the density on the permeability values. ................................................................. 130

Figure 52: Imaginary permeability of Y-type hexaferrite samples as a function of sintering temperature. ................................................................. 131

Figure 53: Magnetic loss tangent of Y-type hexaferrite samples as a function of sintering temperature. ................................................................. 132

Figure 54: (a) X-ray diffraction spectrum of sintered Co$_2$Z hexaferrite powder compared with reference JCPDS file no. 19-0097 [11]. (b) Magnetic moment of Co$_2$Z hexaferrite powder measured using VSM. (c) and (d) SEM images of Co$_2$Z hexaferrite powder at different magnifications.................................................. 141

Figure 55: Real permeability and magnetic loss tangent of a moderately dense (~90%) non-oriented Z-type hexaferrite toroid sample. ........................................ 142

Figure 56: Real permittivity and dielectric loss tangent of a moderately dense (~90%) non-oriented Z-type hexaferrite sample.................................................. 143
Figure 57: Scanning electron microscopy image of Co$_2$Z hexaferrite material which has been reduced to single domain size 0.5-2 µm through ball milling. (a) $3 \times 10^3$ magnification of particles, (b) $1.8 \times 10^3$ magnification of particles. ............................................. 145

Figure 58: Preliminary attempts at orientation of Z-Type hexaferrite material toroid, a 20% increase in permeability is shown over the non-oriented material shown in Figure 55. ............................................................................................................ 147

Figure 59: Preliminary attempts at orientation of Z-Type hexaferrite material toroid, tan(δ$_m$) is shown for samples produced via different magnet rotation speeds. ... 149

Figure 60: Orientated Z-Type hexaferrite material toroid utilizing the new die set, a 64% increase in permeability is shown over the non oriented $\mu_r$ measurement in Figure 55 ............................................................................................................................ 150

Figure 61: Measured (a) permittivity and permeability and (b) magnetic and dielectric loss tangent spectra of torroidal samples of oriented Co$_2$Z ferrite materials optimized for magnetic antenna substrates [3]. ................................................... 151

Figure 62: Measured permeability and magnetic loss of torroidal samples of oriented Co$_2$Z ferrite materials optimized for magnetic EBG design under various levels of applied bias fields applied parallel to the c-axis of the torroid plane. ............ 153

Figure 63: Magnetostriction measurements for a perpendicular c-axis oriented Co$2$Z ferrite compact. Longitudinal and transversal represent an applied magnetic field parallel and transversal to the direction of strain observed, respectively [18].... 154

Figure 64: Ferromagnetic resonance measurements for a perpendicular c-axis oriented Co$_2$Z ferrite slab bonded on piezoelectric PMN-PT crystal as applied electric field of 6 kV/cm and zero field, respectively. Inset illustrates geometry and field
configuration of the multiferroic heterostructure. Here the longitudinal represents an applied magnetic field along d31 direction of PMN-PT slab [18].

Figure 65: (a) Tunability of permeability with a biased magnetic field. Solid line represents theoretical prediction in Eqn. (3); square and circle symbols denote direct measured data tuned by a biased magnetic field and indirect measured value tuned by an electric field, respectively. (b) Measured complex permeability vs. frequency with different biased magnetic fields for a perpendicular c-axis oriented Co2Z ferrite compact [18].

Figure 66: Permeability and magnetic loss tangent as a function of applied field of Co2Z hexaferrite material torroids produced via a modified chemical co-precipitation method.

Figure 67: (a) UWB bow tie antenna element from literature. (b) Optimized bowtie designed to operate with narrow thickness, with reduction in gain.

Figure 68: Bow tie element simulation results; gain is maintained at 3-5dB and return loss measurements indicate good matching over the 3 GHz to 10 GHz band.

Figure 69: Radiation patterns for φ= 0˚ and 90˚ for various frequencies over the operating range of the UWB bowtie element.

Figure 70: (a) Design of 50 ohm matched GNSS SSSA element with a height <2” on a low cost Rodgers™ TMM4 (ε=4.5) substrate. (b) Depiction of 3-D omni-directional radiation pattern of the SSSA element in the higher GNSS operating band (1559MHz to 1611MHz).

Figure 71: (a) Total realized gain of the SSSA element compared to that of Chu's Limit for the given SSSA element size. (b) Return loss of the SSSA element design. (c)
Efficiency, and (d) axial ratio of the SSSA element design. Green bands indicated desired GNSS bands of interest. ................................................................. 175

Figure 72: Comparison of the current SSSA design to that of Chu's Limit, plotted for increased aperture sizes, depicted to show how realizable high gains can be readily achieved. ................................................................................................. 176

Figure 73: Realization of boresight cross polarization minimization for the miniaturized SSSA element design. Optimization of the cross-polarization near the horizon is ongoing. .............................................................................................................. 178

Figure 74: RHCP gain of the SSSA element vs $\theta$ for $\varphi = 0^\circ$ and $45^\circ$, 3 dB beamwidth is indicated to be $\sim 130^\circ$ for the $\varphi = 0^\circ$ plane and $\sim 115^\circ$ for the $\varphi = 45^\circ$ plane. ...... 179

Figure 75: (a) Depiction of a L-Band Archimedean spiral antenna design, (c) a slot Archimedean spiral antenna design, and their respective radiation patterns (b and d) at a center frequency of 1.5 GHz. .................................................................................................................. 180

Figure 76: (a) Total realized gain of the ASA element compared to that of Chu's Limit for the given aperture size. (b) Return loss of the ASA element design. (c) Axial ratio of the ASA element design. ................................................................................ 181

Figure 77: (a) Total realized gain of the SASA element compared to that of Chu's Limit for the given aperture size. (b) Return loss of the SASA design. (c) Axial ratio of the SASA design. .............................................................................................................. 183

Figure 78: (a) Design of conformal dielectric ASA element designed for operation with a center frequency of 1 GHz. (b) Depiction of the 3-D radiation pattern at 1 GHz. (c) Depiction of radiating properties of the ASA antenna design. Gain is close to
Chu's limit at the design frequency, also shown are the antennas return loss and axial ratio respectively. ........................................................................................................ 185

Figure 79: (a) The total realized gain (dB) patterns plotted for various radius of curvature values for varying angle $\theta$ ($\varphi=0$). (b) Depiction of boresight gain depicted for various radius of curvature values. It is important to note that within the desired conformal bands (9” to 21”) no change is apparent. ........................................... 186

Figure 80: (a) Agilent™ Impedance Analyzer and torroid samples of Z-type textured ferrite materials. (b) Measured permittivity and permeability on torroids and plates of oriented Co$_2$Z ferrite materials. (c) Magnetic and dielectric loss tangents measured on oriented Co$_2$Z ferrite materials. ..................................................... 191

Figure 81: (a) Design of a 50 ohm matched GNSS SSSA with radius 2” and a height of 0.48 cm on a Co$_2$Z. (b) Design of an antenna element to fit on conformal surfaces of varying radii......................................................................................................................... 194

Figure 82: (a) Total realized broad side gain of a SSSA element. (b) Simulated return loss of a SSSA element design. (c) Axial ratio of a SSSA element design. ............. 196

Figure 83: (a) Radiation patterns of a SSSA element designed on a Co$_2$Z ferrite substrate with $\varphi=0^\circ$ and (b) with $\varphi=45^\circ$. Also depicted, the 3-D element gain at the center frequency of 1.5 GHz (c). ........................................................................................................................................ 197

Figure 84: (a) Design of a 50 ohm matched GNSS ASA element with a radius 2” and a height of 0.75 cm on a Co$_2$Z hexaferrite substrate. (b) Design of an ASA element fitted on a conformal surface. ............................................................................................................. 198

Figure 85: (a) Total realized gain of an ASA element. (b) Return loss of an ASA element. (c) Axial ratio of an ASA element. ............................................................................................................. 199
Figure 86: (a) Radiation patterns of an ASA antenna designed on a Co$_2$Z ferrite substrate with $\phi = 0^\circ$, (b) with $\phi = 45^\circ$. Also depicted, a 3-D depiction of the elements gain at the center frequency of 1.5 GHz (c).................................................................................................................. 200

Figure 87: (a) Conformal magnetic substrate antenna. (b) 3-D total realized element gain plotted at 1.6 GHz. Antenna radiation parameters are depicted including, total gain compared to Chu's limit (c), return loss (d), and axial ratio (e). ..................... 202

Figure 88: Effect of absorber layers on the gain bandwidth of a dipole antenna compared to a free standing element and a PEC backed element at $\lambda_0/4$ [7]. ....................... 203

Figure 89: (a) Depiction of an ASA element. (b) 3-D radiation pattern of an ASA element at the lowest operating frequency of 400 MHz. (c) Total realized gain of an ASA element. (c) Return loss of an ASA design. (d) Axial ratio of an ASA design. . 205

Figure 90: Ferrite absorbers utilized to enhance the low frequency matching of a spiral antenna. Two absorbers both realistic and theoretical have been employed. While both indicate better low frequency impedance matching, the realistic design case doesn't sacrifice the same amount of gain making it practical for device design. ........................................................................................................................................ 206

Figure 91: (a) Effect of a 2.5 mm thick Co$_2$Z absorber layer beneath an ASA element designed to operate at 1 GHz, a 400 MHz shift is shown in the lowest operating frequency. (b) Broad side gain of the ASA element with and without the ferrite absorber. (c) The frequency dependant magnetic and electric properties of the ferrite absorber layer. .................................................................................................................. 208

Figure 92: Depiction of the scanned beam produced from a phased array [1].......... 212
Figure 93: (a) Design of a SSSA element. (b) 3-D radiation pattern of the element at the GPS frequency of 1.575 GHz. (c) Radiation parameters of the antenna element including broad side gain, return loss, and axial ratio. ........................................... 215

Figure 94: Simulated radiation patterns of a single dielectric SSSA element across the desired operating range of the L-band, showing uniformity of pattern in both the $\phi=0^\circ$ and $\phi=45^\circ$ planes over the low end of the SSSA element's operating band. ............................................................................................................................................................................ 216

Figure 95: Simulated radiation patterns of a 3x3 SSSA element phased array spaced at $\lambda_0/2$ where $\lambda_0=30$ cm across the desired operating range of the L-band, showing uniformity of pattern in both the $\phi=0^\circ$ and $\phi=45^\circ$ planes over the low end of the SSSA element's operating band. ............................................................................................................................................................................ 217

Figure 96: Simulated radiation patterns of a 9x9 SSSA element phased array spaced at $\lambda_0/2$ where $\lambda_0=30$ cm across the desired operating range of the L-band, showing uniformity of pattern in both the $\phi=0^\circ$ and $\phi=45^\circ$ planes over the low end of the SSSA element's operating band. ............................................................................................................................................................................ 218

Figure 97: Depiction of the effect of array spacing on radiation pattern performance of a 3x3 SSSA element phased array where the spacing is equal to (a) $\lambda_{LOF}/4$ and (b) $\lambda_{LOF}/2$. With $\lambda_{LOF}=1$GHz .................................................................................................................. 219

Figure 98: Effect of increasing the number of elements on the broad side gain of an antenna array across the desired GNSS frequency bands. Figure depicts the effect of pattern multiplication utilizing identically oriented elements. ................... 220

Figure 99: 3-D radiation pattern of a 9x9 SSSA element phased array with the spacing of $\lambda_0/2$ at the center frequency of the design (1.5 GHz).............................................................................. 221
Figure 100: 3-D radiation pattern of a 9x9 SSSA element phased array of with spacing of $\lambda_{\text{LOF}}/2$ at the center frequency of the design (1.5 GHz). ................................................. 222

Figure 101: Depiction of the pencil beam radiation patterns at the center frequency of 1.5 GHz produced via a 5x5 SSSA element phased array spaced at $\lambda_{0}/4$ with various scanning angles, (a) $\varphi=0^\circ$, $\theta=0^\circ$ and (b) $\varphi=30^\circ$, $\theta=30^\circ$. ......................................................... 224

Figure 102: Depiction of the radiation patterns produced from a 5x5 SSSA element phased array spaced at $\lambda_{\text{CF}}/4$ across the desired operating range of the L-band, showing uniformity of pattern in both the $\varphi=0^\circ$ and $\varphi=45^\circ$ planes................................. 225

Figure 103: Depiction of the pencil beam radiation patterns at the center frequency of 1.5 GHz produced via a 5x5 ASA element phased array spaced at $\lambda_{\text{CF}}/4$ at various scanning angles, (a) $\varphi=0^\circ$, $\theta=0^\circ$ and (b) $\varphi=30^\circ$, $\theta=30^\circ$. ......................................................... 227

Figure 104: Depiction of the radiation patterns produced from a 5x5 ASA element phased array spaced at $\lambda_{\text{CF}}/4$ over the desired L-band (GNSS) operating range. ........... 228

Figure 105: Depiction of pencil beam radiation patterns produced via a 5x5 phased array spaced at $\lambda_{0}/2$ for the SSSA element. These patterns have been presented in both the $\varphi=0^\circ$ and $\varphi=45^\circ$ planes.................................................................................. 229

Figure 106: Comparison of 3-dB beam widths of 5x5 phased arrays spaced at $\lambda_{0}/2$ for an ASA element (a) and a SSSA element (b). These 3-dB beam widths have been presented in both the $\varphi=0^\circ$ and $\varphi=45^\circ$ planes.............................................. 230

Figure 107: First order dispersion curve of a dielectric cube (a), compared to that of a theoretical curve provided in literature. Results indicate very good matching between the two [10]................................................................................. 237
Figure 108: Depicts the outcome of this study by comparing the results of the FEM simulations to that of a theoretical curve on an identical material provided by literature.......................................................... 237

Figure 109: First order dispersion curve of a dielectric cube with an embedded Sivenpiper structure calculated via FEM software (a), compared to that of a theoretical curve provided in literature. Results indicate very good matching between the two [12]. .......................................................................................................................... 238

Figure 110: First and second order dispersion curves of an idealistic magnetic cube with an embedded Sivenpiper structure from literature [13]........................................... 239

Figure 111: Multi band dispersion curves of an idealistic magnetic cube with an embedded Sivenpiper structure calculated via FEM software to verify the method compared to standard literature designs........................................ 240

Figure 112: Multi band dispersion curves of an idealistic magnetic cube with an embedded Sivenpiper structure calculated via FEM software with $\mu_r = 1$ and $\varepsilon_r = 10$................................................................. 240

Figure 113: Multi band dispersion curves of an idealistic magnetic cube with an embedded Sivenpiper structure calculated via FEM software with $\mu_r = 10$ and $\varepsilon_r = 1$........................................................................................................... 241

Figure 114: (a) Depiction of the phase reflection bandwidth FEM simulation setup. [14] (b) Phase reflection bandwidth measurements from literature. [8] (c) Validation of bandwidth measurements via FEM simulation tools........................................... 242
Figure 115: (a) Effect of the permittivity ($\varepsilon_r$) on the bandwidth of a simulated EBG metamaterial ($\mu_r = 1$). (b) Effect of the permeability ($\mu_r$) on the bandwidth of simulated EBG metamaterial ($\varepsilon_r = 1$) [14].

Figure 116: Effect of changing the height of the EBG metamaterial on the operating frequency. Material parameters for this figure are given in Figure 124.

Figure 117: Effect of changing the patch width of the EBG metamaterial on the operating frequency. Material parameters for this figure are given in Figure 124.

Figure 118: Effect of changing the patch spacing of the EBG metamaterial on the operating frequency. Material parameters for this figure are given in Figure 124.

Figure 119: Results of the incident angle vs. EBG metamaterial bandwidth study. (a) Depicts the induced currents in the EBG substrate for various incidences of plane wave. (b) Shows the orientation of each of the studied cases. (c) Shows the bandwidth of the EBG metamaterial for each case studied.

Figure 120: Depiction of the currents induced by a microstrip above a ground plane for the case of dielectric substrate compared to that of an EBG metamaterial, the ability to reduce currents in the plane is quite apparent.

Figure 121: (a) Current sheet plots for an EBG metamaterial slab. (b) Depiction the effect of a near field spiral radiating aperture placed 1.0 mm above the EBG surface on currents produced in the EBG metamaterial during a normal mode of operation.

Figure 122: Dielectric EBG design on a $\varepsilon_r = 3$ substrate, the center frequency of the design is 1.6 GHz. The approximate bandwidth is shown to be 50% of the L-band.
Figure 123: Dielectric EBG design on a $\varepsilon_r = 6.6$ substrate with a center frequency of $\sim 2.05$ GHz. The approximate bandwidth is 7.5%. ........................................................ 255

Figure 124: Dielectric EBG design on substrate with a $\varepsilon_r = 9.8$, and a center frequency of 1 GHz. The approximate bandwidth is <5%. ...................................................... 256

Figure 125: Magnetodielectric EBG design on a $\varepsilon_r = 10$, $\mu_r = 16$ textured Co$_2$Z substrate with a center frequency of 300 MHz. The approximate bandwidth is 40%. ...... 258

Figure 126: Effect of magnetic loss on the operating frequency of a magnetodielectric EBG metamaterial with a center frequency of 500 MHz. [14].......................... 260

Figure 127: Magnetodielectric EBG design on a $\varepsilon_r = 10$, $\mu_r = 12.5$ textured Co$_2$Z substrate with a center frequency of 1.5 GHz. The approximate bandwidth is 50% of the L-band. .................................................................................................................... 262

Figure 128: (a) Design of an EBG surface for RF device applications. (b) Depiction of a single EBG element employing a Co$_2$Z hexaferrite substrate and a metallic patch. (c) Simulated bandwidth of an EBG sheet......................................................... 263

Figure 129: Depiction of a SSSA element over a low bandwidth dielectric EBG metamaterial for operation in the S-band................................................................. 270

Figure 130: Effect of antenna assembly height on return loss. A comparison of various antenna heights above a ground plane with and without dielectric EBG metamaterials is shown................................................................. 271

Figure 131: Effect of antenna assembly height on efficiency. A comparison of various antenna heights above a ground plane with and without dielectric EBG metamaterials is shown................................................................. 272
Figure 132: Effect of antenna assembly height on broad side gain. A comparison of various antenna heights above a ground plane with and without dielectric EBG metamaterials is shown. .......................................................... 273

Figure 133: (a) Effect of frequency on radiation patterns of the SSSA above a dielectric EBG metamaterial with $\varphi = 0^\circ$. (b) Effect of frequency on radiation patterns of the SSSA above a dielectric EBG metamaterial with $\varphi = 90^\circ$. .................................. 275

Figure 134: (a) Depiction of a SSSA element above a low frequency Co$_2$Z Ferrite EBG metamaterial designed to operate with a center frequency of 300 MHz and a total height of $\lambda_0/100$. (b) 3-D radiation pattern of element at the center frequency, 3.5 dB of gain is observed.......................................................... 276

Figure 135: (a) Broad side gain of the SSSA element compared to that of Chu's Limit over the operating range of the EBG metamaterial. (b) Return loss measurement. (c) Efficiency of the antenna element. (d) Axial ratio of the proposed SSSA element.......................................................... 278

Figure 136: (a) 3-D radiation pattern of an Archimedean spiral antenna designed on a magnetic EBG substrate at a center frequency of 2 GHz. (b) Top view of the spiral element design. (c) Radiating properties including gain, return loss, and efficiency.......................................................... 279

Figure 137: Conformal antenna assemblies utilizing EBG metamaterials with superstrates (a) and without superstrates (b). .......................................................... 281

Figure 138: Material parameters of the Co$_2$Z hexaferrite materials provided by Trans Tech including the permittivity and permeability as well as the loss tangents associated. .......................................................... 282
Figure 139: EBG designed to operate below the ferromagnetic resonance of the unbiased unoriented Co$_2$Z hexaferrite provided by Trans Tech. .............................................. 283
LIST OF TABLES

Table 1: Comparison of operating ranges of a variety of ferrite materials........................99
Table 2: Comparison of parameters of Ni$_{0.5}$Zn$_{0.5}$Fe$_2$O$_4$ and Mg$_{0.5}$Zn$_{0.5}$Fe$_2$O$_4$ hexaferrites produced via a variety of different fabrication methods.................................................99
Table 3: Overview of dielectric antenna elements presented in Chapter 6......................184
Table 4: Commercially available ferrite materials for absorber layers and their respective frequency ranges of interest.................................................................204
Chapter 1: Introduction

1.0 Reason for Study

In order to meet the ever increasing demands of defense and commercial communications systems, novel antenna elements are constantly being developed [1-19]. The goal of these designs is often to reduce the antenna profile and planar dimensions, while at the same time maintaining or enhancing the antenna gain and bandwidth. It is a well known fact of antenna design that the efficiency, gain, and bandwidth of an antenna element varies depending upon its size. It is a direct result of this fact that low frequency antenna systems are comparatively large [20-21]. It is also well known that to maximize gain, antennas require ground planes positioned beneath the element at large distances ($\lambda_{sub}/4$) to achieve optimal efficiency. Due to the long wavelengths inherent to low VHF (.3 - 300 MHz) and UHF (.3 - 300 GHz) bands, these cavities can be rather large. Therefore; with the existing technology, even a small radiating aperture antenna approaching that of Chu's limit [22-23] in size is required to have a large ground plane and substrate cavity making the miniaturization of the antenna assembly largely ineffective [1-2]. It is because of this that development of innovative, size-reduction techniques, that allow antennas to operate without losing performance are in much demand. The goal of this dissertation will be to develop novel materials and metamaterials which can be used to achieve these size reduction goals, while maintaining usable antenna performances.
There are three particular methods of achieving these goals that have recently been gaining popularity. First is the utilization of high permittivity ($\varepsilon_r$) substrates to increase the electrical size of the aperture without increasing its physical size, thereby allowing the antenna to operate at lower frequency bands this is referred to as dielectric loading. These materials also lower the profile of the prospective antenna assemblies due to the fact that the height of the cavity depends on the dielectric properties of the substrate. While promising, these high permittivity materials tend to decrease the overall bandwidths and gains of the antenna due to introducing a mismatch impedance at the feed point [3-9]. In addition these high permittivity materials tend to incorporate high dielectric losses which reduce the efficiency and gain of the antenna assemblies.

The second method gaining popularity is to utilize high permeability ($\mu_r$) magnetic, and magnetodielectric substrates with values of $\varepsilon_r$ close to $\mu_r$. This allows for easy impedance matching between the substrate and free space. In this dissertation it will be shown that while these substrates produce stable return loss measurements, oftentimes over broad frequencies, the gain is sacrificed due to introducing another loss mechanism via the magnetic materials. These materials tend to have high magnetic loss tangents which are even more pronounced at high frequencies (L-Band (1-2 GHz) and above). Also, there is a large problem finding materials which have consistently high values of permeability in the UHF band [10-14].

The third method of volumetric reduction which has been gaining in popularity is that of implementing an electromagnetic band gap (EBG) metamaterial layer beneath the
antenna as a ground plane. EBG metamaterials, due to their intrinsic behavior, simulate a magnetic conductor; this allows for remarkable reduction in height of the antenna [15-19]. This is due to the fact that the EBG ground plane acts as a high impedance magnetic conductor, and does not allow currents to flow in the plane. Therefore, the high-impedance EBG reflective surface does not give rise to the $180^\circ$ phase shift to the incident wave common to metallic ground planes [20]. Essentially, the introduction of the EBG metamaterial eliminates the phase shift introduced by a metallic ground plane, and thus enables the placement of the antenna much closer to the ground plane. These unique properties of the EBG metamaterial can be utilized in reducing the height of antennas by using the EBG as a ground plane. Concomitantly, this design characteristic allows for the antenna to maintain or enhance its gain and bandwidth [19]. However, one of the obstacles in using EBG metamaterials for broadband antenna applications is the narrow band gaps of the EBG metamaterials which restricts the antenna operation to narrow bands [15-19]. This will be addressed at length in this dissertation.

1.1 Dissertation Overview

The discussion of common antenna miniaturization techniques will begin in Chapter 2; topics will include techniques such as utilizing commercially available dielectric substrates and superstrates for their dielectric loading effects. It will be shown that while these techniques can be mildly successful in reducing the overall dimensions of antenna designs as well as improving their radiation performance, they cannot achieve the small sizes and advanced radiation parameters desired in many novel commercial and defense applications; namely, heights of $<\lambda_0/40$, while maintaining high gain, bandwidth,
and efficiency. In the following sections of Chapter 2, techniques employing the use of ultra high permittivity materials for antenna miniaturization will be examined through a materials fabrication perspective. The goal of this discussion will be to develop a material which can operate as a low loss substrate for a miniaturized global positioning system (GPS) antenna design. This material, in addition to being low loss, will be tested with regard to the temperature stability of its dielectric constant \( (\varepsilon_r) \) which defines the range of applications in which this element could potentially be used. Following this discussion a patch antenna design will be proposed for this material, resulting in an antenna assembly which operates close to that of Chu's Limit [22] with a height of \( \sim \lambda_0/40 \). It will be shown; however, that even though a miniaturized antenna is possible utilizing these techniques, the large mismatch impedance due to the high permittivity of the substrate makes broadband operating impossible.

In addition to standard and novel dielectric materials presented in Chapter 2, magnetic materials will be examined as antenna substrates from a materials fabrication perspective to address the aforementioned narrow bandwidth concerns. In particular Chapter 3 will focus on the structural, morphological, and magnetic properties of \( \text{Mg}_{x}\text{Zn}_{1-x}\text{Fe}_2\text{O}_4 \) and other spinel ferrites formed through modified polyol and aqueous co-precipitation methods. These materials will be introduced as low frequency antenna substrates and absorber layers due to their intrinsically low ferromagnetic resonance values (FMR). The synthesis methods presented here will demonstrate promise for low cost industrial scale manufacturing of \( \text{Mg}_{x}\text{Zn}_{1-x}\text{Fe}_2\text{O}_4 \) and other spinel ferrites for a
variety of commercial and defense applications. It will be shown that these materials are applicable for designs up to 100 MHz, and for absorber layers up to 300 MHz.

Following the study of these low frequency magnetic materials, cobalt substituted Y-Type barium hexaferrite (Ba$_2$Co$_2$Fe$_{12}$O$_{22}$) particles (Co$_2$Y) will be introduced for higher frequency antenna designs in Chapter 4. These materials will be introduced via a materials fabrication perspective, synthesized utilizing an modified aqueous co-precipitation chemical synthesis method followed by a single step sintering at low temperatures, at or above 900 °C. Optimized materials will be characterized for structure, morphology, and magnetic properties. All measured properties, including lattice constants, magnetic moment, and coercive field, will be determined to be in close numerical agreement with bulk reference values. The presented method will be shown to produce greater than 12 g of powder per batch (25g/L), with potential for much larger batch sizes, making this process suitable for industrial scale production. Additionally the magnetic and dielectric constants of these materials will be studied, and the concept of texturing will be introduced to see how these electrical and magnetic material parameters can be tuned for optimal device designs. These materials will be shown to be suitable for antenna and EBG designs up to 1 GHz.

Chapter 5 will follow the discussion of Co$_2$Y hexaferrites with the fabrication of cobalt substituted barium Z-Type hexaferrite materials (Co$_2$Z) which will also be demonstrated through a co-precipitation of elements method. These materials will be thoroughly characterized with regard to their in plane orientation and magnetic
properties. Optimization studies will be performed to maximize the permeability and minimize the magnetic losses below ferromagnetic resonance (FMR). This study will be approached in the same way that texturing of the Co$_2$Y substrates was studied in the previous chapter. In addition, the tunability of this material will be examined as a function of applied field, allowing for tunable devices to be fabricated. This material will be shown to be suitable for unbiased device designs up to 1GHz and biased designs well into the L through S-bands. With texturing and orientation it will be shown that the parameters such as permeability ($\mu_r$) and permittivity ($\varepsilon_r$) of the Co$_2$Z ferrites are more suited to device miniaturization than Co$_2$Y hexaferrites.

Following the discussion of the formation of practical dielectric and magnetic materials for antenna and EBG metamaterial device design, both from a materials processing perspective, and in order to determine how suited these materials are to antenna miniaturization novel antenna elements will be examined in Chapter 6. These elements will be proposed through a standard dielectric approach for a variety of potential applications. These antennas will be designed to operate in both the Global Positioning Satellite (GPS) and new Global Navigation Satellite System (GNSS) bands. Using dielectric materials it will be shown that these elements can achieve wide bandwidths and a variety of different polarizations ranging from linear to elliptical and circular, each to suit a variety of potential applications. In particular, antennas with small radiating apertures compared to their operating frequencies such as Archimedean spiral antennas (ASA) and square slot spirals antennas (SSSA) will be investigated in order to create designs which are close to that of Chu's Limit [22]. It will be shown; however, that
due to the dielectric cavities beneath these elements placed at $\lambda_{\text{sub}}/4$, which are required to enhance the gain, the antennas presented in this chapter are bulky and not cost effective.

In the following chapter (Chapter 7) the use of $\text{Co}_2\text{Z}$ hexaferrites as antenna substrates to reduce the profile of antenna assemblies will be examined. It will be shown that while these substrates can reduce the height of the antennas to $\lambda_0/40$ or even $\lambda_0/65$, they negatively affect the efficiency and gain due to the magnetic losses of the substrates, even more so at higher frequencies such as the L-Band (1-2 GHz) and beyond. While these properties can be somewhat negated by creative use of superstrates as shown in Chapter 2, new orientation techniques, and the application of bias fields; new magnetic materials with even lower losses and larger operating frequencies will need to be developed to make these materials practical for commercial and defense department antenna applications. Therefore, in addition to utilizing these materials as antenna substrates, they will also be introduced as absorber layers to increase the low frequency matching of wideband antenna systems. In doing so, it will be shown that these materials can be used in antennas whose frequency bands were not previously applicable to magnetic materials due to the inherently low operating frequencies of magnetic materials (L-Band and above). Utilizing realistic ferrite parameters this will be shown as an effective way to use these novel materials in a new series of antenna designs and to incorporate magnetic materials into new technologies.

In Chapter 8, the low profile dielectric and magnetic antenna elements which were proposed in the previous chapters will be formed into phased arrays which will be
designed to operate in the GPS and GNSS bands. In this chapter it will be shown how element spacing plays a pivotal role in the formation of high gain phased arrays, and how wideband arrays can be designed. Towards this end, studies will be performed to optimize both the scanning angle and 3 dB beam widths of these antennas to make them more attractive for applications in the new GNSS bands. The resulting dielectric and magnetic phased arrays will then be compared with respect to practical applications such as cost, weight, and power handling. It will be shown that even though magnetic substrates incorporate loss into the single element designs it is still possible to achieve high gains out of phased arrays of these elements.

Chapter 9 will introduce the final approach to minimize the planar height of the proposed antenna elements through the use of electromagnetic band gap (EBG) metamaterial structures. In this chapter these metamaterials will be discussed with respect to increasing their inherently low bandwidths and reducing their heights for potential antenna applications. Towards this end both dielectric and magnetic EBG metamaterials will be introduced. Each for its own different application, including narrow and wide band antenna elements. It will be shown that by utilizing standard dielectric materials, reduction in antenna height to $\lambda_0/25$ is possible with the trade off of reduced bandwidth (~5% in the UHF through L-bands) for dielectric EBG metamaterial designs. Utilizing high permeability magnetodielectric materials such as Co$_2$Z hexaferrites it will be shown to be possible to achieve >75% bandwidths with much lower profiles ($<\lambda_0/60$) in the same frequency regions, making them practical for use in many microwave devices. In addition to these results, this chapter will include discussions on the loss mechanics of
these materials, as well as their ability to function as high impedance surfaces. The bandwidths of these designs will be calculated from both plane wave phase response calculations, as is commonly done in literature, as well as by producing the band structure plots (dispersion curves) for these materials. It will be shown that both methods are in agreement in producing accurate results.

The focus of Chapter 10 will be the application of the previous chapters EBG metamaterial designs towards different dielectric and magnetic antenna assemblies. These designs will focus on both dielectric and magnetic EBG metamaterial antenna combinations. The goal of this section will be to determine the optimal case for using each of the prospective EBG designs to suit a variety of different low profile commercial and defense related antenna applications. In particular, dielectric EBG antenna designs will be introduced for low bandwidth, higher operating frequency elements while magnetodielectric EBG designs will be introduced for wider bandwidth designs in lower frequency bands. Elements to be studied in this chapter include wide and narrow band spiral antennas.

Finally, Chapter 11 will be presented as an overview to the discussion and will include conclusions as to which of the many designs which have been presented are the most practical. This chapter will conclude with how the use of magnetic materials can enable these technologies to be open to a larger variety of potential applications, as well as list future goals and research options for these technologies.
1.2 References


Chapter 2: *High Permittivity Dielectric Materials*

2.0 Common Antenna Miniaturization Techniques

2.0.1 Introduction

In this chapter common miniaturization techniques such as dielectric loading utilizing commercially available dielectric substrates and superstrates to miniaturize the planar and profile sizes of antenna elements will be discussed with respect to achieving an antenna assembly which operates close to that of Chu's Limit [1-2]. It will be shown that by utilizing commercially available materials, these techniques can be mildly successful in reducing the overall dimensions of antenna designs; for example the height of a global positioning system (GPS) patch antenna radiating at 1.575 GHz can achieve a height of \( \lambda_o/10 \) utilizing a substrate with a permittivity (\( \varepsilon_r \)) of 9.8 compared to \( \lambda_o/4 \) in free space. However, in this chapter it will be shown that standard commercially available dielectric materials alone cannot achieve the small sizes and advanced radiation parameters desired in many commercial and defense applications, namely antennas with operation heights on the order of \( \lambda_o/40 \) to \( \lambda_o/100 \) and gains of \( >2\text{-}3 \) dB. To achieve these design goals other techniques such as the use of ultra high \( \varepsilon_r \) materials will be employed which can reduce the size of these antenna elements even further (\( \lambda_o/40 \) for \( \varepsilon_r=91 \)). These materials will be introduced from a materials fabrication perspective. In addition to keeping track to see the effect of the miniaturization these materials provide, their radiation properties such as the gain, return loss, and efficiency will also be investigated.
An antenna is considered electrically small when \( ka \leq 1/2 \) [1-2], where \( a \) is the maximum dimension of the antenna, and \( k \) is the wavenumber given by \( 2\pi/\lambda \). The limitations on bandwidth, efficiency, and gain of electrically small antennas were first investigated by Chu [1]. This work established fundamental miniaturization limits and became known as Chu's limit of antenna miniaturization. It is noted that conventional whip and monopole antennas operating at 30 MHz can be 60 to 100 inches in length and are nowhere close to Chu's limit. This is due to significant challenges associated with achieving Chu's limit in designing miniature efficient antennas with optimal gain. A rigorous interdisciplinary effort taking advantage of recent developments in metamaterials and antenna designs is required to approach Chu's limit, as proposed in this dissertation.

2.0.2 Effective Dielectric Constant

Among existing antennas for the study of the effect of dielectric loading, the patch antenna enjoys the advantages of even radiation patterns, large gain, and relative small size. In addition the radiating conditions of this element are widely understood making this element practical for study with regard to changing the dielectric properties of the substrate. A depiction of a standard patch antenna design is shown in Figure 1 [3].
In order to design a working patch antenna, a series of constants need to be set. First, the center frequency of the design needs to be determined. This value is referred to as \((f_r)_{010}\) in Eqn. (1). Here, the 010 refers to the dominant \((TM)_{010}\) mode which is excited in this antenna design. Once this value has been set the remaining parameters such as the length \((L)\), width \((W)\), and height \((h)\), can be determined from Eqn(s). (2-4) utilizing the dielectric constant of the substrate material \((\varepsilon_r)\) [3-5].

\[
(f_r)_{010} = \frac{1}{2L_{eff}\sqrt{\varepsilon_{eff}}\sqrt{\varepsilon_0\mu_0}} = \frac{1}{2(L + 2\Delta L)\varepsilon_{eff}\sqrt{\varepsilon_0\mu_0}}
\]

Eqn. 1 [3]
\[ W = \frac{1}{2 f_r \sqrt{\varepsilon_o \mu_o}} \sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{v_o}{2 f_r \sqrt{\varepsilon_r + 1}} \]  

Eqn. 2 [3]

\[ L = \frac{1}{2 f_r \sqrt{\varepsilon_{reff} \varepsilon_o \mu_o}} - 2\Delta L \]  

Eqn. 3 [3]

\[ \Delta L = 0.412h \frac{(\varepsilon_{reff} + 0.3) \left( \frac{W}{h} + 0.264 \right)}{(\varepsilon_{reff} - 0.258) \left( \frac{W}{h} + 0.8 \right)} \]  

Eqn. 4 [3]

\[ \varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \frac{h}{w} \right]^{-1/2} \]  

Eqn. 5 [3]

It is important to note that the dielectric constant used in the calculation of the antenna length is an effective constant. This is due to the fringing effects presented on the edges of the patch antenna in Figure 1. Equation 5 depicts how this value can be found. This effect is further outlined in Figure 2, where the effective epsilon is given as a function of frequency of operation for a standard patch antenna design with given \( W \) and \( h \).
In this section the results of increasing the $\varepsilon_r$ of a substrate on which a standard coaxial back fed patch antenna is placed is investigated. These results are outlined in Figure 3 where the operating frequency of a narrow band patch antenna is depicted through its return loss measurement [6]. Here it is apparent that the operating frequency decreases as the permittivity increases. This is due to the increased electrical length of the radiating element due to the dielectric loading of the substrate, not any actual increase in the aperture size. From this, the planar minimization effect of the permittivity is directly apparent.
In addition to this planar miniaturization, the increase in permittivity of the substrate miniaturizes the profile of the antenna as well. This is due to the fact that antenna elements are generally placed at a height of $\lambda_{sub}/4$ from the ground plane. This is due to the $180^\circ$ phase shift these perfect electric conductors (PEC) provide to the reflected electromagnetic wave. In this fashion the reflected electromagnetic energy is in phase with the energy radiated from the broad side of the antenna, maximizing the gain. Here $\lambda_{sub}$ is calculated as shown in Eqn (6) where $f_{center}$ is the center frequency of the antenna design and $c$ is the speed of light.

$$\lambda_{sub} = \frac{c}{f_{center}} = \frac{\sqrt{\varepsilon_r \mu_r}}{f_{center}}$$

Eqn. 6

Figure 3: Effect of changing the substrate permittivity on patch antenna operating frequency, one of the more common antenna miniaturization techniques.
What is not apparent from the minimization pictured in Figure 3, is the effect of the increasing dielectric constant on the overall bandwidth of the radiating element. However, it is a generally well known fact that the use of high $\varepsilon_r$ materials, while increasing the electrical size of the antenna apertures, have severe impacts on the radiation and bandwidth of these devices. In particular, there is a large problem with the impedance bandwidth of elements on high $\varepsilon_r$ ceramic substrates [7-8]. This leads to antennas with very narrow bands of operation, which is not desirable for many potential commercial and defense related applications, where wide band antennas are commonly being utilized to cover a variety of operating bands reducing the number of elements used and lowering the overall cost.

2.0.3 Superstrate Designs

The second technique employed in this chapter is the use of a superstrate in antenna element design. These materials can be used to increase the low frequency gain of an antenna [9-10], and thereby enhance the minimization effect provided by a dielectric substrate. This is due to the fact that a higher permittivity material such as a superstrate acts to "soak up" the electromagnetic radiation of the element; in essence, a slot radiator on a dielectric half-space will radiate a factor of $\varepsilon_r^{1.5}$ of more power into the dielectric than into the air half-space [9]. An additional effect of utilizing superstrates in antenna design is to make the antenna a unidirectional radiator [10]. For single-sided loading, the expected maximum achievable miniaturization factor is $\sqrt{\varepsilon_{eff}}$, with $\varepsilon_{eff} = (\varepsilon_r + 1)/2$. In this section the miniaturization effect of a superstrate on an antenna element is examined. It should be noted that adding a superstrate onto the design of an
antenna will increase its profile, which is a concern when low profile antenna development is a main goal. Therefore the goal will be to keep the profile of the superstrates as low as possible.

Figure 4: Effect of superstrates of varying dielectric constants on the broad side gain of a spiral antenna [10].

Figure 4 shows the effect that different (constant \( \varepsilon_r \)) substrates have on the miniaturization of an antenna as viewed through the increase in the elements low frequency gain. From these results it is clear to see that superstrate loading is beneficial in achieving optimal gain and planar miniaturization. This is due to the increased gain at low frequencies which is one of the main design goals of this dissertation. In this section three different types of superstrates will be examined from a potential antenna application perspective; the first superstrate examined was a single layer substrate of varying
permittivity and constant electrical length. The results for this study can be seen in Figure 5, and match the results from literature very well (Figure 4); namely that varying the $\varepsilon_r$ of the superstrate has a drastic effect on the low frequency gain of the antenna. Centering on the -10 dB gain line, it is apparent that there is almost a 100 MHz shift between the case of no superstrate and that of a permittivity of 10. This shows that while maintaining a constant aperture size, the low frequency gain can be increased due to dielectric loading. Achieving this same shift of operational frequency without dielectric loading would require a much larger aperture.

![Miniaturation due to Superstrate](image)

Figure 5: Effect of changing superstrate permittivity on patch antenna operating frequency, one of the most common antenna miniaturization techniques.

The second superstrate design investigated was a multilayer substrate; the goal of this design was to better achieve impedance matching between the antenna and air. In this
design a three layered approach with permittivities of 10.2, 6.15, and 2.2 for each layer was used, respectively. All materials in these simulations are commercially available from Rodgers Materials\textsuperscript{(TM)}. In this study, it was determined that the multilayered approach made impedance matching slightly easier. However, this novel superstrate did not significantly affect the gain over the single layer superstrate case previously presented. Maintaining a constant electrical length in the superstrate layers for this design; however, resulted in a much larger antenna design than what was desired, so this multilayer approach will not be utilized in future designs.

![Graph](image-url)

Figure 6: Effect of tapering the superstrate on the low frequency gain of a slot radiating element [10].
The final investigated superstrate design was a tapered approach presented in literature [10]. In this design the dielectric loading is only present on the areas of the antenna which radiate at low frequencies, namely the outside rings of the spiral antenna (the geometries of these antennas will be studied in depth in chapter 6). The main benefit to this design is that when the superstrate is not placed above the feed point it is much easier to match the antenna, while at the same time enhancing gain at the lower operating frequencies which is the goal of the miniaturization process. Figure 6 shows the effect of these superstrate designs on the broad side gain patterns of a spiral antenna. Here the improvement of the gain at low frequencies is readily apparent. The goal of the future sections of this dissertation will be to maintain these radiation characteristics while at the same time dramatically decreasing the antennas profile.

2.0.4 Conclusions

In this section, common miniaturization techniques such as utilizing dielectric substrates and superstrates have been examined. It has been shown that by utilizing dielectric materials and novel superstrate designs that an aperture antenna can be made electrically larger without increasing its physical size. This is demonstrated with higher gains at lower frequencies. While these techniques have been mildly successful in the development of miniaturized antennas (for their respective aperture sizes), they have not achieved the low profile sizes desired in many commercial and defense applications. These desired sizes are for ultra low profile antennas which have heights on the order of <λ₀/60. Towards this end other techniques will have to be employed which can reduce the
profile of these antenna elements without overly affecting their radiation properties such as the gain, return loss, and efficiency.

In the following sections of this chapter, techniques employing the use of ultra high permittivity materials for antenna miniaturization will be examined through a materials fabrication perspective. The goal of these sections will be to develop a material which can operate as a low loss substrate for miniaturized antenna designs with a profile height on the order of $\lambda_0/40$. Following this discussion, an antenna element will be proposed for this material which operates in the Global Positioning System (GPS) operating band.

### 2.1 High Permittivity Dielectrics Developed as Antenna Substrates

#### 2.1.1 Background

To achieve the goal of miniaturization in antenna design, many groups have turned to high dielectric constant materials to be used as antenna substrates with varying degrees of success [7-9]. Other groups have abandoned this method, and have gone with more novel substrate techniques, such as magneto-dielectric substrates and reactive impedance substrates [11-14]. This is generally due to the fact that high $\varepsilon_r$ substrates by themselves have been shown to severely limit the bandwidth of the antenna elements placed on them. This is due to the severe impedance mismatch imposed when incorporating these high $\varepsilon_r$ substrates. Recently, this behavior has been investigated and it has been shown that this bandwidth reduction can in fact be improved on patch antennas with high permittivity superstrates with varying degrees of success [8]. However, this
loading material increases the physical dimensions of the patch antenna which is undesirable for many applications such as those requiring ultra low profile antennas. These thicknesses are often on the order of the substrates themselves, almost doubling the overall size of the patch antenna assemblies. Also, the gains in bandwidth are not overly large, making these designs only practical for narrow band antennas.

In the previous sections it has been shown how the permittivity is closely related to the miniaturization of an antenna design with respect to its electrical length and operating frequencies. When choosing a high permittivity material for an antenna substrate particular care must be spent on choosing one which will meet the demands of the design. For the design investigated in this chapter, namely a miniaturized narrow band GPS antenna, the goal was a material with a permittivity on the order of 100 allowing for a antenna height on the order of $\lambda_0/40$ (Eqn 6.), a low dielectric loss tangent, a bandwidth of 20-30 MHz, and good thermal stability of its parameters (<10%) over the temperature range of -0 to 80°C. This temperature stability is vitally important if the antenna is to be used in outdoor environments, which is common for miniaturized GPS antennas.

2.1.2 Potential Materials for Antenna Substrate Designs

Some of the most promising and most widely used ceramics for radiating elements are those of the titanate variety. In particular $(\text{Ba}_{1-x}\text{Sr}_x)\text{TiO}_3$ ceramics have been widely used on projects ranging from antennas to capacitor design. They are used because of the tunability in their permittivity ($\varepsilon_r = 1000$-2000) as shown in Figure 7.
While this may seem overly high for antenna applications this permittivity can be lowered via doping with common oxides such as MgO, which will be discussed in detail in the following section. The general non-doped tunability of the permittivity is achieved by interchanging the quantities of barium and strontium within the ceramic. Special care needs to be shown to these values, as small changes in barium content can significantly change the permittivity of the sample [15].

It is clear from both Figure 7 and Figure 8 that this material itself is not ideal for the antenna application presented above. First the permittivity is much too high, making it practically impossible to fabricate a patch which resonates in the frequency range desired due to the impedance mismatch imposed by the high permittivity substrate. Also, the bandwidth of the antenna fabricated on a substrate of that permittivity would not be wide enough for any practical applications. This data, as previously mentioned has been widely documented among antenna researchers [7-8, 11-14]. Since the goal of this design is an antenna that has a bandwidth of 20-30 MHz, a permittivity of 1000 is impractical due to the reduced bandwidth it would provide.
Secondly, the loss tangent provided in Figure 8 for undoped titanates is much too high (.014). This would make the antenna almost impossible to fabricate, and would further deteriorate the antennas performance. Fortunately, researchers have been able to avoid these problems by doping these materials with common oxides. These have been shown to significantly reduce the permittivity to the order of 100, while at the same time reducing the loss tangent of the material. In particular, MgO has been widely used [16]. Figure 8 shows how incorporating MgO into the (Ba\(_{1-x}\)Sr\(_x\))TiO\(_3\), positively affects the loss tangent reducing it to .004 for quantities of MgO >60%. Other oxide materials that have been used in these studies include TaO, and CaO [17].

![Graph showing permittivity of (Ba\(_{1-x}\)Sr\(_x\))TiO\(_3\) for x varying from 0.45 to 0.60](image)

**Figure 7: Dielectric constant of (Ba\(_{1-x}\)Sr\(_x\))TiO\(_3\) for x varying from 0.45 to 0.60 [15].**
Clearly, this material exhibits the properties that make an antenna radiate effectively, namely dielectric properties and loss. However; since the design goals for many commercial and defense applications also require a material that is thermally stable over a large temperature range it still needs to be tested in a laboratory environment. Towards this end, samples of (Ba$_{1-x}$Sr$_x$)TiO$_3$ with differing MgO quantities have been produced in order to test their performance at different temperatures.

2.1.3 Development of Practical Substrate Materials

The process that was used to create these materials was one common to ceramics. It consisted of measuring the constituent powders according to molecular weight, and then mixing them together in a high power ball mill for three hours. These powders were then pressed at 1500 psi, and sintered at 1100 °C for 8 hours. After sintering, the pucks were broken down using a mortar and pestle. Differing quantities of MgO were then
added, and the process was repeated. The only difference was that in the second and subsequent firings, the temperature was increased to 1450°C. The pucks were annealed in an alumina cylinder, surrounded by alumina powder. This was to promote even heating, and to reduce the surface tension that resulted in shape discrepancies of the finished product. These finished pucks then underwent a series of measurements to ensure they were correct for GPS antenna applications.

It is clear to see from the $\theta$-2$\theta$ X-ray diffraction (XRD) data presented in Figure 9(c) that very consistent $(\text{Ba}_{1-x}\text{Sr}_x)\text{TiO}_3$ ceramic (red circles) doped with MgO oxide (blue squares) was produced. It is also clear to see that the permittivity of the material was exactly within the given bands of the design goal which was given in the previous section. However, from the temperature measurement given from the ferroelectric test unit (FTU) in Figure 9(a) and (b) it is clear to see that the change in the dielectric constant over the temperature range of 0 to 80°C are not within the bounds of the above design goals. Namely, that the thermal stability is not sufficiently stable at <10% over the depicted temperature range. However; recent work done with calcium oxide (CaO) doping addresses this problem [17].
Figure 9: Previous work on high permittivity dielectrics designed for Navy shipboard applications, (a) demonstrates the stability of the permittivity with applied voltage. (b) Demonstrates the temperature stability of the permittivity, varying ~10% over the desired operating region. (c) Demonstrates the phase purity of the ceramic dielectric composites with varying MgO weight compositions.

In this section a series of results have been presented which demonstrate the ability of oxide doped (Ba$_{1-x}$Sr$_x$)TiO$_3$ ceramics to operate as high permittivity antenna substrates. In the following section, in conjunction with Trans Tech Inc, an antenna has
been designed which fills the design goals given above. Even though these materials were provided by Trans Tech Inc, the preliminary research into their properties proved invaluable in suggesting what doping should be done on their ceramics. The material provided has great thermal stability, low loss, and a permittivity on the order of 100.

2.2 Antennas on High Permittivity Substrates

In this section a linear GPS patch antenna on a high permittivity substrate will be introduced. The design is rectangular and back fed via a standard 50 Ω coaxial line. The geometry of the design is presented in the Figure 10. The height is given by Eqn. (6), where the material parameters are those given in the previous chapter (ε_r≈100), the center frequency for the design was set to 1.6 GHz. This height correlates to ~λ_0/40, which is much closer to the requirements of novel ultra low profile antenna designs than the standard dielectric materials which were introduced previously.

A large ground plane was used in increase the antennas performance, this was following design constraints which had this element sitting on a metal surface. As was to be expected, the λ/sub/4 thick substrate resulted in a very good return loss at the center frequency of the design, it should be noted; however, that the bandwidth of this antenna was only 4 MHz, which was much lower than the original design goal of 20-30 MHz, this was due to the ultra high permittivity of the substrate material. In Figure 11 a return loss of over -10 dB is shown at the center frequency of the antenna, which can be attributed to the impedance matching for the antenna at this frequency. The impedance value of this
feed network was studied in depth in order to determine how practical a wider band design would be and also in order to get a better understanding of the role that the coaxial feed point plays. The results of this impedance study are shown in Figure 12, where a real part of 49.31 \( \Omega \) and an imaginary part of -25.84 \( \Omega \) is shown, albeit over a very narrow bandwidth. This indicates that this design cannot be used for wideband antenna elements.

![Diagram of antenna design](image)

**Figure 10:** Design of a 50 \( \Omega \) coaxial fed GPS antenna utilizing high permittivity materials \( \varepsilon > 90 \). Simulated utilizing FEM software on an infinite ground plane.
In order to better understand how this antenna radiates the electric field on the patch itself was generated via finite element method (FEM) software. From this figure it can be seen very clearly how linear polarization is achieved for this antenna design. Here, both edges pulse in phase, one in the positive direction and one in the negative. As the signal pulses so do the edges of the conductive radiating element. This exactly mirrors the behavior that one would expect in an antenna that is radiating in the TM$_{010}$ mode (which was outlined in the first chapter of this dissertation, section 2.0.2). Also examined in detail are the radiation parameters of this antenna, including its observed radiation patterns (Figure 14). The directivity of this antenna was simulated via FEM techniques to
be ~3.1, and its gain was simulated to be ~5 dB. These numbers make perfect sense based off its radiation patterns shown in Figure 14.

Figure 12: Simulated impedance matching of a 50 Ω coaxial fed GPS antenna utilizing FEM software on an infinite ground plane. The red curve is the real impedance, and the blue curve is the imaginary impedance.

It is quite apparent from the results provided above that a workable antenna in the GPS frequency is possible utilizing a $\lambda_{\text{sub}}/4$ ($\sim\lambda_{0}/40$) thick high permittivity substrate. However, the bandwidths are severely limited due to the high permittivity material used. Previously, studies have been performed in order to mitigate this concern and techniques such as adding ferrite films to see if the performance of this antenna could be further enhanced [18-20] have been tried. While results have been encouraging, they are not
sufficient enough to increase these bandwidths enough for wide band antenna applications and have therefore not been included in this dissertation.

Figure 13: Simulated electric field on the radiating patch of a 50 Ω coaxial fed GPS antenna utilizing high permittivity materials ($\varepsilon_r > 90$). Simulated utilizing FEM software on a circular ground plane.
Figure 14: Simulated radiation pattern at the center frequency of 1.575 GHz of a 50 Ω coaxial fed GPS antenna utilizing high permittivity materials ($\varepsilon_r > 90$). Simulated utilizing FEM software on a circular ground plane.

2.3 Conclusions

In this chapter a valid process of making miniaturized (~$\lambda_0/40$) GPS antennas have been presented. The main idea presented is that increasing the permittivity of a substrate will decrease the dimensions of a patch antenna needed to radiate at a specific frequency as well as decrease the profile of the antenna design. Towards this end it has been shown that a ultra high permittivity low loss antenna substrate ($\varepsilon_r \sim 100$) can be fabricated. These substrates can achieve the desired magnitudes of many antenna characteristics such as thermal stability, high permittivity, and low loss by utilizing creative doping techniques. However, in approaching antenna miniaturization from this
perspective undesirable outcomes will inevitably occur. These outcomes include the loss of antenna bandwidth, the inability of matching the antennas due to the mismatch impedance from the substrates, and losses in gain. In order to address these limitations, different antenna substrates will be examined in the following chapters. These substrates will utilize the same concepts of dielectric miniaturization; however, in addition they will utilize magnetic materials which have a permeability ($\mu_r$). This will allow for the fabrication of substrates where $\mu_r = \varepsilon_r$, where wide band matching will be more easily achieved. The formation of these substrates will be examined via multiple chemical ferrite processes, and will encompass a wide variety of ferrite materials which can be used as substrates for antenna applications including both spinel and hexaferrites. In the later chapters of this dissertation, these materials will be utilized to show that wide band antenna designs can operate at extremely low profiles ($<\lambda_0/60$).

2.4 References


Chapter 3: Spinel Ferrite Nanoparticle Formation

3.0 Introduction to Spinels

3.0.1 Background and Theory

In this chapter a series of low frequency magnetic materials called spinel ferrites will be investigated. These materials will be discussed from a materials fabrication perspective utilizing various modified co-precipitation of elements techniques developed at Northeastern University [1-3]. After fabrication, the morphologic and magnetic properties of these materials will be investigated. In addition, their magnetodielectric properties will be examined for use as potential substrates for perspective antenna and electromagnetic band gap (EBG) metamaterial substrates.

Figure 15: Depiction of cubic spinel crystal structure, showing where the octahedral and tetrahedral sites reside [4].
The first example of these materials is Nickel-zinc ferrite (Ni\(_{(x)}\)Zn\(_{(1-x)}\)Fe\(_2\)O\(_4\)), a technologically important material system utilized in a wide variety of power electronics and RF applications due to its combination of relatively high permeability (\(\mu_r\)) and resistivity (\(\rho\)). These properties allow this material to be used as low loss inductor and transformer cores as well as EMI suppression devices at higher frequencies than other spinels such as manganese-zinc ferrite (Mn\(_{(x)}\)Zn\(_{(1-x)}\)Fe\(_2\)O\(_4\)). However, in recent years, several U.S. federal agencies have expressed concern over the carcinogenic effects, as well as environmental toxicity of nickel and nickel-containing compounds. Specifically, the U.S. Department of Health and Human Services has recently identified that metallic nickel, as well as nickel-containing compounds are human carcinogens [5]. Additionally, the Environmental Protection Agency (EPA) has classified nickel refinery dust and nickel sub-sulfides as human carcinogens [6]. The environmental impact of nickel as a pollutant is presently being evaluated [7].

In addition to their potential uses as transformer cores, the properties of Ni\(_{(x)}\)Zn\(_{(1-x)}\)Fe\(_2\)O\(_4\) such as the high \(\mu_r\) are promising for applications in absorber layers and low frequency antenna substrates. However, considering the implication on their carcinogenic effects, a low-toxicity, cost effective substitute material with comparable RF and magnetic properties is urgently needed. Since magnesium is divalent and preferentially resides on the octahedral sub lattice similar to nickel (Figure 15), one potential substitute material is magnesium-zinc spinel ferrite (Mg\(_{(x)}\)Zn\(_{(1-x)}\)Fe\(_2\)O\(_4\)). The synthesis of magnesium zinc spinel ferrite has been demonstrated through a variety of methods,
including solid-state reaction [8-15], sol-gel [16], citrate, and other methods [17-18]. Cation substitutions in magnesium-zinc ferrite, such as copper, have also been attempted and their effect on RF and magnetic properties investigated [14, 16]. However, the above methods require high processing temperatures [12] (~1300°C) and produce large particle size variations, which make them less than ideal for many commercial applications. In this work, the structural, morphological, and magnetic properties of magnesium-zinc ferrites, formed through low temperature polyol and aqueous modified co-precipitation methods, are examined for antenna applications. In addition cobalt spinels will also be investigated due to their intrinsically high ferromagnetic resonance (FMR) values, which allow for higher frequency device operation. It should be noted that while this is practical from a device design perspective, cobalt is also a toxic material, and special care should be exercised when working with it.

In the following section of this chapter, utilizing the polyol method, low temperature formation (~160°C) of multiple spinel ferrites in small quantities with high particle size uniformity is demonstrated. In particular, the glycol surfactant chain length is shown to allow control over the average particle size. This capability is of particular significance in synthesizing materials for RF applications, including EMI suppression, and EM absorber coatings which have many applications in antenna design and antenna technologies. For other applications requiring large quantities of high purity spinel ferrites such as substrate fabrication, the aqueous co-precipitation method [1-3] will be employed. Finally, the magnetic, microwave, and morphologic properties of particles
produced by both methods are evaluated as materials to be used in practical ferrite antenna and electromagnetic band gap (EBG) metamaterial designs.

3.1 Polyol Spinel Formation

3.1.1 MgZnFe$_2$O$_4$

Single phase powders of Mg$_{(x)}$Zn$_{(1-x)}$Fe$_2$O$_4$, with compositional parameter $x$ varying from 0 to 1 in 0.1 increments, were produced by utilizing a co-precipitation of elements technique in 100 ml of diethylene (DEG-((HOCH$_2$CH$_2$)$_2$O)) or tetraethylene glycol (TEG-(HOCH$_2$CH$_2$(OCH$_2$CH$_2$)$_3$OH)) heated to ~160°C and stirred at 300 rpm for one hour. Starting ingredients were mixed in the appropriate stoichiometric ratios in the following amounts: 0.835 g of ferrous chloride (FeCl$_2$-4H$_2$O), 0.225 g of magnesium acetate tetrahydrate (C$_2$H$_3$O$_2$Mg·4H$_2$O), 0.231 g of zinc acetate tetrahydrate (C$_4$H$_6$O$_4$Zn·2H$_2$O), and 8.000 g of sodium hydroxide (NaOH). Salts and chlorides were added simultaneously to a 250 ml vessel which was heated to 160 °C utilizing a standard hot plate and subsequently mixed utilizing a magnetic stirrer at 300 rpm. The vessel was covered with a reflux apparatus to reduce the amount of liquid lost during the reaction. Upon completion of the reaction, the solution was allowed to cool and the precipitated particles were filtered magnetically utilizing a methanol rinse. Drying was done at room temperature in a vacuum furnace over the course of 12 hours. After drying, samples underwent structural, morphological, and magnetic characterization via standard θ-2θ X-ray diffraction (XRD), scanning electron microscopy (SEM), and vibrating sample magnetometry (VSM) measurements, respectively.
Figure 16: Comparison of magnetic properties of spinel ferrites formed via different polyol co-precipitation routes [1].

Figure 16(a) depicts the magnetic hysteresis loops acquired via VSM measurements of the Mg$_x$Zn$_{(1-x)}$Fe$_2$O$_4$ spinel ferrite having $x = 0.5$ prepared using DEG and TEG surfactants. Clearly, the magnetic moment in units of emu/g is much higher for the DEG sample. The difference in magnetic moment is attributed in part to the difference in average particle size, which was determined to depend upon the length of the surfactant chain. Specifically, larger average particle size was obtained using DEG compared to TEG as will be shown in the XRD patterns and SEM images to be discussed shortly. The magnetic properties, including saturation magnetization and coercivity of the DEG Mg$_x$Zn$_{(1-x)}$Fe$_2$O$_4$ samples are shown in Figure 20, and are similar to those previously published for nanoparticles of Ni$_x$Zn$_{(1-x)}$Fe$_2$O$_4$ with comparable sizes [16] up to 30 nm, at which point the NiZn spinel ferrite moment becomes higher. Complete data
on this comparison is presented in Table I. Figure 17(a) depicts the hysteresis loops acquired by VSM measurements of $\text{Mg}_x\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ ferrite samples, with $x = 0$ to 1 in increments of 0.2, formed using DEG as surfactant. Saturation magnetization of the samples in Figure 17(a) is plotted as a function of Mg content ($x$) in Figure 17(b). The moment is observed to decrease nearly linearly with increasing values of $x$. This is due to a combination of Mg content and the effect it has on formation temperature, namely the overall phase purity produced, which will be investigated shortly in detail. DEG was chosen for this study due to the higher magnetic moment compared to that of particles produced using TEG.

![Graphs](image.png)

**Figure 17:** Magnetic Moment vs Mg concentration in $\text{Mg}_x\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ spinel ferrites for $x$ varying between 0 and 1 by increments of 0.2 [1].

XRD spectra of $\text{Mg}_x\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ ferrite samples for $x = 0.5$ prepared using DEG and TEG as surfactants, collected in $\theta$-$2\theta$ mode using Cu $k\alpha$ radiation, are shown in
Figure 18(a). Both samples appear to be single phase with markedly different peak widths and heights reflecting mean particle size. Figure 18(b) shows the effect of Mg content for x from 0 to 1 in increments of 0.2 on the XRD spectra of samples produced using the DEG surfactant. Pure phase materials are formed for values of x ≤ 0.5, with secondary phase peaks beginning to appear for x > 0.5, this is due to the effect of Mg on the formation temperature, which has remained constant at 160°C for all samples. The broadening of the diffraction peaks suggests reduced particle size for values of x approaching 1. This has been verified via Scherrer analyses (Figure 23(d)).

Scanning electron microscopy (SEM) images of Mg$_x$Zn$_{1-x}$Fe$_2$O$_4$ ferrite samples for x = 0.5 prepared using TEG and DEG surfactants are shown in Figure 23(a and b), respectively. Both images reveal a collection of spherical particles with a narrow size distribution with, DEG particles of the order of 20-30 nm and TEG particles ~ 10 nm. These images further support that the enhanced saturation magnetization in Figure 16(a), and the increased diffraction peak intensity and reduced full width at half maximum values seen in Figure 18(a) for DEG samples are associated with increased average particle size compared to TEG samples. Additionally, Scherrer analysis, which has been performed on the DEG samples of Figure 23(d), show good agreement with SEM determined particle size.
Figure 18: X-ray diffraction spectra of $\text{Mg}_{x}\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ ferrites ($x = 0.5$) produced using diethylene glycol (DEG) compared to those produced using tetraethylene glycol (TEG) (a). X-ray diffraction spectra of $\text{Mg}_{x}\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ ferrites produced using diethylene glycol (DEG) as a function of Mg content ($0 \leq x \leq 1$) (b) [1].

3.1.2 $\text{NiZnFe}_2\text{O}_4$

One of the main goals mentioned in the previous section on $\text{Mg}_{x}\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ ferrites was the use of these ferrites to replace the more widely used $\text{NiZnFe}_2\text{O}_4$ spinel
ferrites which have been shown to be quite toxic [4-7]. In order to compare these spinel ferrites to those developed in the previous section a routine for the fabrication of these ferrites needed to be developed. Towards this end a modified co-precipitation of elements technique has been developed for the formation of NiZnFe$_2$O$_4$ ferrites. Figure 19 depicts the results of this study where the X-ray diffraction data of the Ni$_{5}$Zn$_{5}$Fe$_2$O$_4$ ferrite is shown.

Figure 19: XRD spectra of Ni$_{5}$Zn$_{5}$Fe$_2$O$_4$ spinel ferrites, plotted as intensity vs. 0-2θ (degrees) indicating high phase purity.
In this study phase powders of $\text{Ni}_3\text{Zn}_3\text{Fe}_2\text{O}_4$ were produced by utilizing a co-precipitation of elements technique in 100 ml of tetra-ethylene glycol. Starting powders were mixed in the appropriate stoichiometric ratios in the following amounts: .835 g of Ferrous Chloride ($\text{FeCl}_2\cdot4\text{H}_2\text{O}$), .217 g of Zinc Acetate Dihydrate ($\text{C}_4\text{H}_6\text{O}_4\text{Zn}\cdot2\text{H}_2\text{O}$), .325 g of Nickel Acetate Tetrahydrate ($\text{(C}_2\text{H}_3\text{O}_2)\text{Ni}\cdot4\text{H}_2\text{O}$), and 8.0 g of Sodium Hydroxide ($\text{NaOH}$). Salts and chlorides were added simultaneously to a larger vessel (250ml flat bottom beaker), which was heated utilizing a hot plate to 160°C and subsequently mixed using a motorized stirrer at 300 rpm for 1 hour. Particles were separated via centrifuge, and a methanol rinse was performed to remove excess glycol. Phase purity was examined via $\theta$-2$\theta$ X-ray diffraction techniques (XRD). Particle size estimations of 8-12 nm were achieved via scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

Figure 20: Comparison of magnetic properties of $\text{Ni}_{3.35}\text{Zn}_{3.65}\text{Fe}_2\text{O}_4$ [19] and $\text{Mg}_{3}\text{Zn}_{3}\text{Fe}_2\text{O}_4$ spinel ferrites are plotted with respect to particle size [1].
A second comparison made between the Ni\textsubscript{5}Zn\textsubscript{5}Fe\textsubscript{2}O\textsubscript{4} and Mg\textsubscript{5}Zn\textsubscript{5}Fe\textsubscript{2}O\textsubscript{4} ferrites with respect to their magnetic properties is shown in Figure 20, where Mg\textsubscript{5}Zn\textsubscript{5}Fe\textsubscript{2}O\textsubscript{4} ferrites produced utilizing DEG are compared to similarly sized particles of Ni\textsubscript{3.5}Zn\textsubscript{6.5}Fe\textsubscript{2}O\textsubscript{4} from literature [19]. Here it is readily apparent that when the particle size is small, the properties of the two ferrites are quite similar.

![Figure 21: XRD spectra of CoFe\textsubscript{2}O\textsubscript{4} spinel ferrites are plotted as intensity vs. 0-20 (degree) indicating high phase purity.](image)

3.1.3 CoFe\textsubscript{2}O\textsubscript{4}

In addition to the previously introduced spinel ferrites and in order to increase the operating frequencies of the prospective antenna and EBG metamaterial substrates.
Single-phase powders of CoFe$_2$O$_4$ were produced by utilizing a co-precipitation of elements technique in 100 ml of tetra-ethylene glycol. Starting powders were mixed in the appropriate stoichiometric ratios in the following amounts: .835 g of Ferrous Chloride (FeCl$_2$·4H$_2$O), .658 g of Cobalt Acetate Tetrahydrate (C$_4$H$_6$O$_4$Zn·2H$_2$O), and 8.0 g of Sodium Hydroxide (NaOH). Salts and chlorides were added simultaneously to a larger vessel (250ml flat bottom beaker), which was heated utilizing a hot plate to 160 °C and subsequently mixed using a motorized stirrer at 300 rpm for 1 hour. Particles were separated via centrifuge, and a methanol rinse was performed to remove excess glycol. Phase purity was examined via θ-2θ X-ray diffraction techniques in Figure 21 (XRD). Particle size estimations of 8-12 nm were achieved via scanning electron microscopy (SEM, Figure 22) and transmission electron microscopy (TEM).

Figure 22: Scanning electron microscopy images of CoFe$_2$O$_4$ spinel ferrites produced via a co-precipitation of elements method in polyol (TEG).
3.2 Particle Size vs. Glycol Type

One interesting result which was noted during the fabrication of spinels utilizing the polyol method was the effect of the glycol chain length on the particle size of the precipitated ferrites. This was first observed through a dramatic lessening of the magnetic properties of the produced powders Mg$_5$Zn$_3$Fe$_2$O$_4$ as observed via vibrating sample magnetometry (VSM). This result is outlined in Figure 16, where the moment of a Mg$_5$Zn$_3$Fe$_2$O$_4$ spinel sample produced via a diethylene glycol is compared to one produced utilizing tetra-ethylene glycol. The reason for the lower moment has been attributed to the smaller particle size, and the fact that the particles are too small to maintain magnetic domains. This hypothesis has been verified via both Scherrer analysis, and through extensive SEM and TEM sample viewing.

Figure 23 outlines the study to determine the size effects of particles produced via different co-precipitation techniques where; (a) shows SEM and TEM images of ferrites with a particle size of 8-10 nm produced utilizing TEG. (b) Depicts particles produced with particle size on the order of 20-30 nm produced utilizing DEG. (c) Shows particles produced with particle sizes on the order of 100-130 nm produced via an aqueous method to be discussed in the following section of this dissertation. (d) Depicts the grain size as a function of Mg concentration (x), calculated via Scherrer analysis.
Figure 23: Depiction of particle size vs. glycol type for Mg$_2$Zn$_2$Fe$_2$O$_4$ spinel ferrites where; (a) shows SEM and TEM images of ferrites with a particle size of 8-10 nm produced utilizing TEG. (b) Depicts particles produced with particle size on the order of 20-30 nm produced utilizing DEG. (c) Shows particles produced with particle size on the order of 100-130 nm produced via an aqueous method. (d) Depicts the grain size as a function of Mg concentration (x), calculated via Sheerer analysis [1].

3.3 Aqueous Spinel Formation:

While the ability to produce multiple types of spinel ferrites has been successfully accomplished via multiple polyol routes including both TEG and DEG methods, the end product of these reactions can only be produced in quantities <1 g (~6g/L). Due to the
low operating frequencies of these materials (which will be discussed in depth shortly) the proposed polyol methods could not produce ferrites in sufficient quantities needed for substrate and EBG metamaterial preparation. It was because of this realization that another method of forming these particles will be introduced in this section. This proposed method is based off of an aqueous co-precipitation of elements technique [1-3], which prepares much larger batches of powder. There are some downsides to this process, such as an additional sintering step, as well as a loss of particle size uniformity, these will be discussed in detail in the following sections.

3.3.1 MgZnFe$_2$O$_4$

Single phase powders of Mg$_{(x)}$Zn$_{(1-x)}$Fe$_2$O$_4$ were produced by co-precipitation in 400 ml of deionized water heated to ~95°C and stirred at 150 rpm for two hours. Starting powders were mixed in the appropriate stoichiometric ratios in the following amounts: 15.90 g of ferrous chloride (FeCl$_2$-4H$_2$O), 4.29 g of magnesium acetate tetrahydrate ((C$_2$H$_3$O$_2$)$_2$Mg·4H$_2$O), 4.39 g of zinc acetate tetrahydrate (C$_4$H$_6$O$_4$Zn·2H$_2$O), 11.67 g of sodium hydroxide (NaOH), and 5.04 g of sodium carbonate (Na$_2$CO$_3$). Salts and chlorides were mixed independently in separate 600 ml vessels each containing 200 ml of deionized water by magnetic stirring for 5-10 minutes. This allowed the chemicals to dissolve prior to combining the two solutions. The solution mixture was placed in a round bottom flask that underwent heating to ~95°C and mechanical stirring at 150 rpm for two hours. To aid in the reaction as a surfactant, 50 ml of tetraethylene glycol (TEG) was added. The addition of the TEG was found to reduce variation in particle size produced in the aqueous method.
Figure 24: XRD spectra of Ni$_{0.5}$Zn$_{0.5}$Fe$_2$O$_4$ and Mg$_{0.5}$Zn$_{0.5}$Fe$_2$O$_4$ spinel ferrites are plotted as intensity vs. θ-2θ (degrees) indicating high phase purity for both materials [1].

After precipitation, which took place over a period of 2 hours, the resulting powders were removed and isolated from the solution utilizing vacuum filtration. These particles then underwent additional rinsing to remove residual NaCl, including repeated ultrasonic vibration, magnetic stirring, and finishing with another round of vacuum filtration. The presence of even small amounts of NaCl can contribute disproportionally to lowering the melting point of particle samples as well as introducing impurities detrimental to magnetic properties [3]. For filtered samples, the removal of NaCl generated by the aqueous method was verified by energy dispersive X-ray spectroscopy (EDX) and XRD measurements. Particles were then dried and calcined at a temperature of 850°C. This temperature is much lower than the 1300°C commonly used in ceramic methods [14].
The X-ray diffraction patterns presented in Figure 24 closely match those of referenced peaks [22] and previously published works [17], indicating pure phase formation of $\text{Mg}_{x}\text{Zn}_{(1-x)}\text{Fe}_2\text{O}_4$ within the definition standards of the instrument. Figure 34(b) shows the real and imaginary permeability of $\text{Mg}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$, torroids sintered at 1100°C for 4 hours and will be discussed in depth in the later sections of this chapter (3.5) with regard to the operational ranges of potential devices utilizing this material as a substrate.

Figure 23(c) shows the average particle size produced via the aqueous technique to be ~100-120 nm, compared to 20-30 nm for the DEG and less than 15 nm for the TEG samples. The distribution of particle sizes for the aqueous method, as seen in Figure 23(c), is broader than the polyol methods using various surfactant chain lengths (see Figure 23(a and b)). The particles of Figure 23(c) also are non-spherical and appear as low aspect ratio rods.

3.3.2 MnZnFe$_2$O$_4$

In addition to producing single phase powders of $\text{Mg}_{(x,\text{Zn}_{(1-x)})}\text{Fe}_2\text{O}_4$ single phase powders of $\text{Mn}_{0.68}\text{Zn}_{2.06}\text{Fe}_2.06\text{O}_4$ were also produced. This was in order to have a variety of samples with different magnetic properties for various antenna applications. These particles were also made by a co-precipitation of elements technique in 400 ml of deionized water heated to ~95°C and stirred at 150 rpm for two hours. Starting powders were mixed in the appropriate stoichiometric ratios in the following amounts: 16.38 g of...
ferrous chloride (FeCl₂·4H₂O), 6.67 g of manganese acetate tetrahydrate ((C₂H₅O₂)₂Mn·4H₂O), 2.28 g of zinc acetate tetrahydrate (C₄H₆O₄Zn·2H₂O), 11.67 g of sodium hydroxide (NaOH), and 5.04 g of sodium carbonate (Na₂CO₃). Salts and chlorides were mixed independently in separate 600 ml vessels each containing 200 ml of deionized water by magnetic stirring for 5-10 minutes, this allowed the chemicals to dissolve prior to combining the two solutions. The solution mixture was placed in a round bottom flask that underwent heating to ~95°C and mechanical stirring at 150 rpm for two hours. To aid in the reaction as a surfactant, 50 ml of tetraethylene glycol (TEG) was added.

After precipitation, which took place over a period of 2 hours, the resulting powders were removed and isolated from the solution utilizing vacuum filtration. These particles then underwent additional rinsing to remove residual NaCl, including repeated ultrasonic vibration, magnetic stirring, and finishing with vacuum filtration. The particles were then pressed at 1000 psi utilizing a 1 inch diameter die set in a uniaxial mechanical press. The resulting pucks were then sintered for 10 hours at 1100 °C. Figure 25 depicts the phase purity of samples produced via this method, as well as the magnetic properties of this sample produced via VSM measurements. Figure 26 depicts the SEM images of Mn₆₆Zn₂₆Fe₂₀₆O₄ showing clear spinel cubic structures.
Figure 25: XRD spectra and VSM data of Mn$_{0.68}$Zn$_{0.26}$Fe$_{2.06}$O$_4$ produced via a modified aqueous co-precipitation method.

Figure 26: SEM images of Mn$_{0.68}$Zn$_{0.26}$Fe$_{2.06}$O$_4$ produced via a modified aqueous co-precipitation method showing clear spinel cubic structures.
Another class of ferrites which were also produced via this method were NiZnFe$_2$O$_4$ spinel ferrites. Again, this was in order to have a variety of samples with different magnetic properties for various antenna applications. These particles were also made by a co-precipitation of elements technique in 400 ml of deionized water heated to ~95°C and stirred at 150 rpm for two hours. Starting powders were mixed in the appropriate stoichiometric ratios in the following amounts: 15.91 g of ferrous chloride (FeCl$_2$·4H$_2$O), 4.977 g of nickel acetate tetrahydrate ((C$_2$H$_3$O$_2$)$_2$Ni·4H$_2$O), 4.391 g of zinc acetate tetrahydrate (C$_4$H$_6$O$_4$Zn·2H$_2$O), 11.67 g of sodium hydroxide (NaOH), and 5.04 g of sodium carbonate (Na$_2$CO$_3$). Salts and chlorides were mixed independently in separate 600 ml vessels each containing 200 ml of deionized water by magnetic stirring for 5-10 minutes. This allowed the chemicals to dissolve prior to combining the two solutions. The solution mixture was placed in a round bottom flask that underwent heating to ~95°C and mechanical stirring at 150 rpm for two hours. To aid in the reaction as a surfactant, 50 ml of tetraethylene glycol (TEG) was added.

After precipitation, which took place over a period of 2 hours, the resulting powders were removed and isolated from the solution utilizing vacuum filtration. These particles then underwent additional rinsing to remove residual NaCl, including repeated ultrasonic vibration, magnetic stirring, and finishing with vacuum filtration. The particles were then placed in an alumina (Al$_2$O$_3$) crucible and sintered in air at 850°C for 6 hours. Figure 27 shows the phase purity achieved from this method via standard θ-2θ XRD
diffraction patterns. Figure 27 also shows the magnetic properties of the NiZnFe$_2$O$_4$ spinel produced via vibrating sample magnetometer. Figure 28 depicts the SEM images of the sintered ferrites. It should be noted that the particles are slightly smaller than the previous spinel case, this is attributed to the fact that the temperature of formation used in this case was lower, as well as the fact that these powders were sintered out of the beaker, without a compacting step.

Figure 27: XRD spectra and VSM data of NiZnFe$_2$O$_4$ spinel ferrites produced via a modified aqueous co-precipitation method.
Figure 28: SEM images of NiZnFe$_2$O$_4$ produced via a modified aqueous co-precipitation method showing clear spinel cubic structures.

3.3.4 CoFe$_2$O$_4$

The final class of spinel ferrites produced for this study was CoFe$_2$O$_4$ spinel ferrites. Again, this was in order to have a variety of samples with different magnetic properties for various antenna applications. These particles were also made by a co-precipitation of elements technique in 400 ml of deionized water heated to ~95°C and stirred at 150 rpm for two hours. Starting powders were mixed in the appropriate stoichiometric ratios in the following amounts: 15.91 g of ferrous chloride (FeCl$_2$·4H$_2$O), 4.977 g of cobalt acetate tetrahydrate ((C$_2$H$_3$O$_2$)$_2$Co·4H$_2$O), 11.67 g of sodium hydroxide (NaOH), and 5.04 g of sodium carbonate (Na$_2$CO$_3$). Salts and chlorides were mixed independently in separate 600 ml vessels each containing 200 ml of deionized water by magnetic stirring for 5-10 minutes, this allowed the chemicals to dissolve prior to combining the two solutions. The solution mixture was placed in a round bottom flask that underwent heating to ~95°C and mechanical stirring at 150 rpm for two hours. To aid in the reaction as a surfactant, 50 ml of tetraethylene glycol (TEG) was added.
After precipitation, which took place over a period of 2 hours, the resulting powders were removed and isolated from the solution utilizing vacuum filtration. These particles then underwent additional rinsing to remove residual NaCl, including repeated ultrasonic vibration, magnetic stirring, finishing with vacuum filtration. The particles were then placed in a Al₂O₃ crucible and sintered in air at 850°C for 6 hours. Figure 29 shows the phase purity achieved from this method via standard 2θ XRD diffraction patterns. Figure 29 also shows the magnetic properties of the NiZnFe₂O₄ spinel produced via VSM measurements. Figure 30 depicts the SEM images of the sintered ferrites. It should be noted that the particles are similar in size to the NiZn spinels due to their similar sintering conditions.
Figure 29: XRD spectra and VSM data of CoFe$_2$O$_4$ produced via a modified aqueous co-precipitation method.

Figure 30: SEM images of CoFe$_2$O$_4$ produced via a modified aqueous co-precipitation method.
3.4 Other Investigated Low Frequency Magnetic Materials

3.4.1 Introduction to FeCo Magnetic Nanoparticles

In addition to spinel ferrites another class of magnetic materials which was investigated were FeCo nanoparticles. These materials were investigated due to their intrinsically high moment and permeability values. It will be shown in the later chapters of this dissertation (8-9) that materials with very high values of permeability are good for potential applications in EBG metamaterial design. The limiting factor; however, on this class of materials is their low operating frequencies limiting them to operation in the kHz bands. Therefore, the antenna elements placed on substrates of these materials would be very large due to the wavelengths associated with these frequencies. Also, the formation of these materials in large enough batches to operate as antenna substrates in these fields would be difficult. However; as these materials do fit the design characteristics of novel materials which have potential in antenna applications they will be included in the investigation.

In this study the formation of Fe$_{0.6}$Co$_{0.4}$ nanoparticles have been examined due to their high intrinsic magnetic moment. The reagents used in the reaction were ferrous chloride (0.836 g), cobalt acetate (0.698 g), and sodium hydroxide (various amounts). In the reaction; the particles were combined in glycol, underwent magnetic stirring (~300 rpm), and heat treatment of 160°C for one hour. The particles are then separated from the glycol via various methanol rinses and types of magnetic filtration. This method has been shown to produce between 0.030 g and 0.120 g of particles depending upon the NaOH concentration and the stability of the applied heating process. The magnetic properties
measured via VSM and standard θ-2θ XRD diffraction patterns have been shown in Figure 31.

Figure 31: X-ray diffraction data of FeCo nanoparticles formed via a modified co-precipitation method in polyol. Also shown is the VSM data of the produced powders.

After the successful production of FeCo nanoparticles, a small study was run to increase their magnetic properties by lowering the weight factor of surfactant and polymerized glycol produced via the precipitation technique. This was done by utilizing a surfactant called polyvinylpropalene (PVP). Figure 32 depicts images of powders at high magnification achieved through SEM images which depict the surfactants of these
particles. Figure 33 depicts the magnetic moment of each of these samples, which is shown to increase with PVP content. It should be noted that while this method has been successful in increasing the magnetic properties of the powders they would need to be produced in much larger quantities before they could be fabricated into antenna substrates, that exercise will not be covered in this dissertation.

Figure 32: Images of FeCo powders at high magnification achieved through scanning electron microscopy which depict the surfactants of these particles as a function of PVP addition.
Figure 33: Depicts the magnetic moment of each of these samples as a function of PVP addition.

3.5 Operational Ranges of Investigated Magnetic Materials

Now that the fabrication of these materials has been completed via both polyol and aqueous routes and in large enough batches to be used as substrates for low frequency antenna designs, it becomes vitally important to define what the actual operating regions of these materials are in terms of practical antenna and device designs. To do this the permeability spectra of these materials have been measured utilizing an Agilent 4294A Precision Impedance Analyzer along with the permeability measurement test fixture with the frequency range of 10 Hz to 110 MHz. These measurements allowed the low frequency permeability to be evaluated.
It is clear from the results provided in Figure 34 that the zero field resonance of NiZnFe$_2$O$_4$ and MgZnFe$_2$O$_4$ spinel ferrites is only around 30 MHz. This can be moved upward somewhat via cobalt doping into the spinel; however, not enough to allow the materials to operate in the 100MHz region with any significant permeability values. The highest zero field measurements for the ferrite spinels are that of the CoFe$_2$O$_4$ spinels which operate at around 300MHz, albeit with very small permeability values on the order of 1.5-2 [23]. The overview of these materials compared to those of the hexaferrite materials which will be introduced in more detail in the following chapters is given in Table 2.

Figure 34: Permeability spectra of various spinel ferrites produced via the aqueous method.

Co doping shows an increase in the resonant frequency.
Table 1: Comparison of parameters of Ni$_{0.5}$Zn$_{0.5}$Fe$_2$O$_4$ and Mg$_{0.5}$Zn$_{0.5}$Fe$_2$O$_4$ ferrites produced via a variety of different fabrication methods.

<table>
<thead>
<tr>
<th>Particle Size</th>
<th>Synthesis Type</th>
<th>$\sigma_s$ (emu/g)</th>
<th>$\mu_i$</th>
<th>$\sigma_s$ (emu/g)</th>
<th>$\mu_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-7 nm</td>
<td>Polyol TEG</td>
<td>24.7</td>
<td>-</td>
<td>27*</td>
<td>-</td>
</tr>
<tr>
<td>20-30 nm</td>
<td>Polyol DEG</td>
<td>37.7</td>
<td>-</td>
<td>37*</td>
<td>-</td>
</tr>
<tr>
<td>80-100 nm</td>
<td>Aqueous</td>
<td>35.9</td>
<td>68</td>
<td>60</td>
<td>58</td>
</tr>
</tbody>
</table>

* Data from (16)

Table 2: Comparison of operating ranges of a variety of ferrite materials.

<table>
<thead>
<tr>
<th>Material:</th>
<th>$\mu_i$</th>
<th>$\varepsilon_i$</th>
<th>$f_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duroid TM3003</td>
<td>1.00</td>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td>(Co$_2$) Z Hexaferrite</td>
<td>~ 14</td>
<td>~ 16</td>
<td>1.2 GHz</td>
</tr>
<tr>
<td>(Co$_2$) Y Hexaferrite</td>
<td>~ 7</td>
<td>~ 15</td>
<td>1 GHz</td>
</tr>
<tr>
<td>(MgZn)$_2$Fe$_2$O$_4$ Spinel Ferrite</td>
<td>~ 70</td>
<td>~ 15</td>
<td>10 MHz</td>
</tr>
<tr>
<td>(MgZn)(Co)Fe$_2$O$_3$ Spinel Ferrite</td>
<td>10 to 20</td>
<td>~ 15</td>
<td>30-70 MHz</td>
</tr>
<tr>
<td>NiZn Spinel Ferrite</td>
<td>~ 60</td>
<td>~ 15</td>
<td>30 MHz</td>
</tr>
</tbody>
</table>

Table 2: Comparison of operating ranges of a variety of ferrite materials.

3.6 Conclusions

In this section the structural, morphological, and magnetic properties of Mg$_{0.5}$Zn$_{0.5}$Fe$_2$O$_4$, MnZnFe$_2$O$_4$, NiZnFe$_2$O$_4$, and CoFe$_2$O$_4$ spinel ferrites, formed through polyol and aqueous co-precipitation methods have been proposed. All methods reported were successful in producing pure phase spinel ferrites. Utilization of the aqueous method resulted in batches with high process yields of up to 25 g/l, and exhibited particle sizes on the order of 100 nm. Utilization of the polyol method produced process yields of up to 6
g/l, with an average diameter in the 30 - 40 nm range with a narrower size distribution that those created by the aqueous technique. Furthermore, it was shown that the polyol method allows control over average particulate size by controlling the chain length of the surfactant glycol. Microwave properties of Mg_{x}Zn_{(1-x)}Fe_{2}O_{4} ferrite have been shown to be a suitable replacement for Ni_{x}Zn_{(1-x)}Fe_{2}O_{4} up to 5 MHz, and with slight cobalt doping can be tuned to match the permeability spectra of the Ni_{x}Zn_{(1-x)}Fe_{2}O_{4} ferrite. As such, Mg_{x}Zn_{(1-x)}Fe_{2}O_{4} is deemed a low toxicity replacement for the technologically significant Ni_{x}Zn_{(1-x)}Fe_{2}O_{4} ferrites. The synthesis methods presented here demonstrate promise for low cost, industrial scale manufacturing of Mg_{x}Zn_{(1-x)}Fe_{2}O_{4} for a variety of commercial applications.

The potential operating ranges of these materials were then investigated in order to determine how they could be used as antenna and EBG metamaterial substrates. In doing so it was determined that these materials would only work for very low frequency designs; however, additional doping can be used to increase the zero field ferromagnetic resonance values. Furthermore the moment can also be tailored as needed by utilizing off stoichiometric values of iron as demonstrated through MnZn spinels. For these reasons these materials will also be introduced as EMI absorber layers in addition to antenna and EBG metamaterial substrates in the following chapters.

3.7 References

[1] A. Daigle, et al., "Structure, morphology and magnetic properties of Mg(x)Zn(1-x)Fe2O4 ferrites prepared by polyol and aqueous co-precipitation methods: A
low-toxicity alternative to Ni(x)Zn(1-x)Fe2O4 ferrites," (submitted for publication) (2011).


Chapter 4: Aqueous \( \text{Co}_2\text{Y} \) Hexaferrite Nanoparticle Formation

4.0 Introduction to \( \text{Co}_2\text{Y} \) Hexaferrites

4.0.1 Crystal Structure and Theory

Following the study of the low frequency spinel ferrite materials introduced in Chapter 3, it has become readily apparent that higher frequency magnetic materials will be needed for practical antenna substrates and electromagnetic band gap (EBG) metamaterial designs. This need is especially pronounced if antenna designs are to operate in the L (1-2 GHz) and S-bands (2-4 GHz), which include both the Global Positioning System (GPS) and Global Navigation Satellite System (GNSS) frequency bands. These bands are of particular interest in a variety of commercial and defense related applications.

Towards this end, in this chapter, cobalt substituted Y-Type barium hexaferrite \(^1\) \((\text{Ba}_2\text{Co}_2\text{Fe}_{12}\text{O}_{22})\) particles will be introduced via a materials fabrication perspective, utilizing an aqueous co-precipitation chemical synthesis method \(^2\text{-}^4\). Optimized materials will be characterized in this chapter for structure, morphology, and magnetic properties. All measured properties, including lattice constants, magnetic moment, and coercive field, will be shown to be in close numerical agreement with bulk reference values \(^5\text{-}^6\). In addition to the morphologic and magnetic properties, the magnetic and dielectric constants of these materials will be studied, and the concept of texturing will be introduced to see how these material parameters can be tuned for optimal device designs.
Figure 35: The (110) cross-section shows examples of M-type $[(\text{Ba},\text{Sr})\text{Fe}_{12}\text{O}_{19}]$ (a), Y-type $[(\text{Ba},\text{Sr})_2\text{Me}_3\text{Fe}_{12}\text{O}_{22}]$, (b) and Z-type $[(\text{Ba},\text{Sr})_3\text{Me}_2\text{Fe}_{24}\text{O}_{41}]$ (c) hexaferrites. All compounds are made up of R, S and T layers, or minor modifications of them [1].

The crystal structure for this material is pictured in Figure 35(b) [1], where the smallest hexagonal symmetry consists of 18 oxygen layers and the length of the c axis is 43.56 Å [5]. These hexaferrite materials are optimal for device applications for a variety of reasons including the fact that their zero field ferromagnetic resonance (FMR) value is
around 1 GHz, also these materials have their easy plane perpendicular to the c-axis another benefit for device applications. The soft in-plane magnetic properties of planar hexagonal ferrites make it possible to operate without or with very small magnetic bias fields, which in turn allows for the miniaturization of many RF devices. In particular, Co$_2$Y hexaferrite materials have been demonstrated to possess a high permeability of $\mu \approx 4$ in the frequency range from 0.1 to 900 MHz, thus making them suitable for RF device design [5-8].

It is because of these technologically significant properties that the need for efficient large scale production of pure phase hexaferrite materials is increasing. The most common method for the fabrication of these materials is the ceramic method [7-10]. However, this method can be inefficient and time consuming, requiring multiple annealing and sintering steps at 1100°C or higher to achieve pure phase materials with the desired microstructure. Other fabrication methods have been proposed to address some of these limitations. One method in particular that has been used in the fabrication of Ni-Zn ferrites is the co-precipitation method which requires only a single calcification [2-4, 11-13]. Furthermore, the co-precipitation method results in very small particle sizes which reduce the calcification temperatures necessary for pure phase materials, this is due to the Herring scaling law [14]. The method presented in this chapter will be shown to produce greater than 12 g of powder per batch (25g/l) with potential for much larger batch sizes, making this process suitable for industrial scale production.
Standard θ2θ X-ray diffraction (XRD) studies presented in this chapter will indicate that pure phase Co2Y hexaferrite material can be achieved at 900°C. This temperature is significantly lower than the standard processing temperature of 1100°C employed within the conventional ceramic method [15-18]. Size and shape of particles have been characterized by scanning electron microscopy (SEM) while the magnetic properties were studied by vibrating sample magnetometry (VSM). Measured structural and magnetic properties closely matched those of bulk ceramic materials [16-17], indicating that the proposed approach may serve as a large scale, cost effective substitute to conventional ceramic processing of hexagonal ferrite materials.

4.1 Aqueous Hexaferrite Formation [12]

4.1.1 Cobalt Substituted Barium Y-Type Hexaferrite Material

Single phase powders of Co2Y were produced by utilizing a co-precipitation of elements technique in 800 ml of de-ionized water heated to 95°C, and stirred at 150 rpm for 2 hours. Starting powders were mixed in the appropriate stoichiometric ratios in the following amounts: 3.91 gm of BaCl2, 25.95 gm of Fe(III)Cl3, 3.8 gm of CoCl2, 16 gm of NaOH, and 8.0 gm of Na2CO. Salts and chlorides were diluted in de-ionized water independently in 400 ml beakers, after which they were added simultaneously to a larger vessel which was heated to 95 °C, and subsequently mixed utilizing a motorized stirrer. 50 ml of tetra-ethylene glycol was added during the mixing process to serve as a surfactant which aided in particle formation [2].
Figure 36: Energy dispersive X-ray spectroscopy measurements, indicating the successful removal of Na and Cl from the filtration process described in 4.1.1.

After precipitation, which took place over a period of 2 hours, the resultant powders were filtered utilizing vacuum filtration to remove excess water and NaCl. These precipitated particles then underwent additional rinsing, including ultrasonic filtration and magnetic stirring before subsequently being dried and pressed. The goal of the thorough filtration process was to eliminate excess NaCl formed during the reaction. The removal of NaCl proved to be vitally important due to the impact of NaCl on the sintering process. The presence of small amounts of NaCl contributed to the lowering of the melting point of the sample often resulting in melted materials at very low temperatures [4, 10]. For the filtered samples, the removal of NaCl was verified by energy dispersive x-ray spectroscopy (EDX) and XRD diffraction patterns (Figure 36).
Figure 37: (a) X-ray diffraction (XRD) intensity as square root for the sample processed at 900°C. (b) Simulated pure phase curve from peak locations given in literature [16] (a.u. designates arbitrary units) (4).

Figure 38: (a) Vibrating sample magnetometer (VSM) measurements of ferrites after removal from beaker (dotted line) and subsequent sinter at 900°C (solid line). (b) Comparison of magnetic properties for different sintering temperatures at 800°C (dotted
line), 900°C (short dashed line), 1000°C (long dashed line), 1100°C (dash dot dash line), and 1200°C (solid line). (c) Saturation magnetization ($M_s$) changes with sintering temperature as well as coercive field ($H_c$), changes with sintering temperature. All measurements performed at room temperature (4).

After filtration, powders were dried and pressed at 2000 lbs/in$^2$ in a 1.25 inch stainless steel die and subsequently sintered at various temperatures ranging from 700-1100 °C for 14 hours. The effect of sintering can be seen in Figure 39(a) which depicts the XRD scans of the as-prepared and sintered samples. Pure phase formation of the Co$_2$Y ferrite is achieved at a temperature of 900 °C, which is significantly lower than the 1100 °C reported in literature [12-14]. Figure 39(b) depicts the XRD spectra of the low temperature sintered samples on a log scale and shows the evolution of the sample phases from their constituent spinel phases to M-type ferrites, and finally to a pure phase Co$_2$Y hexaferrite materials. Figure 39(c) depicts the lattice parameters, $a$ and $c$, of the Y-type ferrite as a function of temperature along with bulk values included as a reference [17, 18]. Single phase Y-type ferrite formation was observed after sintering at 900 °C in Figure 37(a). Lattice parameters evolved with sintering temperature matching those of bulk materials only at temperatures above 1000 °C. This may be due to the fact that at 900 °C the Co$_2$Y hexaferrite material contains a high defect density, such as oxygen vacancies that reduces unit cell volume and corresponding lattice parameters.
Figure 39: (a) X-ray diffraction patterns (SQRT) for ferrite powders produced at different sintering temperatures (a.u. designates arbitrary units). (b) Logarithm scale of X-ray intensity versus 2θ with symbols denoting phases, where closed circles denote Y-type ferrite peaks, open squares denote M-type ferrite peaks (BaFe_{12}O_{19}), open circles denote spinel phases (CoFe_{2}O_{4} and Fe_{3}O_{4}), and open triangles denote as prepared precursor phases (BaCO_{3}) and oxides. (c) Lattice parameters of ferrite powders produced at different sintering temperatures plotted against bulk values (denoted by dashed lines) (4).
4.1.2 Magnetic Properties and Crystallography

Magnetic hysteresis loops measured via VSM of as-prepared powders and those sintered at 900 °C are compared in Figure 38(a). As-prepared powders exhibit a relatively low magnetic moment of 12 emu/g and a relatively high coercive field of 1500 Oe. This result is expected since, based on the X-ray diffraction data of Figure 39, the as-prepared powders contain a mixture of spinel and other oxides, with no evidence for the Co$_2$Y phase. In contrast, powders sintered at 900 °C exhibit a relatively high magnetic moment of 27.82 emu/g and a relatively low coercive field of 106.3 Oe. This is also in agreement with XRD results where only the Co$_2$Y phase was observed. Both the magnetic moment and the coercive field of powders sintered at 900°C are in good agreement with bulk reference data [16-17]. Hysteresis loops of powders sintered at different temperatures are compared in Figure 38(b). It is clear from this figure that relatively small changes are observed in the hysteresis loops for samples sintered at temperatures above 900°C, this is in agreement with the 0-2θ XRD pattern results of Figure 39(a) where single Co$_2$Y phase formation was observed in this sintering temperature range. It has been shown that as the sintering temperature increases there is a downward trend in the coercivity (Figure 38(c)), this follows what would be expected from the Ostwald ripening of particles as a result of sintering. Finally, Figure 38(c) shows the effect of sintering temperature on the saturation magnetization, $4\pi M_S$, values calculated from the VSM data by taking into account the bulk density of the powders. Above temperatures of 800°C values in this figure closely match those of published data [16, 17] within the margin of experimental uncertainty. This matches the XRD data shown in Figure 39.
As previously mentioned, in order to obtain the optimum annealing temperature to achieve a single phase material after a single sintering, many samples were prepared utilizing different sintering times and temperatures. For filtered samples, 900 °C was found to be the optimal temperature at a sintering time of 14 hours; however, very good samples have also been produced at sintering temperatures as low as 800 °C. In Figure 39, the crystal structure is shown to evolve with sintering temperature to result in pure phase Y-type hexaferrite. Figure 37 depicts the pure phase XRD data acquired after heat treatment at 900 °C with published reference data [18]. It is clear from this comparison that pure phase Y-type particles have been achieved.

Figure 40 shows scanning electronic microscope (SEM) micrographs acquired from samples sintered at different temperatures. Figure 40(a) illustrates the as-prepared powder after being dried from the beaker. A random distribution of nano sized particles and agglomerations can be seen in the micrograph. The micrograph of a sample sintered at 800 °C is shown in Figure 40(b). Here, thin hexagonal platelets having an average diameter of ~1-2 µm and thicknesses of .1 to .2 µm are observed which are consistent with the hexagonal symmetry of Co$_2$Y in addition, smaller particles having random shapes and sizes are visible. This result is consistent with the XRD spectra in Figure 39(a) where the samples sintered at 800 °C where determined to possess a mixture of Co$_2$Y and spinel phases. Scanning electron micrographs (SEM) of samples sintered at 900 °C and 1000 °C are shown in Figure 40(c and d), respectively. Particles in these micrographs are predominantly hexagonal, in agreement with XRD pattern results where the formation of the single Co$_2$Y hexaferrite phase was observed. Particle size is observed
to increase with sintering temperature from an average diameter of ~1-2 µm at 900°C to >2 µm at 1000°C.

After the optimization of these processes, the chemical synthesis was further refined to produce larger amounts of powder. Directly, the scalability of the process was evaluated by increasing the single batch size from 6 gm to 12 gm (25 g/l). After optimization, greater than 12 gm of pure phase Co₂Y powder could be produced for each batch. Energy dispersive X-ray spectroscopy (EDXS) measurements indicate no excess NaCl, and XRD measurements indicate almost a complete phase match. Low magnetic field measurements of the initial \(4\pi M_s\) for unfiltered samples was ~2000 G, which is very close to published data [16-17], and very stable for all the sintered samples >800 °C varying less than 5%. The coercivity is also shown to be very stable varying between 70 and 115 Gauss for the un-oriented sintered powders sintered at temperatures from 900 - 1200 °C.
After phase verification via standard θ-2θ X-ray diffraction, the magnetodielectric parameters of the pucks were measured via an Agilent A4991 Materials Analyzer in order to determine their permeability and permittivity values. Before doing so, the pucks were machined into toroids (the description of this process is given in section 4.3.1) this data is given in Figure 41 and Figure 42, and represents a non-textured Co$_2$Y hexaferrite material. This data is comparable to literature with published values of ~3-5 [17], it should be noted; however, that the density of the material plays a pivotal role in the value of the permeability measured, and that additional sintering steps can increase this value.
Figure 41: Permeability spectra of non oriented Co$_2$Y hexaferrite toroid material produced via a modified aqueous chemical processing technique.

Figure 42: Permittivity spectra of non oriented Co$_2$Y hexaferrite toroid material produced via a modified aqueous chemical processing technique.
4.1.3 Conclusions on the Co-precipitation Method

In the proceeding section of this chapter a method to produce large quantities of $\text{Ba}_2\text{Co}_2\text{Fe}_{12}\text{O}_{22}$ hexaferrite materials has been presented. Phase purity has been verified via $\theta$-$2\theta$ X-ray diffraction data at formation temperatures as low as 900$^\circ$C, and has been further verified via comparing the powders magnetic properties to bulk values utilizing a vibrating sample magnetometer (VSM). To understand how this material would operate as either an antenna or EBG substrate the permeability, permittivity, and their corresponding loss tangents have been examined via a Agilent A4991 Materials Analyzer. A permeability of $\sim 2$ was measured up to 1 GHz, with very low magnetic loss values on the order of .01 up to almost 1 GHz. The permittivity of this sample was measured to be between 12.5 and 15 over the operating range up to 1 GHz.

The next step in the process to utilizing these materials as substrates for antenna and EBG metamaterial designs was to optimize the materials through a novel texturing process with respect to their permeability and permittivity values. The need for this process as well as the results of the texturing will be fully outlined in the following chapters of this dissertation.

4.2 Orientation Provided by the Rotational Magnet Setup

4.2.1 Introduction/Reason for Study

Key ferrite material requirements for realizing broadband EBG metamaterials and antenna substrates include high remnant magnetization ($M_r/M_s$) in the plane of the textured ferrite substrate and low magnetic losses. The combination of these two material
properties will result in permeability dispersions that will enable broadband operation of the EBG metamaterial and antenna substrates. Hexagonal ferrites of the Y-type have been identified as promising candidates for EBG metamaterial and antenna applications due to high permeability values (~3) and high FMR frequencies (~1 GHz) attributed to a high magnetocrystalline anisotropy field (> 9 kOe) [13-15]. In the previous section of this dissertation a method of producing large quantities of Co$_2$Y hexaferrite materials has been proposed. In this section these powders and compacts will be optimized for antenna and EBG metamaterial applications. This optimization process is called texturing, [15,19] and consists of aligning the magnetic domains of the material so that they are all in the easy plane, the plane which is perpendicular to the c-axis [2]. In this section the process for orienting Co$_2$Y hexaferrite materials will be discussed in depth, and the effect of this texturing on the properties of the Co$_2$Y hexaferrite material will be shown.

The first step in the orientation process was to grind the compacts produced via the single sintering method to single domain size powders. This has been achieved via ball milling in a Fritsch (TM) Planetary mono mill PULVERISSETTE 6 classic line ball milling machine. Prior to milling, the samples were hand ground through a 75 µm sieve. This step was to ensure a narrow size distribution in the final milling process. After hand grinding the samples (3 g at a time), they were placed in an 80 ml agate holder with 7 large (10 mm) and 6 small (6 mm) agate balls. These balls were selected after many trials to again limit the size distribution of the final powder. The 80 ml agate holder was filled to the level of the top of the agate balls with reagent alcohol then placed into the
mill. The mill was run for 6 hours at 350 rpm with 30 minute intervals. In between the intervals a 5 minute pause was used, allowing the slurry to settle. Each subsequent interval was run in the opposite direction to ensure even particle size distribution. Scanning electron microscopy images of cobalt-substituted hexagonal Y-type barium ferrite (Ba$_2$Co$_2$Fe$_{12}$O$_{22}$, CoY) particles produced by this method are shown in Figure 43(a and b). In these images it is shown that the particles exhibit uniform size distribution with an average diameter on the order of 0.5 to 2 µm, consistent with single magnetic domain size [15-20].

Figure 43: Scanning electron microscopy image of Co$_2$Y hexaferrite powder which has been reduced to single domain size 0.5-2 µm through ball milling. In (a), a 2.20x10$^3$ magnification of particles, and in (b) a 9.00x10$^3$ magnification of particles is shown.
The next step in the texturing process was the magnetic alignment of these single domain particles. This was achieved utilizing a rotating magnetic field apparatus (shown in Figure 44(c)). In this process, the particles were dispersed in water at a ratio of 2-4 g to 30 ml (depending on desired puck thickness). The slurry was subsequently placed in an ultrasonic vibrator for 30 minutes to reduce the number of particle agglomerations. These
particles were then loaded into a 1 inch diameter non magnetic stainless steel die via a pipette and the excess water was removed. The powder was then pressed with a hydraulic press while being subjected to a rotating magnetic field (~7500 Oe) in the plane of the compact due to a mechanically rotating permanent magnet. The induced magnetic anisotropy is evident from magnetic hysteresis loops in Figure 44(b), here hysteresis loops with the magnetic field applied in the plane of the compact exhibit high remnant magnetization, a factor of 2.4 higher than that of the hysteresis loops with the magnetic field applied perpendicular. The processing methods described above are capable of producing ferrite materials with high magnetic permeability values in the ultra high frequency (UHF), L-, and S- frequency bands in a cost-effective way, allowing for the development of EBG metamaterials and antenna substrates.

4.2.2 Orientation Effect Viewed Through Vibrating Sample Magnetometry

In order to see the effect of the orientation process on the Co2Y hexaferrites two different techniques have been employed. The first technique was to see the changes in squareness of the hysteresis loops produced via vibrating sample magnetometry (VSM) for in plane and out of plane measurements. This was done with respect to different processing conditions, such as rotational speed of the magnet and post orientation sintering conditions such as time and temperature (°C). The second technique employed was the use of θ-2θ X-ray diffraction (XRD) to compare oriented and non oriented samples, this will be discussed in depth in section 4.2.3. Together these two measurements have allowed for the thorough characterization of degree of orientation in these materials.
Figure 45: Depiction of the orientation effect of the rotational magnet setup through in-plane and out of plane hysteresis loops produced via vibrating sample magnetometry comparing oriented (α 3) and non oriented samples (α 4).

Figure 45 outlines the effect of the orientation procedure on two samples; the first, (α 3) was produced utilizing the rotational setup in Figure 44(c). The second (α 4) was formed utilizing the same setup with the rotational magnet removed. Samples were pressed into 1 inch pellets at a pressure of 1000 psi utilizing a mechanical press and a non-magnetic die set. In and out of plane measurements were performed via vibrating sample magnetometry (VSM). Slight variations in the non oriented sample at saturation are attributed to measurement error. It is clear from the figure that the orientation effect is quite pronounced. The ratio of in plane to out of plane squareness (1.96:1) is vastly different for oriented samples than for those which are not oriented (~1:1).
Figure 46: Depiction of the orientation effect of the rotational magnet setup through in plane and out of plane hysteresis loops produced via vibrating sample magnetometry for various rotation speeds.

Figure 46 depicts the effect of rotation speed of the magnet (shown in Figure 44(c)) on the in plane and out of plane hysteresis loops of the as prepared hexaferrite pucks. When comparing the in plane to out of plane squareness ratios it is apparent that pucks produced via slower magnet rotation speed have better orientation. This is consistent with other published works which have utilized similar setups [15].

In addition to monitoring the rotation speed of the magnet in the orientation setup, it was also important to optimize the post compaction sintering process employed for densification. Figure 47 depicts how post orientation sintering can positively affect the orientation of the compact. Here, the ratio of in plane to out of plane squareness is increased from a value of 1.96 for a green "unfired" sample to a value of 2.41 after it has been densified in a furnace.
Figure 47: Depiction of the orientation effect of the rotational magnet setup through in plane and out of plane hysteresis loops produced via vibrating sample magnetometry for pre and post sintered compacts.

4.2.3 Orientation Effect Viewed Through X-Ray Diffraction

As previously mentioned in order to see the effect of the orientation process on the ferrites two different techniques have been employed. The first technique was discussed in the previous section. The second technique employed was the use of X-ray diffraction (XRD) to compare oriented and non oriented samples. The theory behind this study was that oriented compacts would see an increase in the intensity of their crystallographic peaks in the c-plane. It is clear from Figure 48 that the in plane diffraction peaks of the oriented hexaferrite materials are increased compared to those of the non oriented samples. The first example of this is the (1,1,0) peak; here a >50% reduction is shown in the oriented sample. Other examples that show texturing are the (0,0,X) peaks such as (0,0,15) where the oriented compact is 3 times the intensity of the
non oriented compact. It should be noted that for a perfectly oriented compacts there would be no (1,1,0) peak; however, there are many reasons why this is impractical. First, the ball milling process results in a Gaussian distribution of particle size. While the average size is single domain some particles are larger and have multiple domains which are not necessarily in the same direction. The ratios of these peaks serve to give a numerical estimation to the orientation effect.

![XRD of Oriented Compacts vs. non-Oriented Compacts](image)

**Figure 48:** Depiction of X-ray diffraction data for oriented and non oriented compacts of Co$_2$Y hexaferrite materials. Significant reduction in out of plane refraction peaks is observed.

### 4.3 Discussion of Operational Ranges for Device Design

#### 4.3.1 Optimization of Permeability

The operating regions of devices fabricated utilizing hexaferrite materials are controlled by the materials ferromagnetic resonance value (FMR) and the materials intrinsic properties such as the permeability and magnetic loss tangents. In order to
prepare textured cobalt substituted barium Y-type hexaferrite compacts for the measurement of these magnetodielectric properties, toroids were machined from the sintered compacts using a diamond coring bit and standard drill press. In order to prevent chipping and cracking of the samples during the drilling process the hexaferrite compacts were bonded in-between two standard laboratory glass slides using Crystal Bond epoxy. The outer diameter of the resulting toroids, determined by the inner diameter of the die, was 1.25 inches. The inner diameter of the toroids, determined by the outer diameter of the coring bit, was 7/16 inches.

All complex permeability measurements were carried out using Agilent A4991 Materials Analyzer. The real part of permeability and the magnetic loss tangent as a function of frequency are shown in Figure 49 and Figure 50. There are several notes and observations: First, the maximum frequency for the fixture used in the measurement is 1 GHz, therefore the measurement above 1 GHz is not reliable. Second, with the real part of permeability below 10, the instrument noise level is around $8 \times 10^{-3}$. In other words, the instrument cannot resolve loss tangent below $8 \times 10^{-3}$.

Samples $\alpha-10$ and $\alpha-16$ in Figure 49 and Figure 50 are the textured hexaferrite samples (prepared under the influence of a rotating magnetic field). These samples possess a slightly higher permeability values than isotropic samples, as predicted by theory. It is anticipated that the value of the real part of the permeability (presently equal to 1.5) can be increased by increasing the density of the hexaferrite compacts. This can be
achieved by a combination of higher uniaxial pressure during green body formation and longer dwell time during the sintering process. The magnetic loss tangent of all measured samples is below 0.01.

Figure 49: Initial permeability and magnetic loss tangents of oriented and non-oriented samples of Co$_2$Y hexaferrites.
Figure 50: Effect of orientation on initial permeability and magnetic loss tangents of oriented and non-oriented samples of Co$_2$Y hexaferrites.

It should be noted that the uniaxial pressure utilized in the preparation of hexaferrite compacts is limited by the pellet die. For samples in Figure 49 and Figure 50, a low pressure die was used, thus limiting the pressure to 1000 psi. In order to increase the allowable pressure and facilitate the production of highly dense compacts (>80% of bulk value), another die set was designed and machined out of high strength non magnetic stainless steel alloy thusly increasing the allowable pressure to above 1500 psi. Green body compacts were prepared using the new die set with an outer diameter of approximately 16 mm and thickness of approximately 3 mm. These Y-type hexaferrite green body compacts were prepared and sintered at 950 °C. Complex permittivity measurements were performed directly on the compacts after sintering.
A real permeability value of approximately 1.7 was measured for a Y-type hexaferrite sample with the magnetic loss tangent below 0.0 produced utilizing the new die set. While the real value of the permeability is higher than that previously depicted, it is still somewhat low. While increasing the pressure, the density of the compact improved by about 10% to approximately 88% of bulk value, clearly produced an increase in the real permeability it was not sufficient to meet the needs of broadband EBG metamaterials or antenna substrates.

In order to increase this density further, a study was done which was aimed at optimizing the sintering temperature of oriented green body compacts. Since the formation temperature of cobalt substituted barium Y-type hexaferrite is generally considered to be around 1150 °C [12-15], sintering the samples near that temperature was expected to result in higher density (>95%) and consequently higher permeability values. The results of this study are shown in Figure 51 where the permeability was measured to be 2.0, 2.3, 2.6, and 2.6 for the samples sintered at 1100, 1150, 1200, and 1250 °C. As such, increasing sintering temperature directly resulted in increased permeability values. An increase of 75% in permeability is evident in increasing the sintering temperature from 1050 to 1250 °C. It should be noted that in order to expedite permeability measurements for the purpose of process refinement, a lower frequency impedance analyzer was utilized. Specifically, the Agilent 4294A Precision Impedance Analyzer with the frequency range of 10 Hz to 110 MHz was used, along with the permeability measurement test fixture. These measurements allowed the low frequency permeability to be evaluated. While the measurement range of the instrument didn't allow the natural
resonance frequency to be observed it still provided reliable values up to 110 MHz that were sufficient for process refinement purposes.

![Graph](image)

**Figure 51: Optimized permeability of Y-type hexaferrite green body compacts sintered at a variety of different temperatures to see the effect of the density on the permeability values.**

4.3.2 Optimization of Magnetic Losses

The imaginary part of the permeability is shown in Figure 52, similarly to the real part of the permeability it is observed to increase with temperature. Values of approximately 0.02 were recorded for samples sintered at 1100 and 1150 °C. Values of approximately 0.06 were recorded for samples sintered at 1200 and 1250 °C. Magnetic loss tangents were calculated for all samples using the data in Figure 52 in Figure 53. The loss tangent is also observed to increase with sintering temperature with a value of
approximately 0.01 at 1100 and 1150 °C and 0.025 at 1200 and 1250 °C. As such, the best Y-type hexaferrite samples offer real permeability values of 2.6 and also a magnetic loss tangent of 0.025.

Figure 52: Imaginary permeability of Y-type hexaferrite samples as a function of sintering temperature.
In this section of the dissertation, the optimization of cobalt substituted barium Y-type hexaferrite compact processing in terms of refined sintering temperature and density has produced a significant improvement in the real part of the permeability from 1.5 to 2.6. At the same time the magnetic loss tangent increased from 0.01 to 0.025. These samples represent a low loss magnetic alternative to the current commercially available dielectric materials available for EBG metamaterial and antenna substrate design.

4.4 Conclusions

In this chapter Co$_2$Y hexaferrite (Ba$_2$Co$_2$Fe$_{12}$O$_{22}$) particles have been synthesized utilizing an aqueous co-precipitation chemical synthesis method followed by a single step sintering at or above 900 °C. This material was chosen due its intrinsically high
ferromagnetic resonance values which are higher than that of the spinel ferrites introduced in the previous chapter. Optimized materials were characterized for structure, morphology, and magnetic properties. All measured properties, including lattice constants, magnetic moment, and coercive field, were determined to be in close numerical agreement with bulk reference values. Control over average particle size was demonstrated by varying sintering temperature as well as through extensive ball milling studies. The present method has been shown to produce greater than 12 g of powder per batch (25 g/L) with potential for much larger batch sizes, making this process suitable for industrial scale production.

In addition to showing how this material can be made through a co-precipitation of elements perspective, this material was then optimized for antenna and EBG applications. Specifically, the idea of texturing of the hexaferrite was introduced. This was done through the use of permeability measurements, as well as loss tangent measurements done on torroids of Co$_2$Y both textured and not textured. The effect of texturing was shown through a variety of measurements including vibrating sample magnetometry and X-ray diffraction. This procedure has been optimized with respect to orientation speed of the permanent magnet, pressure, particle size, and sintering environment. Showing a 75% increase in permeability over the non textured compacts. Through this method a real permeability value of 2.6 was shown through 1.0 GHz, with a loss of 0.0025.
4.5 References


Chapter 5: Aqueous Z-Type Hexaferrite Nanoparticle Formation

5.0 Introduction to Z-Type Hexaferrites

In the previous chapters it has been shown that there is a need for high permeability (\(\mu_r\)) and permittivity (\(\varepsilon_r\)) magnetodielectric materials for antenna substrate miniaturization and electromagnetic bad gap (EBG) metamaterial design. The goal of these substrates is to utilize these high magnetodielectric parameters to maximize the electrical size of the radiating apertures through magnetodielectric loading, without sacrificing their radiation parameters. However, due to their intrinsic nature, many magnetic materials which exhibit the desirable parameters of high \(\mu_r\) and \(\varepsilon_r\) do so outside of the radio frequency (RF) or microwave regions where antennas and EBG metamaterials normally operate [1]. Examples of materials with favorable material parameters but undesirable operating ranges are the spinel ferrites and FeCo nanoparticles which have been outlined in Chapter 3. In Chapter 4, Y-type hexaferrites were introduced due to their intrinsically higher operating ranges. \(\text{Co}_2\text{Y}\) ferrites in particular and have been shown to have ferromagnetic resonance values around 1.0 GHz and have oriented \(\mu_r\) of 2.5-3 and \(\varepsilon_r\) of 12-15 respectively. While these values are more suitable for the production of novel miniaturized RF devices than spinel ferrites, the difference in the values of \(\mu_r\) and \(\varepsilon_r\) make impedance matching difficult due to the difference of the wave impedance of the substrate to that of free space. This has been outlined in equations 1-3, [2] where Equation 1 is the wave impedance of free space, Equation 2 is the wave impedance of an oriented \(\text{Co}_2\text{Y}\) hexaferrite material, and Equation 3 is the wave impedance of an oriented \(\text{Co}_2\text{Z}\) hexaferrite material with \(\mu_r\approx\varepsilon_r\) which will
be proposed later in this chapter. From these equations it is readily apparent how Co$_2$Z hexaferrites lend themselves very well to antenna and EBG metamaterial substrate design. Further mathematical relationships for wave propagation for anisotropic compacts have been studied extensively in literature [3].

$$\eta_{air} = \frac{\mu_r}{\varepsilon_r} = \sqrt{\frac{4\pi \times 10^{-7}}{8.854 \times 10^{-12}}} = 377\Omega$$

Eqn (1)[2]

$$\eta_{Co_2Y\ Ferrite} = \frac{\mu_r}{\varepsilon_r} = \sqrt{\frac{(4\pi \times 10^{-7}) \times 2.5}{(8.854 \times 10^{-12}) \times 15}} = 154\Omega$$

Eqn (2)[2]

$$\eta_{Co_2Z\ Ferrite} = \frac{\mu_r}{\varepsilon_r} = \sqrt{\frac{(4\pi \times 10^{-7}) \times 12.5}{(8.854 \times 10^{-12}) \times 12}} = 384\Omega$$

Eqn (3)[2]

In this chapter the formation of Co$_2$Z hexaferrite material is examined through a modified aqueous co-precipitation of elements method followed by a single sintering [4-5]. Phase verification will be achieved via standard $\theta$-2$\theta$ X-ray diffraction (XRD) measurements. Magnetic properties will be verified via vibrating sample magnetometry (VSM). Following verification, the particles will then be milled to appropriate single domain sizes for orientation in a rotating field to maximize the $\mu_r$ and $\varepsilon_r$ values. This
study will be approached utilizing the same methods presented on Co$_2$Y hexaferrite materials in the previous chapter. The magnetodielectric properties will be measured utilizing an Agilent Material Analyzer A4991 (for 1-1 GHz measurements) in conjunction with an Agilent 4294A Precision Impedance Analyzer (for 1-100 MHz measurements). In addition, the tunability of this material will be examined as a function of applied field, allowing for tunable devices to be fabricated which can operate with small bias fields. This material will be shown to be suitable for unbiased device designs up to 1.1 GHz and while biased this material can be used well into the L and S-bands. In presenting the effect of orientation on these materials it will be shown that the parameters of the Co$_2$Z ferrites are more suited to EBG metamaterials and antenna substrates than Co$_2$Y hexaferrites.

5.0.1 Crystal Structure and Theory

As with the Co$_2$Y hexaferrite described in the previous chapter, Co$_2$Z is a hexaferrite with its easy plane parallel to the c-axis. Figure 35(a) outlines the structure of this material, which can be seen as a superposition of Y and M type structures. In fact, the magnetic properties of the Z-type hexaferrites can be shown to be equal to the sum of the M and Y structures [6]. The saturation magnetization of Co$_2$Z hexaferrite is given in literature to be ~3300 Gauss [7-9], and the anisotropy field is given to be 13,000 Oersted [6].
5.1 Aqueous Hexaferrite Formation

5.1.1 Cobalt Substituted Barium Z-Type Hexaferrite Materials

The formation of Co$_2$Z hexaferrite through a modified aqueous co-precipitation of elements method followed by a single sintering step [4-5] is presented. Single phase powders of Co$_2$Z were produced by utilizing a modified co-precipitation of elements technique in 450 ml of de-ionized water followed by a single sintering. The reaction vessel was heated to 95 °C and stirred at 300 rpm for 2 hours. Starting powders were mixed in stoichiometric ratios with the following amounts: 3.91 g of BaCl$_2$, 25.95 g of Fe(III)Cl$_3$, 3.8 g of CoCl$_2$, 16 g of NaOH, and 8 g of Na$_2$CO. Prior to mixing, salts and chlorides were diluted independently in 225 ml of de-ionized water, after which they were added simultaneously to a larger vessel which was heated to 95 °C, and subsequently mixed utilizing a motorized stirrer. 50 ml of tetra-ethylene glycol was added during the mixing process to serve as a surfactant and aid in particle formation [10].

After the reaction, the by-products of the reaction such as NaCl and excess water, were removed from the precipitants through a filtration process. This process consisted of vacuum filtration, then a single rinse where dried particles were added to 400 ml of water and stirred at 300 rpm for 30 minutes utilizing a magnetic stirrer. These particles then underwent ultrasonic vibration for 30 minutes to break up any agglomerations. The excess water was then removed via vacuum filtration. After verification of the removal of NaCl via energy dispersive X-ray spectroscopy (EDXS), powders were mechanically pressed into compacts at 1000 psi using a stainless steel die and a uniaxial hydraulic press (Figure 140).
44(c)), and sintered at 1250 °C for 10 hours in air. The rate of heating and cooling used in the formation of the Co$_2$Z hexaferrites was 5 °C/min.

Figure 54: (a) X-ray diffraction spectrum of sintered Co$_2$Z hexaferrite powder compared with reference JCPDS file no. 19-0097 [11]. (b) Magnetic moment of Co$_2$Z hexaferrite powder measured using VSM. (c) and (d) SEM images of Co$_2$Z hexaferrite powder at different magnifications.

Phase purity of the samples was verified with XRD measurements. A representative θ-2θ spectrum collected using Cu kα radiation is shown in Figure 54(a). All peaks in the spectrum were indexed to a hexagonal Z-type ferrite structure based on
JCPDS reference file no. 19-0097 [8]. The static magnetic properties of the samples were measured using Vibrating Sample Magnetometry (VSM). A typical hysteresis loop of loose Co$_2$Z hexaferrite powder is shown in Figure 54(b). Saturation moment of as prepared ferrite powder (assuming bulk density) was measured to be 3310 G, in good agreement with bulk reference data of 3350 [6-8]. Rough density values of \(~90\%\) were measured on as sintered pucks allowing for this density assumption. Scanning electron microscopy (SEM) images of the sintered ferrite powder are shown in Figure 54(c) and (d). Large regular hexagonal grains with diameters of up to 20 µm are clearly visible in the images.

![Real permeability and magnetic loss tangent](image)

Figure 55: Real permeability and magnetic loss tangent of a moderately dense (~90\%) non-oriented Z-type hexaferrite toroid sample.
The complex $\mu$ and $\varepsilon$ of the samples machined into either torroids ($\mu$) or circular plates ($\varepsilon$) was measured using Agilent Material Analyzer A4991, the process for making these samples will be discussed in the following section (5.2.2). Typical spectra for non-oriented samples are shown in Figure 55 and Figure 56. Here, complex $\mu$ measurements of Co$_2$Z hexaferrite samples have shown moderate real $\mu_r$ values on the order of 6.8 and magnetic loss tangent values on the order of .01 to 0.1. As well as $\varepsilon_r$ values $\sim$15, with a dielectric loss tangent of .01 over the majority of the operating range. The lack of orientation, or crystallographic texturing, of the Co$_2$Z hexaferrite samples was deemed the reason for these values. These values are in good agreement, allowing for differences in density, with those in previously published works [12-16].
As previously mentioned, no magnetic field was applied during the formation of the green body compacts, therefore the anisotropic hexaferrite particles were randomly distributed within the compact. In order to increase the \( \mu_r \) and further optimize the magnetic loss tangent, a magnetic field orientation similar to the one used in the previous chapter (Chapter 4) was applied in the following sections. The results of these studies will show that magnetically oriented Co\(_2\)Z hexaferrite substrates offer a favorable combination of high \( \mu_r \) and \( \varepsilon_r \), along with low loss tangents, to facilitate high performance EBG metamaterial and antenna substrate design.

5.2 Magnetodielectric Properties of Oriented Z-Type Toroids

5.2.1 Orientation of Co\(_2\)Z Hexaferrite Materials

The first step in the orientation process was to grind compacts produced via the single sintering method to single domain size (1-2 \( \mu \)m). This particle size has been achieved via ball milling in a Fritsch (TM) Planetary mono mill PULVERISETTE 6 classic line ball milling machine. Prior to milling, the sample was hand ground through a 75 \( \mu \)m sieve, this step was to ensure narrow size distribution in the final milling process. After hand grinding the sample (3 g at a time), it was placed in an 80 ml agate holder with 8 large (10 mm) and 7 small (6 mm) agate balls. These balls were selected after many trials to again limit the size distribution of the final powder. The reasoning for the different number of balls from the number used on the Co\(_2\)Y type powder in the previous chapter has been linked to the different densities of the compacts. The 80 ml agate holder was filled to the level of the top of the agate balls with reagent alcohol to aid in milling then placed into the mill. The mill was run for 8 hours at 400 rpm in 30 minute intervals. In
between the intervals a 5 minute pause was used allowing the slurry to settle, each subsequent interval was run in the opposite direction as the previous run. A scanning electron microscope (SEM) image of cobalt-substituted hexagonal Z-type barium ferrite particles produced by this method is shown in Figure 57 (a and b). The particles exhibit a uniform size distribution with an average diameter on the order of 0.5 to 2 µm, consistent with single magnetic domain size.

Figure 57: Scanning electron microscopy image of Co$_2$Z hexaferrite material which has been reduced to single domain size .5-2 µm through ball milling. (a) 3x10$^3$ magnification of particles, (b) 1.8x10$^3$ magnification of particles.

The next step in the texturing process was the alignment of these single domain particles. This was achieved by using the rotating magnetic field apparatus shown in Figure 44(c). In this process, the particles were dispersed in water at a ratio of 2-4 g of powder to 30 ml of water or alcohol. This slurry was subsequently placed in an ultrasonic
vibrator for 30 minutes to reduce the number of particle agglomerations. These particles were then loaded into a nonmagnetic steel die via a plastic 3 ml pipette, the excess water was removed from the cylinder after the particles had been allowed to settle in the rotating field. The powder was then pressed with a hydraulic press at 1000-1500 psi while being subjected to a rotating magnetic field of ~5000-7500 Oersted in the plane of the compact. The goal of the magnetic orientation process was to align the anisotropic ferrite particles with their crystallographic axes perpendicular to the compact plane to maximize the $\mu_r$ [13, 17]. After orientation the particles were densified in a box furnace in air at 1250 °C for 10 hours.

It should be noted that the initial low frequency magnetic permeability measurements presented in this section were performed in-house to expedite process refinement. Later samples discussed in this dissertation were sent out for high frequency permeability and permittivity measurements. Here, the Agilent 4294A Precision Impedance Analyzer with the frequency range of 10 Hz to 110 MHz was used along with the permeability measurement test fixture. These measurements allowed the low frequency permeability to be evaluated. While the measurement range of the instrument didn't allow the natural resonance frequency to be observed it still provided reliable values up to 110 MHz that were sufficient for process refinement purposes.
Figure 58: Preliminary attempts at orientation of Z-Type hexaferrite material toroid, a 20% increase in permeability is shown over the non-oriented material shown in Figure 55.

5.2.2 Preparing Samples for Measurement

After sintering, round compacts with an outer diameter of approximately 16 mm and thickness of approximately 3 mm had a cylindrical hole with a diameter of approximately 8 mm drilled in the center using a diamond coring bit. In order to keep the edges of the torroids clean during the drilling process, the compacts were mounted to glass slides prior to drilling utilizing Crystalbond\textsuperscript{TM} epoxy. Special care was given to ensure the holes were in the center of the torroid samples, as different ring circumference weighed heavily on the measured permeability of the torroid samples. After drilling, the
toroids were removed from the glass slides and the extra bonding epoxy was removed by rinsing the samples with acetone.

5.2.3 Optimization of Magnetodielectric Properties of \( \text{Co}_2\text{Z} \) Hexaferrites

The toroids produced via the method described in the previous section were used for the \( \mu_r \) and magnetic loss tangent measurements in this section. Figure 58 and Figure 59 show the \( \mu_r \) and \( \tan(\delta_m) \) of two \( \text{Co}_2\text{Z} \) hexaferrite samples produced via this method. The \( \mu_r \) of the first sample produced via this method was measured to be 8.2. The second sample was measured with a \( \mu_r \) of 8.6. The differences in these samples was that they were oriented with the rotational speed of the magnetic set to 30 (sample 1) and 20 rpm (sample 2), respectively. As such, reduced rotation speed of the magnetic field resulted in increased permeability values. An increase of 5% in permeability is evident in decreasing the magnetic field rotation speed from 30 to 20 rpm. This is consistent with the results presented on \( \text{Co}_2\text{Y} \) hexaferrites in the previous chapter.

Magnetic loss tangents were calculated for all samples in Figure 59. The loss tangent is observed to remain largely independent of processing conditions with a value of approximately \(<0.2\) at the highest measurement frequency of 110 MHz. In order to make samples described in this section are promising for antenna substrate applications this number will need to be dramatically lowered to be \(~.01\). However, they exhibit relatively high magnetic permeability (>8) and relatively low magnetic loss tangents (<0.2) at frequencies up to 110 MHz which is encouraging for EBG metamaterials which will be examined in depth in Chapter 9. Optimization of the processing of oriented ferrite
compacts in terms of magnetic field rotation speed, has produced a significant improvement in the real part of the permeability of Z-type hexaferrite samples from 6.8 to 8.6. At the same time the magnetic loss tangent remained relatively low at 0.2.

Figure 59: Preliminary attempts at orientation of Z-Type hexaferrite material toroid, $\tan(\delta_m)$ is shown for samples produced via different magnet rotation speeds.

In order to further increase the value of $\mu_r$, many aspects of the orientation process had to be optimized. First, since the rotational magnet was permanent, the field strength could not be altered. However, the position of the pressed compact relative to the center of the magnetic field could still be changed. To optimize the setup in this regard, a new die set was designed. This die set was designed so that the powder, after settling inside the cylinder would be in the center of the magnetic field, allowing for maximum field
strength ~7500 Oe vs ~5000 Oe in the previous case. The results of this new die set are shown in Figure 60. Here a $\mu_r$ of 10.8 is shown for a machined toroid of Co$_2$Z material, this value is a 64% improvement over the initial non-oriented $\mu_r$ value of 6.8.

![Graph](image)

**Figure 60:** Orientated Z-Type hexaferrite material toroid utilizing the new die set, a 64% increase in permeability is shown over the non oriented $\mu_r$ measurement in Figure 55.

Further increases to the permeability of oriented Co$_2$Z hexaferrite materials was shown through altering the amount of time spent in the ultrasonic machine prior to orientation. Samples made with one hour of ultrasonic vibration instead of 30 minutes demonstrated a $\mu_r$ on the order of 12.5. The best sample of this series is shown in Figure 61, and was the first Co$_2$Z hexaferrite sample which was measured on the Agilent Material Analyzer A4991. Here the $\mu'$ is given to be 12.5, and the $\varepsilon'$ is shown to vary between 10 and 12.5 over the frequency range of interest. The zero-field FMR value of
the material can be estimated from this figure to be around 1 GHz, which is to be expected from literature [7]. The magnetic and dielectric loss tangent measurements of this material is also shown in Figure 61.

![Figure 61](image.png)

Figure 61: Measured (a) permittivity and permeability and (b) magnetic and dielectric loss tangent spectra of torroidal samples of oriented Co$_2$Z ferrite materials optimized for magnetic antenna substrates [3].

Figure 62 depicts a sample of Co$_2$Z material which has been annealed in oxygen instead of air. Here the initial $\mu_r$ is measured to be 16.5, which is significantly higher than the samples produced in air and shows an increase of ~140% in the permeability of the non oriented Co$_2$Z hexaferrite sample. This has been attributed to the phase purity the excess oxygen gives the single sintering formation. This sample was measured utilizing a
Agilent E864A 45MHz-50GHz PNA series network analyzer with a 7mm HP 85050C precision airline. Matlab\textsuperscript{(TM)} was used to extract both the $\mu'$ and $\mu''$ data. It should be noted that the airline used in these measurements was not rated for $<1$ GHz, so there are some small inconsistencies in the data presented, these are even more pronounced in the loss measurements due to the thinness of the sample compared to the measured wavelength. In addition to zero field measurements the effect of an applied field on the $\mu$ was shown to demonstrate how this material could be used in L and S-Bands applications. This bias field was applied in parallel to the c-axis to see the effect on the permeability. Here a permeability of 5 is shown through the entirety of the L-band.
5.3 Electric Field Tuning of Ferromagnetic Resonance [18]

In this section the tunability of the fabricated Co$_2$Z hexaferrite material is examined for potential uses in tunable devices. This was achieved by creating a Co$_2$Z/PMN-PT heterostructure for measurement. In this way the electrical tuning of ferromagnetic resonance (FMR) at X-band can be seen. The structure of the design consists of a magnetostrictive microwave ferrite (Z-type hexagonal ferrite) and a PMN-PT piezoelectric crystal (Figure 64).

Figure 62: Measured permeability and magnetic loss of torroidal samples of oriented Co$_2$Z ferrite materials optimized for magnetic EBG design under various levels of applied bias fields applied parallel to the c-axis of the torroid plane.
First, in order to determine the electric field tunability the dependence of strain with magnetic field, i.e. magnetostriction, of the oriented Co$_2$Z ferrite was measured. The results of this study are depicted in Figure 63. The longitudinal and transverse orientations represent an external magnetic field aligned parallel and transverse to the direction of strain, respectively. The magnetostriction denotes the magnetostriction coefficient in the longitudinal and transverse geometries, respectively. This magnetoelastic nature of Z-type ferrite is extremely important in realizing an E-field tunable magnetic device, although it has been largely negligible in conventional high frequency ferrite devices.

Figure 63: Magnetostriction measurements for a perpendicular c-axis oriented Co2Z ferrite compact. Longitudinal and transversal represent an applied magnetic field parallel and transversal to the direction of strain observed, respectively [18].
The FMR measurements were performed at 9.55 GHz while an electric field of 6 kV/cm (or zero) was applied across the PMN-PT crystal, the results of this study are shown in Figure 64. The theoretical equation for FMR of a hexagonal ferrite material is given in Eqn (1). These measurements were inspired by a recent study on Sr Co$_2$Z hexaferrite materials which demonstrated low-field magneto electric effects at room temperature [19]. The measurement has demonstrated a pronounced microwave tunability of the multiferroic heterostructure, indicated by a FMR resonance field shift of 38 Oe while an electric field of E=6 kV/cm was applied, as presented in Figure 64. The Co$_2$Z ferrite shows a FMR linewidth ($\Delta H$) of 735 Oe and 755 Oe, corresponding to 0 and 6 kV/cm, respectively. Note that the resonance field $H_r$ is 840 Oe without electric field, whereas an electric field lowers FMR resonance field by 38 Oe. It obviously arises from an stress-induced anisotropy field by application of the electric field. This induced magnetic field is assumed to be along the applied magnetic field, yielding a reduction in the resonance field measured. It clearly indicates an electrical tunability of microwave resonance field.

$$f = \gamma' \sqrt{H(H + H_a + 4\pi M)}$$

Eqn (1) [18]
Figure 64: Ferromagnetic resonance measurements for a perpendicular c-axis oriented Co$_2$Z ferrite slab bonded on piezoelectric PMN-PT crystal as applied electric field of 6 kV/cm and zero field, respectively. Inset illustrates geometry and field configuration of the multiferroic heterostructure. Here the longitudinal represents an applied magnetic field along d31 direction of PMN-PT slab [18].

In order to obtain the tunability of permeability controlled by an electric field applied across the PMN-PT slab, a relationship between the permeability and the magnetic field was determined. At low frequencies, i.e., off-resonance frequency, the
permeability can be expressed as shown in Eqn (2). As an extension of this equation the permeability tuning rate with applied magnetic field can be described as shown in Eqn (3).

\[ \mu \approx \frac{4\pi M}{H + H_\phi} \]

Eqn (2) [18]

\[ \frac{\Delta \mu}{\mu_0} = \frac{\mu(H) - \mu(0)}{\mu(0)} = \frac{4\pi M}{H + H_\phi} - \frac{4\pi M_r}{H_\phi} \frac{4\pi M_r}{H_\phi} + 1 \]

Eqn (3) [18]

It should be noted that in these equations M(H) is expressed as a function of H, and when H=0 the 4\pi M in Eqn (2) is 4\pi Mr. According to Eqn. (3), the trend of permeability with respect to the bias magnetic field in terms of remenance, 4\pi Mr =275 G, and the in-plane anisotropy field, H_\phi=20 Oe has been demonstrated. The solid line plotted in Figure 65 represents a theoretical prediction of the dependence of the rate of change in permeability with respect to the applied magnetic field. To verify the accuracy of the theoretical prediction, the complex permeability of a sample of Co_2Z hexaferrite material was measured with different applied magnetic fields (0-1000 Oe). The measurement technique employed was a standard co-axial air-line technique using a vector network analyzer over a frequency band from 0.5–5 GHz. The measured data plots are given in Figure 66 and are closely matched to the theoretical curve. Finally, the
tunability of permeability with electric field in terms of resonance shift controlled by an electric field and supported by theoretical calculation was demonstrated. That is, the permeability change tuned by 38 Oe of induced magnetic field under the application of 6 kV/cm of electric field was measured. It was revealed that the permeability changed by 16%, corresponding to a permeability tunability of 2.7 %/ kV-cm-1. Since the Co₂Z ferrite has a zero field resonance frequency of 1.0 GHz, we assume that the resonance frequency is tuned by 256 MHz due to 16% of permeability change under the application of E=6 kV/cm in accordance with the limitation imposed by Snoek’s law. Furthermore, the indirectly measured value is also plotted in Fig. 4 as a hollow circle symbol and it is seen to also plot on the theoretical curve.
Figure 65: (a) Tunability of permeability with a biased magnetic field. Solid line represents theoretical prediction in Eqn. (3); square and circle symbols denote direct measured data tuned by a biased magnetic field and indirect measured value tuned by an electric field, respectively. (b) Measured complex permeability vs. frequency with different biased magnetic fields for a perpendicular c-axis oriented Co2Z ferrite compact [18].

As previously mentioned, this measurement has been verified via a manufactured sample of Co2Z material where the initial $\mu_r$ has been plotted as a function of applied field for fields ranging from 100 to 1000 Oe (fields 400-1000 not pictured). The results of this study are shown in Figure 66, and follow what would be expected based off of Snoek's Limit [13]. Namely that increasing the bias fields will increase the FMR value of
the material, while lowering the $\mu_r$ value. Snoek's product says that that multiplying these two values together will result in a constant value, and the constant value is dependent upon the material under study. For example Ti and Zn substituted Co$_2$Z hexaferrites have higher initial permeability but lower zero field FMR frequencies [20].

![Figure 66: Permeability and magnetic loss tangent as a function of applied field of Co$_2$Z hexaferrite material torroids produced via a modified chemical co-precipitation method.](image)

In summary, an electric field tunability of permeability for Co$_2$Z ferrite was presented by a Co$_2$Z/ PMN-PT multiferroic heterostructure, indicating a pronounced tuning of $\mu_r$, with a -16% change with an electric field of 6 kV/cm. In a meantime, a calculated curve of $\Delta\mu/\mu_0 \sim H$, derived from the measured data, and has also been
presented. These results reveal great potential for tuning of permeability by electric field based on the present multiferroic structure.

5.4 Conclusions

In order to find materials which are suitable for antenna and electromagnetic band gap metamaterial substrate applications at higher frequencies, including but not limited to the L and lower S-bands, the fabrication of Co$_2$Z material has been demonstrated through a co-precipitation of elements technique. The phase purity of this material has been examined through a single sintering technique via X-ray diffraction, and the magnetic properties have been compared to bulk materials via vibrating sample magnetometry. This material has been thoroughly characterized with regard to its in plane orientation and magnetic properties. Optimization studies have been performed to maximize the permeability and minimize the magnetic losses below ferromagnetic resonance (FMR). Permeability values for oriented samples were given to be 16.5 compared to 6.8 for non-oriented samples. In addition, studies have been performed utilizing bias fields to increase the operational ranges of these materials into the S-band with permeabilities >5. In addition the tunability of this material has been examined as a function of applied field, allowing for tunable devices to be fabricated. This material has proven to be more practical for device fabrication than the Co$_2$Y hexaferrites introduced in the previous chapter due to its intrinsically higher permeability values, and its wave impedance value which is close to that of free space.
5.5 References


Chapter 6: *Antenna Element Design on Dielectric Materials*

6.1 Introduction

The previous chapters of this dissertation have focused on a discussion of practical magnetodielectric materials for antenna and electromagnetic band gap (EBG) metamaterial substrate applications. The goal of those chapters was to locate practical materials and more importantly, to determine over what frequency range these materials could operate. In this, and the following chapters, practical antenna elements will be examined with respect to these potential frequency ranges. The approach to be covered in this chapter is the design of these elements through a standard $\lambda_{\text{sub}}/4$ dielectric cavity approach. Utilizing this method, a variety of potential wide and narrow band aperture elements will be introduced. These designs will include; linear polarized elements such as the bow tie antenna [1-4], and circular polarized designs such as; the Archimedean spiral antenna (ASA) [5-7], the slot Archimedean spiral antenna (SASA), and the square slot spiral antenna (SSSA) [9-10]. Antennas with small radiating apertures compared to their operating frequencies such as the bow tie antenna and spiral designs will be investigated heavily in order to create designs which are close to that of Chu's Limit [11-12]. It should be noted that due to the dielectric cavities beneath almost all the elements presented in this chapter with heights of $\lambda_{\text{sub}}/4$, which are required to enhance the gain, the antennas presented are generally bulky and not cost effective to produce. This will be addressed in subsequent chapters by utilizing these same element designs on novel magnetodielectric substrates.
Numerous commercial applications, such as weather and Earth science radar, automotive radar, wireless communications, radio frequency identification, etc. as well as military security, surveillance and communication antenna applications are in the ultra high frequency (UHF (.3-3 GHz)) through X-band (~7-12 GHz). Due to the size of this potential operating bandwidth there is a significant interest in developing small, efficient, and ultra wideband antennas (UWB) operating in these frequency bands for high power radar applications. Employing multiple antenna elements to cover such a wide frequency range is often prohibitive due to space, weight, and cost limitations as well as electromagnetic interference (EMI) concerns. Additionally, the size of the antennas at low frequencies impose severe limitations on their deployment. Size reduction is conventionally achieved at the expense of gain. Therefore, new design approaches are necessary to maintain optimal efficiency and gain while allowing for a significant antenna size reduction and therefore a reduction in cost while maintaining desired antenna operating parameters such as gain, bandwidth, polarization stability, and pattern purity. The goal of this chapter will be to develop antennas which operate over large bandwidths (as defined via their return loss [13]) in the UHF through X-band, which also operate over the frequency regions outlined for the magnetodielectric materials outlined in Chapters 3-5. In addition to the aforementioned wide bandwidths these elements should also have high efficiency, gain, and pattern purity.
6.2 Wide Band Element Designs

6.2.1 Bow Tie Antenna

In this section two different bow-tie antennas will be introduced. The first antenna is presented in Figure 67(a and b) and is a recent design from literature [3]. This antenna utilizes a thin substrate with one side of the bowtie being parasitically fed from the other through the substrate itself. The antenna is designed with a feed network to match the input of the design to 50 $\Omega$. It should be noted for this particular design the gain will not be overly high due to the fact that the ground plane is not placed at $\lambda_{\text{sub}}/4$ from the radiating element. While this results in good omnidirectional performance, this antenna should radiate an estimated 3 dB lower than Chu's Limit due to this limitation. This design implementation also makes the use of an EBG substrate impossible, magnetodielectric substrates; however, can still be used.

Figure 67: (a) UWB bow tie antenna element from literature. (b) Optimized bowtie designed to operate with narrow thickness, with reduction in gain.
Utilizing the antenna in Figure 67(a) as a starting point, the antenna in Figure 67(b) was designed to optimize the antennas gain and increase the operating range. This antenna was designed utilizing FEM simulations on a substrate which has a $\varepsilon_r = 6.15$, and a height of 1.37 mm ($\lambda_0/70$) with a center frequency of 3.1 GHz. The antenna is fed through a specially designed feed network consisting of a twin lead transmission line to a microstrip line ($L_1, L_2, L_3, W_1, W_2, W_3$) which allows for matching to a 50Ω input. The remaining parameters of the bowtie were optimized for return loss measurements ($L_{11}, L_{12}, L_g$). The optimum parameters utilizing FEM software were found to be: $L_{11} = 4$ mm, $L_{12} = 11.2$ mm, $L_g = 6.9$ mm, $L_1 = 3.2$ mm, $L_2 = 11.3$ mm, $L_3 = 5.1$ mm, $W = 1.87$ mm, $W_1 = 1.4$ mm, $W_2 = 2.9$ mm, $W_3 = 2.8$ mm, $c = 1.0$ mm, and $L = 15.8$ mm. The overall dimensions of the antenna are 36 mm by 34.6 mm (~$\lambda_0/2.7$). Figure 68 outlines the basic radiation parameters with return loss measurements that indicate good matching over the 3 GHz to 10 GHz band. The broad side gain is maintained at 3-5 dB over this range, which is approximately 3-5 dB below Chu's Limit. This element could easily be tuned for L-band applications by increasing the planar dimensions.

While these designs are promising in covering the UHF through X-bands in terms of gain and return loss by utilizing an ultra thin element. In reality, they are not sufficient for ultra wideband applications due to their poor radiating properties, an example is their inability to maintain radiation pattern stability as depicted in Figure 69. Possible solutions to this problem are to utilize either planar patch bow tie elements, or planar slotted
bowties. It should be noted; however, that due to the material studies which have been presented in the previous chapters, an antenna which can maintain is omnidirectional performance over 1 octave is sufficient, due to the frequency limitations of the materials themselves.

Figure 68: Bow tie element simulation results; gain is maintained at 3-5dB and return loss measurements indicate good matching over the 3 GHz to 10 GHz band.
The second bow tie investigated for this discussion was a cavity design on a dielectric half space. However, the simulations of this design have not been included in this dissertation for the following reasons. First, based on the design protocols, [4] the size of the planar antenna element is given in Eqn(s) 1 and 2. This results in a 22 cm design at 1 GHz which is much too large considering the goals of this dissertation. Secondly, the reported bandwidths utilizing these designs are on the order of 10%, which are not suitable for L-Band applications.

\[
Width = \frac{(1.6 \times \lambda_0)}{\sqrt{\varepsilon_r}}
\]
\[ Length = \frac{(0.8 \times \lambda_0)}{\sqrt{\varepsilon_r}} \]

Eqn (2) [4]

6.2.2 Planar Spiral Antennas (SSSA Element)

Due to the formation of next-generation receivers in the Global Navigation Satellite System (GNSS). New antenna element designs are needed to optimize the accuracy and availability of signals which up to this point have been solely utilizing the Global Positioning System (GPS). The new designs, need to have a high omni-directional gain pattern while at the same time minimizing cost and weight. They also need to be optimized as RHCP receiving elements with a low cross-polarization value. For this reason a series of circular polarized elements will be introduced.

Figure 70: (a) Design of 50 ohm matched GNSS SSSA element with a height <2” on a low cost Rodgers\textsuperscript{TM} TMM4 (\(\varepsilon=4.5\)) substrate. (b) Depiction of 3-D omni-directional radiation pattern of the SSSA element in the higher GNSS operating band (1559MHz to 1611MHz).
Perhaps the most promising of these elements is a square slot spiral antenna (SSSA). This element is pictured in Figure 70 and is based off of designs from literature [9-10]. This antenna has been optimized with regard to a single resistor termination on each arm (47 Ω) to operate as a high gain right-hand circular polarized (RHCP) receiving device. Normally a Klopfenstein taper which is comprised of >15 resistors along the spiral arm would be used to attenuate the current in the spiral arms and improve the axial ratio and cross polarization. However, for this design a single chip resistor was used for two reasons; first, for ease of fabrication due to the use of a superstrate in the design; secondly, literature indicates that utilizing a correct single resistor termination will not have an overly large effect on the axial ratio and cross polarization values and will actually increase the low frequency gain leading to a smaller and more compact design [10].

Another reason a SSSA element has been chosen for this application due to the inherently lower operating frequencies of these devices compared to those of similarly sized circular spirals (~22% lower), thus allowing for weight and size reduction. This is due to the fact that the lowest operating frequency of a SSSA element is given by \( D = \lambda_0/4 \), where the lowest operating frequency of an Archimedean spiral antenna is given by \( D = \lambda_0/\pi \). It both cases \( D \) is the diameter of the design. Another reason for the utilization of a slot spiral over the normal Archimedean spiral is due to the enhancement of gain inherent with slot radiating elements, which makes the antenna better suited for the
design goal of a high gain antenna one of the main design considerations of the GNSS and GPS high gain radar systems [10].

The proposed SSSA design is shown in Figure 70(a), where the antenna is designed on a 5.72 cm by 5.72 cm square ground plane utilizing a Rodgers™ TMM4 \(\varepsilon_r=4.5\) substrate/superstrate. The aperture size is 5.72 cm by 5.72 cm which encompasses the spiral. The spiral itself is defined by the width of the slot \(w_1=0.0762\) cm and the width of the stripline \(w_2=0.2286\) cm. The antenna has been matched to 50 \(\Omega\), via the superstrate to be back fed by a standard coaxial line. A superstrate has been used for three reasons, first to optimize the omni-directional nature of the radiation pattern; secondly, to adjust the input impedance of the spiral to match a standard 50 \(\Omega\) coaxial cable line, and thirdly, to minimize the planar dimensions of the antenna design via dielectric loading. This is shown by the fact that the antenna is matched for frequencies lower than expected via the \(D=\lambda/4\) assumption for a free space design. The total height of the proposed antenna is <2". Figure 70(b) demonstrates the 3-D radiation field (total realized gain) around the antenna at the center frequency of the higher operating GNSS band a (1559MHz to 1611MHz). This pattern is standard to what would be expected for spiral antennas, and shows good omni-directional performance which is one of the design considerations which is why a spiral antenna design was chosen.

Figure 71 depicts the relevant antenna properties of the SSSA design within the desired GNSS operating bands of 1164 MHz-1300 MHz and 1559 MHz-1611MHz (shaded in green). The SSSA element has been optimized with respect to Chu's limit for
the current aperture size of 2"x2"; however, this can be scaled towards larger designs to increase the gain for other applications. This allows for a small antenna size with respect to achievable gain based on applications, an overview of achievable gains is shown in Figure 72 and will be discussed shortly. The return loss of the SSSA element is pictured in Figure 71 and is very well suited for the GNSS operating bands, allowing for <-10dB over both of the desired bands minimizing the radiation loss associated with antenna mismatch to the standard 50 Ω coaxial cable. In fact, the antenna is matched with a lowest operating frequency of 0.75 GHz. The efficiency is >60% for the first operating band and >75% for the second band. These numbers can be optimized with respect to slot size, and dielectric loss tangent. Finally, the axial ratio while being slightly elliptical due to the nature of the single termination resistor slot spiral design, doesn't hinder the cross polarization (>10 dB) of the RHCP nature of the design which will also be discussed in depth (Figure 73) with the radiating properties shortly.
Figure 71: (a) Total realized gain of the SSSA element compared to that of Chu's Limit for the given SSSA element size. (b) Return loss of the SSSA element design. (c) Efficiency, and (d) axial ratio of the SSSA element design. Green bands indicated desired GNSS bands of interest.
Of particular interest in the design of this antenna is the realization of high gain. It should be noted that for a particular antenna aperture size the gain is limited by Chu's limit which is linked to the largest dimension of the design. This dimension is then used as the radius of a omnidirectional radiating sphere [11-12]. In Figure 72, the broad side gain of the designed antenna is plotted against Chu's limit for various radius sizes. Very good agreement is shown for the original design of a 2"x2"x2" square and the equivalent Chu's limit. Scaling of this this SSSA element design towards a larger planar size should increase the gain accordingly. With the plotted Chu's limits the approximate size requirements to achieve almost any gain inherent to the design constraints is shown.

![Figure 72: Comparison of the current SSSA design to that of Chu's Limit, plotted for increased aperture sizes, depicted to show how realizable high gains can be readily achieved.](image_url)
In order to reduce multipath which is undesired to the prospective design and antenna utilization, cross-polarization and back lobes need to be minimized. This can be achieved via many distinct routes. First, the use of a large ground plane will reduce the back lobes. Unfortunately, this is not advantageous to the design goals; which are to minimize weight and planar size. Also, oftentimes the antenna element will be mounted above a pole, and a large ground plane will increase drag in inclement weather which needs to be avoided. Therefore other methods need to be approached. Thankfully the SSSA design can be tuned relatively easily to be RHCP or LHCP based off the windings of the spiral arms, and the termination resistor value used. In Figure 73 the cross polarization of the design is shown at the broad side of the antenna, where the RHCP gain is shown to be ~10 dB higher than the undesired LHCP component, and when compared to the total realized gain it is apparent that the RHCP is the only usable polarization. Current simulations indicate that this behavior is constant along the 3 dB beam width, and will be optimized with future designs to provide cross-polarization as near to the horizon as possible. One possible methods of optimization of this value includes the use of a Klopfenstein taper instead of a single termination resistor, this however will make it much more difficult to use a superstrate in the design due to the protruding resistors.
Figure 73: Realization of boresight cross polarization minimization for the miniaturized SSSA element design. Optimization of the cross-polarization near the horizon is ongoing.

Important consideration has been spent with regard to optimizing the radiation patterns of the desired antenna elements; for example, a ground plane backed spiral antenna has been designed, which is known to have good omni-directional performance. In addition a superstrate has been designed to smooth the radiation pattern over the elevation of the design. Figure 74, depicts the RHCP gain patterns of the designed SSSA element over the desired bands. Here, the 3-DB beam width of the antenna is \( \sim 130^\circ \) in the \( \varphi = 0^\circ \) plane and \( \sim 115^\circ \) in the \( \varphi = 45^\circ \) plane.
Figure 74: RHCP gain of the SSSA element vs $\theta$ for $\phi = 0^\circ$ and $45^\circ$, 3 dB beamwidth is indicated to be $\sim 130^\circ$ for the $\phi = 0^\circ$ plane and $\sim 115^\circ$ for the $\phi = 45^\circ$ plane.

In conclusion, to meet the desired goals of pattern uniformity, broad bandwidth, and high gain a square slot spiral antenna (SSSA) has been proposed. This antenna has been optimized with regard to a single resistor termination to operate as a high gain right-hand circular polarized (RHCP) receiving device. The SSSA element has been chosen for this application due to the inherently lower operating frequencies of these devices.
compared to those of comparably sized circular spirals (~22% lower) [9], thus allowing for weight and size reduction as well as gain enhancement over standard dual arm spiral designs. The gains of these antennas over the potential operating regions of the materials in the previous chapters is quite encouraging. This antenna element has also been designed to operate over the frequencies which the magnetodielectric materials presented in the previous chapter have been shown to operate.

Figure 75: (a) Depiction of a L-Band Archimedean spiral antenna design, (c) a slot Archimedean spiral antenna design, and their respective radiation patterns (b and d) at a center frequency of 1.5 GHz.

6.2.3 Planar Spiral Antennas (ASA and SASA Elements)

In addition to the SSSA element design presented in the previous section a variety of other wideband elements have been examined such as the Archimedean spiral antenna
(ASA) and the slot Archimedean spiral antenna (SASA). These elements have also been examined for potential magnetodielectric and EBG substrate designs though in less detail due to their inherently larger apertures. These antenna elements are pictured in Figure 75.

![Figure 76](image)

**Figure 76:** (a) Total realized gain of the ASA element compared to that of Chu's Limit for the given aperture size. (b) Return loss of the ASA element design. (c) Axial ratio of the ASA element design.
Figure 76 depicts the relevant antenna properties of the SSSA design within the desired GNSS operating bands of 1164 MHz-1300 MHz and 1559 MHz-1611 MHz. The ASA element has been optimized with respect to Chu's limit for the current aperture size of 7.5 cm by 7.5 cm; however, this can be scaled towards larger designs to increase the gain for other applications as demonstrated on the SSSA element. The return loss pictured in Figure 76 of the ASA is very well suited for GNSS bands, allowing for <-10 dB over the entirety of the L-band minimizing the radiation loss associated with antenna mismatch to a standard 50 Ω coaxial cable, to which the antenna has been tuned. The efficiency (not pictured) is >60%. This can be optimized with respect to slot size, and dielectric loss tangent as with the previous element case. Finally, the axial ratio is shown to be slightly elliptical.

Figure 77 depicts the relevant antenna properties of the SASA design within the desired GNSS operating. The SASA has been optimized with respect to Chu's limit for the current aperture size of 7.5 cm by 7.5 cm. The return loss pictured in Figure 77 of the SASA is very well suited for GNSS bands, allowing for <-10 dB over both of the desired bands minimizing the radiation loss associated with antenna mismatch to the standard 50 Ω coaxial cable, to which the antenna has been tuned. The efficiency (not pictured) is >60%. The axial ratio for this design is has a very good polarzation purity, with an axial ratio ~1.5-2 overthe entirity of the operating range. The overview of the results of this antenna and those previously introduced in this chapter can be seen in table 3.
Figure 77: (a) Total realized gain of the SASA element compared to that of Chu’s Limit for the given aperture size. (b) Return loss of the SASA design. (c) Axial ratio of the SASA design.

6.2.4 Conformal Spiral Antennas

Many novel antenna applications require fitting of antenna elements to a curved surface such as the fuselage of an aircraft. Towards this end, simulations have been run to
determine the effect of curvature on an element on its radiation parameters. The element used in this study was the ASA element [4-6] due to its ease of simulation. Figure 78(a) Depicts the design of a conformal dielectric ASA element utilizing a $\varepsilon=4.5$ Rodgers™ TMM4 substrate. Here the thickness of the spiral arm is 2.4 mm, and the spacing between spiral arms is 2.4 mm as well. The total diameter of the element is ~5 cm, and it has been designed to operate in the GNSS and GPS bands. Figure 78(b) Shows the radiation patterns achieved at the frequency of 1 GHz of the antenna design. Good omnidirectional performance is shown. Figure 78(c) depicts the general radiating properties of the ASA element. Gain is shown to be close to Chu's limit at the design frequency of 1 GHz, also shown are the antennas return loss and axial ratio respectively. It should be noted that due to the fact that the FEM tool used to simulate these designs cannot place a feed port on a curved surface a raised port was used.

<table>
<thead>
<tr>
<th>Antenna Property</th>
<th>ASA</th>
<th>SASA</th>
<th>SSSA</th>
<th>Thin Bowtie</th>
<th>Cavity Bowtie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Size</td>
<td>7.5 cm*7.5 cm</td>
<td>7.5 cm*7.5 cm</td>
<td>5.3 cm*5.3 cm</td>
<td>3.6 cm*3.6 cm</td>
<td>22.2 cm*14.1 cm</td>
</tr>
<tr>
<td>Substrate $\varepsilon_r$</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>6.15</td>
<td>4.5</td>
</tr>
<tr>
<td>Height</td>
<td>5 cm</td>
<td>5 cm</td>
<td>5 cm</td>
<td>1.37 mm</td>
<td>5 cm</td>
</tr>
<tr>
<td>Gain</td>
<td>-2 dB</td>
<td>-2 dB</td>
<td>-3 dB</td>
<td>-5 dB</td>
<td>-5 dB</td>
</tr>
<tr>
<td>Frequency</td>
<td>1-2+ GHz</td>
<td>1-2+ GHz</td>
<td>3-2+ GHz</td>
<td>3-9+ GHz</td>
<td>~10%</td>
</tr>
<tr>
<td>Polarization</td>
<td>Elliptical</td>
<td>Circular</td>
<td>Elliptical</td>
<td>Linear</td>
<td>Linear</td>
</tr>
</tbody>
</table>

Table 3: Overview of dielectric antenna elements presented in Chapter 6.
Figure 78: (a) Design of conformal dielectric ASA element designed for operation with a center frequency of 1 GHz. (b) Depiction of the 3-D radiation pattern at 1 GHz. (c) Depiction of radiating properties of the ASA antenna design. Gain is close to Chu's limit at the design frequency, also shown are the antennas return loss and axial ratio respectively.

To understand the effect of varying the radius of the conformal designs, the radiation patterns for varying angle $\theta$ ($\varphi=0^\circ$), as well as broad side gain are depicted on the dielectric ASA element as a function of the radius of curvature of the substrate in Figure 79. It is important to note that within the generally desired conformal bands (9" to 21") the gain patterns are not overly dependent on the radius of the conformal design. When the radius of curvature is set to be a more drastic number such as <5" the effect is quite pronounced.
Figure 79: (a) The total realized gain (dB) patterns plotted for various radius of curvature values for varying angle $\theta$ ($\varphi=0$). (b) Depiction of boresight gain depicted for various radius of curvature values. It is important to note that within the desired conformal bands (9” to 21” ) no change is apparent.

### 6.4 Conclusions

In this chapter the simulation of wideband antenna elements suited to antenna miniaturization have been examined through a standard dielectric approach. This approach consisted of studying designs readily available in literature which could operate over the operating frequencies of the magnetodielectric materials which have been presented in the previous chapters. It has been shown that elements such as the bowtie, the Archimedean spiral antenna, and the square slot spiral antenna can all achieve wide bandwidths and a variety of different polarizations ranging from linear to elliptical and circular in the desired operating ranges of the GNSS and GPS bands. In particular antennas with small radiating apertures compared to their operating frequencies such as
Archimedean spiral antennas and square slot spiral antennas have shown great promise due to the fact that they operate at low frequencies with smaller apertures than the standard bow tie designs as a function of free space wavelength ($\lambda_0$). It has also been shown how these designs can be tuned to fit conformal surfaces, making these antenna elements applicable to a wider range of potential applications.

However, due to the fact that these antennas have been examined through a dielectric approach, ($\lambda_{sub}/4$) cavities are needed beneath these elements to enhance the gain. Otherwise the gain is generally very low as in the case of the thin bow tie design introduced. The requirement of these cavities make these antenna designs bulky, heavy, and not cost effective. An attempt to reduce the planar height of these antenna elements will be introduced in the following chapters by utilizing ferrite substrates and EBG metamaterials based off the materials studies of the previous chapters.

### 6.5 References


Archimedian Spiral Antenna and Feed Structure," Proc. IEEE Souteastcon, vol. 1,


(2004).

no. 64, (1948).

Chapter 7: Ferrites in Antenna Design

7.1 Chapter Goals/Previous Works

The previous chapter of this dissertation focused on the use of dielectric substrates in antenna design. In that chapter, it was shown that while these antenna elements had favorable radiating properties, including wide bandwidths and gains approaching Chu's limit, they were not useful in a practical sense. This was due to the large (λ_{sub}/4) cavity backings used in the elements design to enhance the gain, which in turn significantly affected their respective weights and costs. Recently, a good deal of research with novel materials such as reactive impedance substrates, magnetodielectric substrates and ferrite films has been done to address this problem [1-6].

In this chapter, these concerns will be addressed through the use of hexaferrite substrates and absorber layers; namely, the use of the Co₂Z hexaferrites and spinel ferrites with high permeability (μ_r) and permittivity (ε_r) which have been introduced in Chapter(s) 3-5. These materials will be simulated in antenna assemblies as antenna substrates and absorbers using realistic magnetic and dielectric properties. The goal of this study will be reducing the profile and planar dimensions of the antenna assemblies utilizing elements such as the Archimedean (ASA) and square slot spiral antennas (SSSA) whose geometries have been introduced in the previous chapter.
Figure 80: (a) Agilent™ Impedance Analyzer and torroid samples of Z-type textured ferrite materials. (b) Measured permittivity and permeability on torroids and plates of oriented Co$_2$Z ferrite materials. (c) Magnetic and dielectric loss tangents measured on oriented Co$_2$Z ferrite materials.

In addition to reducing the profile and planar dimensions of the simulated antenna assemblies by utilizing magnetodielectric loading. Using materials such as the Co$_2$Z hexaferrite material introduced in Chapter 6 with values of $\varepsilon_r$ close to $\mu_r$ allows for easy impedance matching, allowing for stable return loss of the element over wide bandwidths. However, it will be shown that while these substrates can reduce the height of the antennas to $\lambda_0/40$ or even $\lambda_0/65$ while maintaining broad bandwidths, they negatively affect the efficiency and gain of the antenna elements due to the high magnetic losses of the substrates at higher frequencies (>300 MHz). While these properties can be somewhat negated by creative use of superstrates and bias magnets, these materials alone are not sufficient for practical novel miniaturized antenna substrates in anything other
than the upper VHF and lower UHF bands until their magnetic loss parameters can be lowered to less than .01 over the desired operating range. To develop magnetodielectric L-band and higher frequency antenna substrates one of two techniques needs to be employed. The first potential technique is to apply bias fields to the substrate, increasing the permeability and lowering the magnetic loss tangents. The second technique would be to develop new magnetic materials with even lower losses and higher operating frequencies. Recent work in commercial ferrites utilizing potassium doping by TransTech (Skyworks inc.) has been mildly successful in increasing the zero field ferromagnetic resonance values of Co$_2$Z ferrites from 1-1.1 GHz; however, this alone is insufficient for operation in the majority of the L-band.

Therefore, in addition to utilizing these materials as antenna substrates they will also be introduced as absorber layers [7-10] to increase the low frequency matching of wideband antennas which operate over much larger frequency ranges, including the S (2 GHz to 4 GHz) through X-bands (~7 GHz to 12 GHz). Utilizing realistic ferrite parameters this will be shown as an effective way to use these materials in antenna designs even with relatively high losses. This will also allow for the use of magnetodielectric materials in applications such as S and X-band antenna designs where before they would not work well due to their zero field ferromagnetic resonance values of ~1 GHz. Other ways to circumnavigate the low gain inherent to these antennas will be examined in the following chapters such as placing these elements in phased arrays for higher gain (Chapter 8) and with electromagnetic band gap (EBG) metamaterial substrates (Chapters 9 and 10).
7.2 Ferrite Substrates

7.2.1 Planar Approach SSSA Design

Utilizing the magnetodielectric loading effect these novel substrate materials provide, it is possible to design ultra low profile antennas which have applications in network enabled weapons (NEWs) which operate utilizing newer positioning technologies such as software defined radio (SDR). There is great demand for many bandwidths of operation of these designs, but this chapter will focus on designs in the UHF (.3-3 GHz) band which encapsulates both the Global Positioning System (GPS) and Global Navigation Satellite System (GNSS). This is due to the fact that this is where the hexaferrite materials introduced in Chapters 4 and 5 operate. Due to the high \( \varepsilon_r \) and \( \mu_r \) values, these antennas will be extremely low in profile due to magnetodielectric loading. To demonstrate this effect, the height of a theoretical antenna assembly with the center frequency of 1.575 GHz (GPS), on a Co\(_2\)Z substrate will have a height of \( \lambda_{\text{sub}}/4 \) which is equivalent to \( \lambda_0/60 \). However, it should be noted that in order to operate in frequencies >1GHz which are above the zero field ferromagnetic resonance (FMR) value of the Co\(_2\)Z material small bias fields must be used. These can be achieved utilizing small permanent magnets along the edge of the antenna design.
Figure 81: (a) Design of a 50 ohm matched GNSS SSSA with radius 2" and a height of 0.48 cm on a Co$_2$Z. (b) Design of an antenna element to fit on conformal surfaces of varying radii.

The first element examined on magnetic substrates in this chapter will be the SSSA element pictured in Figure 81, the general design of this antenna has been shown in Figure 70 in the previous chapter. Here, the antenna has been adapted to operate on a ferrite substrate with a significant reduction in height ($\lambda_d/60$) for ultra low profile antenna applications. The material parameters of the substrate used in this design are $\varepsilon’=15$, $\varepsilon’’=.0025$, $\mu’=14$, $\mu’’=.05$. To quantify this reduction; previously, the height of the antenna was 4.95 cm utilizing a $\varepsilon_r=4.5$ substrate, the design on a Co$_2$Z magnetic substrate boasts a profile of only 0.48 cm. This is over a >85% reduction in volume. This makes these antennas very promising for applications which require reduced drag, such as airplane mounts and NEWs. As with the dielectric designs in addition to planar designs conformal antennas will also be introduced, this will make these antennas even more practical for the aforementioned applications.
The radiation results of the element in Figure 81(a) are given in Figure 82. Here the broad side single element gain is shown to be between -2 and 0 dB over the desired operating spectrum namely the GPS frequency band. There is slightly more variance over the entirety of the GNSS band (which encompasses a slightly larger region of the L-band), but this can be optimized with novel superstrate techniques as introduced in Chapter 2. It should be noted that this is a significant reduction in gain over the previous SSSA design on a dielectric substrate. This is due to the fact that previously the antenna was designed on a low loss dielectric substrate, and in this case the antenna is designed on a lossy magnetic substrate ($\mu''=.05$). This incorporates a secondary loss tangent mechanic in the substrate, which severely affects the efficiency of the antenna (not pictured) which is only ~20% efficient over the operating range depicted compared to the 60-70% efficiency in the dielectric case. This value can be significantly increased by operating in bands such as the upper VHF and lower UHF bands where the ferrites magnetic loss tangents are lowered, such as <400 MHz for unbiased designs. Figure 82(b) depicts the return loss of the element, showing good matching over the desired bandwidth namely GNSS and GPS bands. This has been attributed to the fact that the $\varepsilon_r \approx \mu_r$ as discussed in Chapter 5. Finally, the axial ratio of the SSSA design is shown in Figure 82(c), here the purity of the circular polarization is readily apparent with an axial ratio close to 1 over the entirety of the operating range.
Figure 82: (a) Total realized broad side gain of a SSSA element. (b) Simulated return loss of a SSSA element design. (c) Axial ratio of a SSSA element design.

In addition to the standard radiation results presented in Figure 82, studies were performed to examine the pattern purity of the SSSA design over the GNSS and GPS bands. Spiral antennas in general are known for their inability to maintain pattern performance over their exceedingly wide bandwidths; however, since this design only uses a small portion of the operating range of the spiral antenna, namely the GNSS and GPS bands this is not a concern in this application. Figure 83 depicts the radiation
patterns in both the $\varphi = 0^\circ$ and $\varphi = 45^\circ$ cases, as well as the 3-D radiation pattern of the antenna at the center frequency of 1.5 GHz. Good pattern stability is shown over the depicted band.

![Radiation plots](image)

**Figure 83:** (a) Radiation patterns of a SSSA element designed on a Co$_2$Z ferrite substrate with $\varphi = 0^\circ$ and (b) with $\varphi = 45^\circ$. Also depicted, the 3-D element gain at the center frequency of 1.5 GHz (c).

The second antenna element reviewed in this chapter is an ASA element. This design is shown in Figure 84, and is an extension of the antenna used in Chapter 6 in Figure 75. As is previously mentioned, a magnetically oriented Co$_2$Z hexaferrite substrate is employed ($\varepsilon' = 16$, $\varepsilon'' = 0.0025$, $\mu' = 14$, $\mu'' = 0.01$). For pattern uniformity a dielectric superstrate is used. The radiating element has a planar dimension of 7.5 cm ($\sim \lambda_o/3$) x 7.5 cm on a side. And a height of 0.75 cm ($\lambda_{sub}/4 + H_{ss}$). The thickness of the line is 2.25 mm, and the radius change of the spiral is 12.8 mm.
Figure 84: (a) Design of a 50 ohm matched GNSS ASA element with a radius 2" and a height of 0.75 cm on a Co$_2$Z hexaferrite substrate. (b) Design of an ASA element fitted on a conformal surface.

The radiation results of the element in Figure 84(a) are given in Figure 85. Here the broad side single element gain is shown to be between -5 and 0 dB over the desired operating spectrum namely the GPS band. As with the SSSA design there is slightly more variance over the entirety of the GNSS band, but it is slightly more stable overall than the SSSA design due to the lower magnetic loss tangent used in the simulation. It should be noted again that there is a significant reduction in gain over the previous ASA design on a dielectric substrate due to the fact that the antenna is designed on a lossy magnetic substrate. Figure 85(b) depicts the return loss of the element, showing good matching over the desired bandwidth. Finally, the axial ratio of the ASA design is shown in Figure 85(c), here the purity of the circular polarization is readily apparent with an axial ratio close to 1 over the entirety of the operating range.
Figure 85: (a) Total realized gain of an ASA element. (b) Return loss of an ASA element. (c) Axial ratio of an ASA element.

As with the previous ferrite substrate design, the final aspect of the design which was examined was the pattern purity of the ASA element over the GNSS and GPS bands. Figure 86 depicts the radiation patterns in both the $\varphi = 0^\circ$ and $\varphi = 45^\circ$ case, as well as the
3-D radiation pattern of the antenna at the center frequency of 1.5 GHz. Good pattern stability is shown over the depicted bands.

Figure 86: (a) Radiation patterns of an ASA antenna designed on a Co$_2$Z ferrite substrate with $\phi = 0^\circ$, (b) with $\phi = 45^\circ$. Also depicted, a 3-D depiction of the elements gain at the center frequency of 1.5 GHz (c).

7.2.2 Conformal Approach

The next step in the design process was to fit these antenna elements onto a conformal surface. This was in order to make them applicable to alternative antenna applications such as those which require retrofitting the antenna to a conformal surface such as fuselage. This has been achieved for the ASA element in Figure 87. Here a 0.5 cm height conformal Co$_2$Z-Type design is shown. This height is due to a superstrate layer used to normalize the input impedance to ~50 ohms. It is clear from Figure 87(d) that the
return loss patterns depicts favorable operation from 1.2 to >2 GHz. While the gain is low ~2 to 2 dB over the operating band and slightly unstable around 1.375 GHz it is fairly stable over the bands of interest namely the GNSS and GPS bands. In this case there is a slight enhancement of gain in the conformal antenna approach due to the utilization of a dielectric superstrate in the conformal design. Figure 87(c) depicts the axial ratio value over the frequency range from 1-2 GHz, while high over specific portions of the operating band, these numbers can be optimized by changing the material parameters, and by thoroughly optimizing the designs through optometric FEM simulations. Figure 87(b) depicts the 3-D radiation pattern of the element at the center frequency of the design (1.6 GHz).
Figure 87: (a) Conformal magnetic substrate antenna. (b) 3-D total realized element gain plotted at 1.6 GHz. Antenna radiation parameters are depicted including, total gain compared to Chu's limit (c), return loss (d), and axial ratio (e).

7.3 Ferrite Absorbers

7.3.1 Previous Works

The previous sections of this chapter have demonstrated how the Co$_2$Z hexaferrite material can be used as a substrate for various antenna designs. In doing so the achievable bandwidths and gains of these antennas have been demonstrated. It has been shown that utilizing realistic ferrite properties gains on the order of -2 to 2 dB are achievable with efficiencies on the order of 20%, and that higher gains and efficiencies would require
lower magnetic losses within the magnetodielectric substrate materials. These results indicate that current ferrite technologies are not sufficient to act as antenna substrates; however, this does not mean that they are unable to play a role in ultra wide band (UWB) antenna designs. Recently these ferrites have been used as ground plane coatings to absorb the low frequency signal of UWB antenna designs [7-11].

Figure 88: Effect of absorber layers on the gain bandwidth of a dipole antenna compared to a free standing element and a PEC backed element at λ₀/4 [7].

Figure 88 outlines the effect of a commercially available ferrite ground plane coating for a dipole antenna. Here, it is apparent that while the coating negatively affects the high frequency gain, it increases the low frequency gain to the same as a free standing antenna design. Since the Co₂Z ferrite has a high resonant frequency with a high μ" well
into the L-band it is practical for this application. Table 4 outlines the commercially available ferrite materials which could be used for this application.

<table>
<thead>
<tr>
<th>Trans-Tech</th>
<th>Ferrite Type</th>
<th>Useful Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ferrite-50</td>
<td>300 – 700MHz</td>
</tr>
<tr>
<td></td>
<td>TT1-109</td>
<td>100 – 300MHz</td>
</tr>
<tr>
<td></td>
<td>TT1-2800</td>
<td>200 – 400MHz</td>
</tr>
<tr>
<td></td>
<td>TT2-4000</td>
<td>200 – 500MHz</td>
</tr>
<tr>
<td></td>
<td>Co2Z</td>
<td>100 – 1500MHz</td>
</tr>
</tbody>
</table>

Table 4: Commercially available ferrite materials for absorber layers and their respective frequency ranges of operation [7].

7.3.2 Novel Absorber Designs

In order to see the effect of realistic ferrite materials as absorber layers. A standard ASA element was designed to operate at 400 MHz (D= \(\lambda_0/\pi\) = \(~23\) cm). This antenna and its radiation results are pictured in Figure 89. Here, Figure 89(c) depicts the total realized broad side gain of the element, which is stable at around 5 dB over the desired band. The return loss is pictured in Figure 89(d), which indicates good matching starting at 400 MHz which is to be expected based off of the initial design constraint (D= \(\lambda_0/\pi\)). Finally the axial ratio of the designed antenna is very close to 1 over the entirety of the operating band. Figure 89(b) denotes the 3-D radiation pattern of the element at the lowest operating frequency of 400 MHz.
Figure 89: (a) Depiction of an ASA element. (b) 3-D radiation pattern of an ASA element at the lowest operating frequency of 400 MHz. (c) Total realized gain of an ASA element. (c) Return loss of an ASA design. (d) Axial ratio of an ASA design.

Below the antenna element pictured in Figure 89(a) two different absorber layers were placed in order to determine the effect of both on the operating frequencies and gain of the element. In these simulations the thicknesses of the absorber layers were set to 2.5 mm. The first absorber was a theoretical absorber with a constant $\varepsilon'$=6.5, $\varepsilon''$.0019, $\mu'$=10.0, and $\mu''$=5.0 (Figure 90(c)). The result for this first absorber are shown in Figure 90(a and b), here the low frequency return loss is improved from a lowest operating
frequency of 400 MHz to 250 MHz. Unfortunately due to the constant magnetic losses of
the absorber layer the gain suffers over the entirety of the radiating spectrum.

The second absorber layer introduced was a more realistic spinel ferrite design
(Chapter 3) which was simulated with frequency dependant $\varepsilon$ and $\mu$ values shown in
Figure 90(d) [7, 10]. Here the same shift in the lowest operating frequency is shown, yet
the loss in gain is localized to the zero field ferromagnetic resonance (FMR) value of the
material which is outlined in Figure 90(a and b). These results are very promising for the
use of spinel ferrites as absorbers.

Figure 90: Ferrite absorbers utilized to enhance the low frequency matching of a spiral
antenna. Two absorbers both realistic and theoretical have been employed. While both
indicate better low frequency impedance matching, the realistic design case doesn't sacrifice the same amount of gain making it practical for device design.

The final absorber investigated in this chapter was one which utilized the Co$_2$Z textured ferrite materials introduced in Chapter 5. This absorber was applied to an ASA element with a lowest operating frequency of 1 GHz (D= 9.5 cm) with similar radiation patterns to the antenna shown in Figure 89. This was done in order to see the effect of the FMR of the material on the radiation parameters. The results of this design are shown in Figure 91 where (a) shows the effect of a 2 mm thick Co$_2$Z absorber layer beneath a ASA element designed to operate at 1 GHz. From this figure a 400 MHz shift is shown in the lowest operating frequency, which correlates with the $\mu''$ given in Figure 91(c). Figure 91(b) depicts the broad side gain of the ASA element with and without the ferrite absorber. The loss in gain over the frequency region of which the ferrite is lossy is readily apparently; however, above this region the antenna continues to operate as normal. Finally, Figure 91(c) shows the frequency dependant magnetic and electric properties of the ferrite absorber layer which was used in the simulation of these elements, these data match closely with the measured properties of Co$_2$Z hexaferrites given in Figure 61.
Figure 91: (a) Effect of a 2.5 mm thick Co$_2$Z absorber layer beneath an ASA element designed to operate at 1 GHz, a 400 MHz shift is shown in the lowest operating frequency. (b) Broad side gain of the ASA element with and without the ferrite absorber. (c) The frequency dependant magnetic and electric properties of the ferrite absorber layer.
7.4 Conclusions on Ferrite Designs

In this chapter the use of Co₂Z hexaferrites as antenna substrates to reduce the profile of antenna designs and increase their operating bandwidths has been thoroughly examined. Utilizing standard Archimedean spiral designs (ASA) as well as more novel square slot spirals (SSSA) it has been shown that these substrates can reduce the height of the antennas to λ₀/40 or even λ₀/60, significantly reducing the weight and associated drag of these elements. However, due to the high losses of these materials, gains >0 dB are difficult to achieve. Efficiency has also shown to be a problem when utilizing these materials, as they each show only about a 20% radiation efficiency. With optimization of orientation, these numbers should increase as the magnetic loss tangent is decreased. These designs have also been adapted to fit on conformal surfaces with minor degradation to their radiation parameters making these designs practical for a variety of commercial and defense related applications such as aerospace and low profile antenna systems.

In addition, to utilizing these materials as antenna substrates in this chapter they were also introduced as absorber layers, along with spinel ferrites to increase low frequency matching of wideband antennas. It was shown that utilizing realistic ferrite parameters, the loss in gain can be minimized to only exist around the zero field FMR frequency of the ferrites used. Over this region the low frequency S11 response has been shown to be significantly increased. The use of these absorbers has been shown as an
effective way to use these materials in antenna designs where large bandwidths are required such as S and X-band antenna designs.

7.5 References


Chapter 8: *Phased Array Design*

### 8.1 Introduction to Dielectric Phased Arrays

#### 8.1.1 Theory of Phased Arrays

![Diagram of phased array](image)

Figure 92: Depiction of the scanned beam produced from a phased array [1].

The goal of this chapter will be to introduce phased arrays [1-7] to increase the gain of the elements which have been introduced in previous chapters [8, 9]. Both the dielectric (Chapter 6) and magnetic (Chapter 7) substrates will be examined in this chapter. Special consideration will be paid to elements which radiate within the Global Navigation Satellite System (GNSS) and Global Positioning Satellite (GPS) bands. However, before introducing the results of the simulations it is important to understand how the gain values of phased arrays are calculated.
First, the radiation pattern of a single element is defined in Equation 1 as a function of $\theta$ and $\varphi$. Equation 2 gives a positioning element to the radiation pattern, which allows for linearly combining the patterns of multiple elements which are spaced at different points on a plane. Finally, Equation 3 gives the phased array output $Y$ as a function of elements which are weighted by a compiled weighting factor $w_i$. Equation 4 is a simplification of this equation, and depicts the Array Factor (AF) which is a summation of each individual antennas weighting factor. Finally, Equation 5 gives the definition of the array factor utilizing the steering vector. In this equation $T$ is the transpose operator. It should be noted that if the elements used in a phased array are identical and have the same physical orientation, then the radiation pattern of the array is simply the array factor multiplied by the radiation pattern, this is called pattern multiplication [2], and will be the case for the antenna elements studied in this chapter, namely Archimedean spiral antennas (ASA) and square slot spiral antennas (SSSA).

$$R(\theta, \varphi)$$

Eqn. (1)[2]

$$r_i = (x_i, y_i, z_i)$$

Eqn. (2)[2]

$$Y = R(\theta, \varphi)w_1 e^{-jkr_1} + R(\theta, \varphi)w_1 e^{-jkr_1} + \cdots + R(\theta, \varphi)w_1 e^{-jkr_1}$$

Eqn. (3)[2]
\[ Y = R(\theta, \varphi) \sum_{i=1}^{N} w_i e^{-jkr_i} = R(\theta, \varphi)AF \]

Eqn. (4)[2]

\[ AF = \sum_{i=1}^{N} w_i e^{-jkr_i} = w^T v(k) \]

Eqn. (5)[2]

8.1.2 Dielectric Element used in Array Study

The first element to be studied in an array in this chapter is a SSSA element [8] on a dielectric substrate. The design of the element is pictured in Figure 93, and is based off of the SSSA elements presented in the previous chapters (6 and 7). Here gain is plotted to be almost equal to Chu's Limit at the design frequency of 1 GHz and only slightly lower over the remainder of the GNSS and GPS bands. In addition to the favorable gain, this element boasts a return loss that is less than -10 dB over the entirety of the desired spectrum. In this case, due to the square shape, the single resistor termination, and the smallness of the radiating aperture, the polarization is slightly elliptical as depicted in Figure 93(c).
Figure 93: (a) Design of a SSSA element. (b) 3-D radiation pattern of the element at the GPS frequency of 1.575 GHz. (c) Radiation parameters of the antenna element including broadside gain, return loss, and axial ratio.

8.1.3 Effect of Increasing the Number of Elements

In order to see the effect of adding additional elements on the radiation pattern of the array it is important to determine the non-arrayed radiation pattern of the element. These plots are pictured in Figure 94. It is clear from this figure that over the operating bands for which this antenna has been designed, namely GNSS and GPS (L-Band) these patterns are very uniform. It should be noted that for certain elements such as spiral antennas these patterns tend to degrade as the frequencies are increased. Since this design only calls for operation in the L-band, which is between 1 and 2 GHz, this antenna
element can operate at frequencies where these dramatic shifts in pattern performance are not apparent. This is crucial for the optimization of arrayed elements.

Figure 94: Simulated radiation patterns of a single dielectric SSSA element across the desired operating range of the L-band, showing uniformity of pattern in both the $\phi = 0^\circ$ and $\phi = 45^\circ$ planes over the low end of the SSSA element’s operating band.
Figure 95: Simulated radiation patterns of a 3x3 SSSA element phased array spaced at $\lambda_d/2$ where $\lambda_d=30$ cm across the desired operating range of the L-band, showing uniformity of pattern in both the $\varphi=0^\circ$ and $\varphi=45^\circ$ planes over the low end of the SSSA element's operating band.

The first array examined was a simple 3x3 array, setup and simulated utilizing FEM software. This was achieved through the use of master and slave boundaries and an element spacing of $\lambda_d/4$ where $\lambda_d=30$ cm which is the lowest operating frequency of the L-band. The results of this array setup on the radiation patterns as a function of frequency are shown in Figure 95. Here a dramatic increase in the gain is shown over the case of a single element. This is to be expected due to the array factor introduced by utilizing 9 elements instead of 1, and the simulated gains closely those which would be expected in theory following the formulas introduced in the array theory section in the beginning of this chapter. It should be noted that arrays are generally spaced at $\lambda_d/2$. However due to
the wide bandwidth of these elements this spacing is difficult to achieve. The $\lambda_0/4$ spacing is equivalent to $\lambda_{C1}/2.67$. This means that the maximum gain for this simulation should occur at $\lambda_0/2$ spacing, which is between 1.5GHz and 1.7GHz (which is optimal for the GNSS and GPS bands) this is exactly the results of the simulation.

![Simulated radiation patterns of a 9x9 SSSA element phased array spaced at $\lambda_0/2$](image)

Figure 96: Simulated radiation patterns of a 9x9 SSSA element phased array spaced at $\lambda_0/2$ where $\lambda_0=30$ cm across the desired operating range of the L-band, showing uniformity of pattern in both the $\phi=0^\circ$ and $\phi=45^\circ$ planes over the low end of the SSSA element's operating band.

The effect of increasing the number of elements even further is examined in Figure 96. Here, the radiation patterns of a simple 9x9 array again spaced at $\lambda_0/4$ where
\( \lambda_0 = 30 \text{ cm} \) setup and simulated utilizing FEM software are shown. The increase in gain can again be seen due to the increase in directionality of the array with broad side gains almost double that of the case in Figure 94. It is clear to see from this figure how phased arrays can achieve extremely high gains given a large number of elements and proper spacing. However, as previously mentioned these spacing constraints become much more complicated when utilizing wide band elements. Therefore the effect of this spacing was studied and the results are shown in Figure 97. Here it is reinforced that optimal gains and patterns are shown at \( \lambda_0/2 \) spacing which is to be expected, and that by placing elements closer together results in sacrificing array gain.

Figure 97: Depiction of the effect of array spacing on radiation pattern performance of a 3x3 SSSA element phased array where the spacing is equal to (a) \( \lambda_{LOF}/4 \) and (b) \( \lambda_{LOF}/2 \). With \( \lambda_{LOF} = 1 \text{GHz} \).
In Figure 98, the overall effect of adding additional array elements while maintaining a constant array spacing is examined as a function of frequency at the broad side of the array. It is clear from this figure that increasing the gains of the antenna array is possible by utilizing more and more elements, and that maximum gain is most limited by the total array size. Since the elements are identical and all oriented in the same direction, the assumption is that the patterns would be identical and the intensities of the elements would be multiplied due to pattern multiplication, and this is exactly the result simulated utilizing FEM tools.

![Figure 98: Effect of increasing the number of elements on the broad side gain of an antenna array across the desired GNSS frequency bands. Figure depicts the effect of pattern multiplication utilizing identically oriented elements.](image)

Figure 98: Effect of increasing the number of elements on the broad side gain of an antenna array across the desired GNSS frequency bands. Figure depicts the effect of pattern multiplication utilizing identically oriented elements.
One of the most important aspects of a phased array is the scan angle for which it operates which is defined by the 3 dB beam width. In this section the scan angle of the dielectric array element will be examined to determine how the element will operate in a phased array environment. To act as a control for the study a non-scanned beam will be formulated for a 9x9 array spaced at $\lambda_0/2$ to act as the control for the study. This result is shown in Figure 99, where the maximum gain is given to be 23.9 dB at 1.0 GHz. Here the standard pencil beam is shown, which is a result of the pattern multiplication defined in section 8.1.1.

Figure 99: 3-D radiation pattern of a 9x9 SSSA element phased array with the spacing of $\lambda_0/2$ at the center frequency of the design (1.5 GHz).
In Figure 100 the radiation pattern of a 9x9 element array spaced at $\lambda_0/2$ is plotted for a scan angle of $\theta = 45^\circ$ and $\varphi = 45^\circ$. Here the maximum gain is plotted to be 19.6 dB; compared to the 23.9 dB in the case where the array is not scanned, the difference is 4.3 dB. This indicates that the 3 dB scan angle for this array design is slightly less than 90°. This value is close to what is to be expected for a radiating element of this type, and the actual scan angle could be increased via novel superstrate techniques, or by varying the element type [4, 8]. Typically elements such as patch antennas or slot radiators which radiate with omnidirectional performance have the highest scan angles in a phased array.

![3-D radiation pattern of a 9x9 SSSA element phased array with spacing of $\lambda_{LOF}/2$ at the center frequency of the design (1.5 GHz).](image)

Figure 100: 3-D radiation pattern of a 9x9 SSSA element phased array of with spacing of $\lambda_{LOF}/2$ at the center frequency of the design (1.5 GHz).
8.2 Introduction to Magnetic Phased Arrays

8.2.1 SSSA Array

In this section a SSSA array is examined via the use of magnetic substrates. The design of the antenna element is the same as the design in the previous section, which was first introduced in Chapter 6 and adapted for magnetic substrates in Chapter 7. The return loss for the magnetic case (Figure 81) has previously shown that the lowest operating frequency of the antenna design is around 1 GHz and is stable to >2 GHz. This means that the antenna is well matched over the entirety of the GNSS band for which the phased array has been designed. The broad side gain of this antenna element is pictured (Figure 81), indicating gains between -2 dB and 0 dB over the GNSS band. It should be noted that this gain is significantly lower than that of the design presented for a dielectric substrate. This is due to the higher losses in the magnetic substrate. However, the height of this antenna is much smaller which makes this design easier to implement. It should also be noted that since this design will be used in a multiplicative phased array the gains of the elements will be cumulative, so relatively high gains will still be achieved. Another beneficial parameter of this antenna element design is the purity of the axial ratio (Figure 81), the antenna maintains very good circular polarization over the entirety of the GNSS band.

The results of placing this magnetic antenna element in a 5x5 array, spaced at $\lambda_{CF}/4$ with $\lambda_{CF}=1.5$ GHz are shown in Figure 101. Here the broad side gain is shown to be 13.5 dB. It should be noted that this is not optimal spacing for these elements; however, the goal of these designs are to fit the array into a small size. The total size of
this 5x5 array is 62.5 cm x 62.5 cm, so while it may suffer slightly in overall gain, it makes up for that fact with a more compact design.

Figure 101: Depiction of the pencil beam radiation patterns at the center frequency of 1.5 GHz produced via a 5x5 SSSA element phased array spaced at $\lambda_0/4$ with various scanning angles, (a) $\varphi=0^\circ$, $\theta=0^\circ$ and (b) $\varphi=30^\circ$, $\theta=30^\circ$.

Figure 102 depicts how this array acts over the entirety of the desired GNSS and GPS bands (L-Band) here the $\varphi=0^\circ$ and $\varphi=45^\circ$ planes have been plotted. It is clear from these plots that the array of element is very directional, with 3 dB beam widths on the order of 15-20$^\circ$ (this will be outlined in depth in section 8.2.5). There are some small side lobes due to the spacing concerns which have previously been addressed. These side lobes are more pronounced on wide band arrays due to the constant effective spacing between the elements as the design frequency changes.
8.2.2 SSSA Scanning Angle Study

As has been shown in the case of the dielectric phased array design it is possible to utilize FEM simulation tools to scan the array through a series of angles. This is done through the use of master and slave boundaries and allowing for multiple scanning angles. This method was employed to determine the 3 dB scan range of the 5x5 element array. The results of this study are shown in Figure 101(b), here the 3 dB scan angle of the SSSA magnetic phased array is given to be approximately 70° which is to be expected for this type of element.
8.2.3 ASA Array

In this section an ASA array is examined via the use of magnetic substrates. The design of the antenna element is the same as the design in the previous section, which was first introduced in Chapter 6 and adapted for magnetic substrates in Chapter 7. The return loss has previously shown (Figure 85) that the lowest operating frequency of the antenna design is around 1 GHz and is stable to > 2 GHz. This means that the antenna is well matched over the GNSS band for which the phased array has been designed. The broad side gain of this antenna element is pictured in Figure 85, indicating gains between -2 dB and 0 dB over the GNSS bands have been achieved. It should be noted again that this gain is significantly lower than that of the design presented for a dielectric substrate. This is due to the higher losses in the magnetic substrate. However, the height of this antenna is much smaller which makes this design easier to implement. It should also be noted that since this design will be used in a multiplicative phased array the gains of the elements will be cumulative, so relatively high gains will still be achieved. Another beneficial parameter of this antenna element design is the purity of the axial ratio that the antenna maintains over the entirety of the GNSS band.

The results of placing this magnetic antenna element in a 5x5 array, spaced at $\lambda_{CF}/4$ with $\lambda_{CF}=1.5$ GHz are shown in Figure 103. Here the broad side gain is shown to be \(~21$ dB. The main reason that this gain is higher than the SSSA case is due to the slightly lower magnetic loss tangent used in the simulation ($\mu''=0.01$ vs $\mu''=0.05$). Again, it should be noted that this is not optimal spacing for these elements; however, the goal of
these designs are to fit the array into a small size. The total size of this 5x5 array is 62.5 cm x 62.5 cm, so while it may suffer slightly in overall gain, it makes up for that fact with a more compact design.

![Figure 103: Depiction of the pencil beam radiation patterns at the center frequency of 1.5 GHz produced via a 5x5 ASA element phased array spaced at $\lambda_{CF}/4$ at various scanning angles, (a) $\phi = 0^\circ$, $\theta = 0^\circ$ and (b) $\phi = 30^\circ$, $\theta = 30^\circ$.](image)

Figure 104 depicts how this array acts over the entirety of the desired GNSS and GPS bands (L-Band) here the $\phi=0^\circ$ and $\phi=45^\circ$ planes have been plotted. It is clear from these plots that the element is very directional, with 3 dB beam widths on the order of 15-20° (this will be outlined in depth in section 8.2.5). There are some small side lobes due to the spacing concerns which have previously been addressed.
8.2.4 ASA Scanning Angle Study

As has been shown in the case of the dielectric phased array it is possible to utilize FEM simulation tools to scan the array through a series of angles. This method was employed to determine the 3 dB scan range of the 5x5 ASA element array at its center frequency. The results of this study are shown in Figure 103(b), here the 3 dB scan angle of the ASA magnetic phased array is given to be approximately 70° which is to be expected for this type of element.
8.2.5 Beam Width Study

When designing a phased array one of the most important concepts is forming beams which are highly directional, also known as forming "pencil beams". Therefore, it was important to determine the 3 dB beam width of these arrays and how they change with frequency. This was done by plotting the radiation patterns in the θ-plane versus the frequency. It can be seen from Figure 105 how the 3 dB beam width of the array changes with frequency. This should continue to improve as frequency increases, which means that the electrical length of the radiating elements will be closer and closer to standard λ₀/2 array spacing.

Figure 105: Depiction of pencil beam radiation patterns produced via a 5x5 phased array spaced at λ₀/2 for the SSSA element. These patterns have been presented in both the φ= 0° and φ= 45° planes.
In order to compare the beam sizes of the two proposed magnetic antenna arrays, Figure 106 has been provided. From this figure it is apparent that the 3 dB beam widths for the designs are similar, with the case of the ASA element having a slightly narrower beam. This may again be attributed to the varying magnetic loss tangents in the materials.

Figure 106: Comparison of 3-dB beam widths of 5x5 phased arrays spaced at $\lambda_0/2$ for an ASA element (a) and a SSSA element (b). These 3-dB beam widths have been presented in both the $\phi=0^\circ$ and $\phi=45^\circ$ planes.

### 8.3 Conclusions

In this chapter the use of phased arrays utilizing circularly polarized antenna elements has been examined through the use of both dielectric and magnetic antenna elements. The results of the use of dielectric antennas in phased arrays resulted in gains on the order of 20 dB for a 4x4 element arrays spaced at $\lambda_0/2$. However; as these antennas require large cavities on the order of 4-5 cm to maintain these operational gains, it makes them heavy and hard to work with. For this reason, and for applications where profile is more of a design constraint, such as mounted phased arrays which need to minimize drag,
phased antenna arrays utilizing magnetic materials have also been proposed. These elements have intrinsically lower gains due to the magnetic losses in the. Utilizing a 5x5 element array of these antenna elements spaced at $\lambda_{CE}/4$, gains on the order of 13-20 dB have been shown. In addition to these gains, studies have been performed which examine the beam widths of these designs as well as their applicability towards steering. It has been shown that these phased arrays have 3 dB scan angles on the order of 70°.

8.4 References


Chapter 9: EBG Design

9.0 Introduction to EBG Metamaterials

9.0.1 Goal of Chapter

The final approach to minimize the planar height of the proposed antenna elements will be through the use of electromagnetic band gap (EBG) metamaterial substrates. In this chapter these metamaterials will be discussed with respect to the magnetic and dielectric materials introduced in the previous chapters (Chapters 2-6). The goal of this chapter will be twofold; the first goal will be to determine how the bandwidths of the EBG metamaterials can be calculated. Secondly this value will be maximized while concurrently keeping the profile of the metamaterial as thin as possible for potential ultra low profile antenna applications. In this chapter it will be shown that by utilizing high permeability (μ_r) and low permittivity (ε_r) materials it is possible to achieve >75% bandwidths for these metamaterials in the L-band. This band includes both the Global Navigation Satellite System (GNSS) as well as the Global Positioning System (GPS) bands, which have been introduced in the previous chapters. This study will make these EBG metamaterial substrates practical for use with the antenna elements designed in the previous chapters such as the square slot spiral antenna (SSSA) and the Archimedean spiral antenna (ASA), and applicable to a wide array of technologies.

9.0.2 Background

Recent advances in the wireless communications industry are placing ever increasing demands on antenna elements to be more compact and still maintain the favorable microwave performance metrics, including gain, bandwidth, and efficiency of
their larger counterparts [1-5]. However, due to a general reliance on electrically conducting ground planes for these devices, substrates with relatively large thickness are often required. This is due to the $\pi$ phase shift associated with electromagnetic wave reflection from an electrically conducting surface. More specifically, ground planes approximating a perfect electric conductor (PEC) are placed at a distance of $\lambda_{\text{sub}}/4$, where $\lambda_{\text{sub}}$ is the design frequency wavelength within the substrate material from the radiating aperture, thus allowing for constructive interference in the direction of radiation. Antenna profile height is therefore determined by the constitutive parameters of the material, namely the dielectric constant $\varepsilon_r$ and permeability $\mu_r$.

As an alternative to utilizing PEC ground planes, perfect magnetic layer (PML) ground planes can also be used. These layers act as high impedance surfaces (HIS) and reflect electromagnetic waves radiated from the antenna element without introducing any phase shift [6]. It is because of this potential for profile reduction that much work has been dedicated in recent years to develop PML for use as ground planes for antenna elements. One of the most common ways to realize a PML surface is utilizing electromagnetic band gap (EBG) metamaterials consisting of metallic Sievenpiper structures [1, 7-9]. These structures act as PMLs due to the fact that electric currents are unable to propagate on the surface of the metamaterial. Current flow is restricted due to the capacitance associated with the separation between patch elements allowing the EBG metamaterial surface to operate as a HIS. The EBG metamaterial thus eliminates the phase shift associated with reflection from PEC, and enables the placement of the antenna element much closer to the ground plane.
There are, however, important limitations associated with EBG metamaterials as they are inherently resonant structures which are characterized by a narrow bandwidth. This shortcoming is particularly pronounced at low frequencies, e.g. the ultra high frequency band (UHF) and below. This is mainly due to patch size constraints that will be discussed in detail shortly. Typically, the standard dielectric approach to EBG design leads to less than 5% bandwidth at 1 GHz if the height is maintained at $\lambda_o/20$, where $\lambda_o$ is the design frequency wavelength in free space, this is not practical when the desired heights of the entire antenna assembly needs to be $< \lambda_o/60$.

In this chapter, the behavior of EBG metamaterials will be thoroughly investigated in an effort to identify methods of increasing the bandwidth without sacrificing performance. In particular, substrate material characteristics such as permittivity and permeability have been studied. It is shown that many of the problems traditionally associated with EBG metamaterials can be mitigated utilizing novel and practical materials such as magnetically oriented cobalt-substituted barium Z-type hexaferrites (Co$_2$Z), as well as advanced metamaterial designs allowing for bandwidths of 50% - 75% at low operating frequencies. In the past, magnetic materials in EBG design have only been utilized as tile absorbers allowing for impedance matching below typical operating frequencies of all-dielectric EBG designs emulating the behaviors shown in Chapter 7 [1,4]. These studies lay the groundwork for realizing ultra-low profile high performance antenna elements with a broad operating bandwidth, a long sought goal of the microwave engineering community.
9.1 Bandwidth of EBG Metamaterials

Metamaterials are artificial structures that can be designed to exhibit electromagnetic properties not commonly found in nature. The metallo-magnetic and dielectric EBG materials to be examined in this dissertation are comprised of periodically spaced metallic scatterers embedded in otherwise RF transparent magnetic and dielectric materials. The periodic structure of these materials produces forbidden frequency bands in which electromagnetic waves cannot propagate, as well as pass bands in which wave propagation is possible. Therefore, in electromagnetic band gap (EBG) metamaterials, the wave propagation is determined by the band structure (dispersion curves) of the material. In this way the EBG metamaterial bandwidth can be determined.

9.1.1 Dispersion Curves to Designate Bandwidth

In order to determine the bandwidth of these EBG metamaterials it was necessary to fabricate their dispersion curves via finite element method (FEM) tools to determine where the pass bands and band stop regions were. A validation of this technique is shown in Figure 107 where the first order dispersion curve of a dielectric cube was compared to the published theoretical curve for an identical dielectric cube [10]. It is clear to see that the methods employed to calculate the dispersion curves via FEM techniques clearly match those of literature.
Figure 107: First order dispersion curve of a dielectric cube (a), compared to that of a theoretical curve provided in literature. Results indicate very good matching between the two [10].

The second effort in the formulation of dispersion curves for EBG metamaterials was to create a curve for a dielectric cube which also had the metallic Sivenpiper structure [11] embedded in it.

Figure 108: Depicts the outcome of this study by comparing the results of the FEM simulations to that of a theoretical curve on an identical material provided by literature.
While the curves are similar, there are small discrepancies that are apparent due to the assumptions made by the software, namely there are not conductive losses in the simulation. That being said, the results are encouraging and will be used to verify the EBG metamaterial bandwidths by plotting multi-order dispersion curves.

Figure 109: First order dispersion curve of a dielectric cube with an embedded Sivenpiper structure calculated via FEM software (a), compared to that of a theoretical curve provided in literature. Results indicate very good matching between the two [12].

In order to see the bandwidth of the EBG metamaterial it is necessary to plot the first two dispersion curves of the structures, in doing so the bandwidth can easily be defined. Figure 110 outline this effect for a standard dielectric EBG metamaterial in literature [13]. The band gap region is outlined to be between 3.5 and 5.9 GHz. Figure 111 outlines the simulated results from FEM simulations. These simulations can directly be compared to show the effectiveness of this result. The provided data show again that
the FEM simulations are in good agreement with previously published works. Utilizing this method, EBG band gap simulations were run on structures with varying $\varepsilon_r$ and $\mu_r$ values. The results of simulations for $\varepsilon=10$ $\mu=1$, and $\varepsilon=1$ $\mu=10$ are shown in Figure 112 and Figure 113 respectively.

![Figure 110: First and second order dispersion curves of a idealistic magnetic cube with an embedded Sivenpiper structure from literature [13].](image-url)
Figure 111: Multi band dispersion curves of an idealistic magnetic cube with an embedded Sivenpiper structure calculated via FEM software to verify the method compared to standard literature designs.

Figure 112: Multi band dispersion curves of an idealistic magnetic cube with an embedded Sivenpiper structure calculated via FEM software with $\mu_r = 1$ and $\varepsilon_r = 10$. 
9.1.2 Reflected Wave Phase to Designate Bandwidth

In the band gap region the EBG metamaterial reflects the radiation that is incident on the EBG surface. The EBG substrate acts as a high-impedance reflecting surface. Unlike a metal surface, which introduces a 180-degree phase shift at the point of reflection, the EBG surface approximates a perfect magnetic conductor (PMC) surface at which energy is reflected in phase with the incident wave. Thus, the radiating element of the antenna can be situated adjacent to the EBG surface and the image fields interference associated with the lack of $\lambda_{sub}/4$ cavity mitigated. Further, the use of EBG substrates addresses the issues associated with surface waves that are excited in conventional antenna structures. Surface waves can reduce the radiation efficiency of antenna elements and cause interference between elements in arrays and co-located antennas. The EBG structure prevents the formation of surface waves within the forbidden frequency bands,
and thus provides the potential for improvement in antenna performance. The usable bandwidth of the EBG when operating as a PMC is considered to be the frequency range over which the phase of the reflection coefficient is bounded by $\pm 45^\circ$ as defined by literature [8]. Figure 114 gives an example of how this measurement of the EBG bandwidth is performed. Here, verification of data from literature is replicated via FEM simulation tools (Figure 114(c)).

![Figure 114: (a) Depiction of the phase reflection bandwidth FEM simulation setup. [14] (b) Phase reflection bandwidth measurements from literature. [8] (c) Validation of bandwidth measurements via FEM simulation tools.](image)
9.2 Optimizing EBG Bandwidth

9.2.1 Effect of $\varepsilon$ and $\mu$ of Substrate

One of the obstacles in using EBG metamaterials for broadband antenna applications is the relatively narrow band gaps of the EBG metamaterials in comparison with the bandwidth of the antenna element, which restricts the antenna assembly to operation in a narrow band. As demonstrated via band gap dispersion curves, the frequency dispersion of the EBG can be controlled by varying the permittivity and permeability of the substrate [14]. The effect of the permittivity on the bandwidth of the EBG metamaterial can be understood through simple lumped element analysis of the design. The capacitance of Sievenpiper EBG structure is given in Eqn. 1 as a function of the permittivity values of air and substrate material. The inductance is given in Eqn. 2 as the product of the permeability and the thickness of the substrate. The product of permittivity (capacitance) and permeability (inductance) values of the EBG metamaterial gives the square of the inverse resonance, as defined in Eqn. (3) [8]. The bandwidth of the EBG metamaterial is proportional to the square root of the inductance over the capacitance [8]. Therefore, increasing the substrate permittivity will decrease the bandwidth, which is exactly the behavior observed in Figure 115(a). For this study the height of the EBG was 1.0 cm, the patch size was 1.0 mm, the patch spacing was 0.15 mm, and the via radius was 0.1 mm. The geometric setup for this FEM simulation is shown in Figure 114.
Figure 115: (a) Effect of the permittivity ($\varepsilon_r$) on the bandwidth of a simulated EBG metamaterial ($\mu_r=1$). (b) Effect of the permeability ($\mu_r$) on the bandwidth of simulated EBG metamaterial ($\varepsilon_r=1$) [14].

\[
C = \frac{D \varepsilon_o (\varepsilon_r + 1)}{\pi} \ln \frac{2D}{\pi g}
\]
Eqn (1)

\[
L = \mu_0 \mu_r h
\]
Eqn (2)

\[
F_{res} \propto \frac{1}{\sqrt{(L \times C)}}
\]
Eqn (3)
The next parameter examined through numerical modeling was the substrate permeability. The results of this study are shown in Figure 115(b). For this study the same values of height, patch width, spacing, and via radius were the same as those used for the study in Figure 115(a). From this figure, the changing permeability appears to have the exact opposite effect on the bandwidth as the permittivity. Namely, increasing the permeability to $\mu_r=10$ (while maintaining a hypothetical $\varepsilon_r=1$) allows a bandwidth of 200%. While $\varepsilon_r=1$ and $\mu_r=10$ are not found in any material existing in nature, especially over the frequency range indicated, it is nevertheless informative to isolate the effects of permittivity and permeability on EBG metamaterial bandwidth to help guide the design process. It should also be noted that the bandwidths for these values are in close agreement with the bandwidths determined by band gap dispersion curves in Figure 112 and Figure 113, as such, either method can be used to define the operating bandwidth of the EBG metamaterial.

From the results in Figure 115 it is apparent that for higher values of $\mu_r$, bandwidths on the order of 7:1 to 8:1 can be achieved. It is important to reiterate that although these bandwidths can be achieved, high $\mu_r$ and low $\varepsilon_r$ materials such as used in the FEM simulations do not exist in nature. Therefore, it is important to determine what values are realizable with existing materials, and how these material parameters will translate into realistic EBG metamaterial performance. Having recognized the importance of high permeability in achieving broadband EBG metamaterial performance the use of hexaferrite materials, in particular Co$_2$Z ferrites (introduced in Chapter 5), will be
examined in the following sections due to a favorable combination of permittivity, permeability, and natural resonance frequency.

9.2.2 Effect of Patch Height and Spacing

In addition to altering the operating bands of these metamaterials via changing their magnetodielectric properties, they can also be controlled by varying the dimensions of the capacitive patches, the spacing between them, and height of the patches above the ground plane. Figure 116 depicts the effect of changing the height of the substrate on the operational frequency of an EBG metamaterial designed on an alumina substrate. It is shown that as the height (h) increases, the lowest operating frequency decreases. A slight increase in bandwidth can also be seen as the height increases, this corresponds well with results from literature [9]. Another method to lower the operating frequency of the EBG metamaterial is to increase the patch size (w), this is outlined in Figure 117; however, while increasing the patch size will give favorable shifts in frequency it is shown to negatively affect the bandwidth of the EBG metamaterial, this is also to be expected from literature [9]. Finally Figure 114 outlines the effect of increasing the spacing (s) between the capacitive patches. It is shown that decreasing the spacing between these elements decreases the operating frequency of the metamaterial system, and for higher spacing values the bandwidths of the EBG metamaterials is significantly reduced.
Figure 116: Effect of changing the height of the EBG metamaterial on the operating frequency. Material parameters for this figure are given in Figure 124.

Therefore in order to operate a EBG metamaterial at low frequencies, increasing the height of the metamaterial is the best solution as it increases the overall bandwidth in addition to lowering the materials operating frequency. This result shows that the premier factor in EBG design other than the magnetodielectric properties of the substrate itself, which has been examined in detail in the previous section of this chapter, is the height of the EBG metamaterial. However, since the height of these materials is a constant value set to some fraction of the free space wavelength, the only other methods to reduce the operating frequencies are the patch size and spacing, both negatively affect the overall bandwidth.
Figure 117: Effect of changing the patch width of the EBG metamaterial on the operating frequency. Material parameters for this figure are given in Figure 124.

Figure 118: Effect of changing the patch spacing of the EBG metamaterial on the operating frequency. Material parameters for this figure are given in Figure 124.
9.2.3 Effect of Varying Incident Angle

When developing a ground plane for antenna applications it becomes vitally important to determine how the plane reacts to plane waves at various incident angles. This is due to the fact that as receivers, antennas can receive signal from a variety of angles depending upon their beam width and mechanical steering or orientation. To determine the effect of incident angle on EBG metamaterial performance a series of simulations have been conducted. The goal of this study was to see the effect of changing the incident angle of the plane wave on the bandwidth of the EBG metamaterial. Towards this end, the phase reflection method has been employed to determine the bandwidth. Figure 119 indicates the results of these simulations. First, in Figure 119(a) the current in the substrate between the EBG patches is shown for a variety of incident angles for $\varphi$ and $\theta$ varying between $90^\circ$ and $0^\circ$. The results indicate that currents begin to flow in the direction of the incident wave. It should be noted that while currents do flow within the substrate they are small currents, as within the operating bands of the EBG metamaterial it acts as a high impedance surface thusly limiting current flow, this will be discussed in depth in the next section of this dissertation (9.3). The little current that does flow can be attributed to losses in the dielectric substrate as well as conductive losses in the patches. Figure 119 (b) depicts how these currents have been simulated via FEM tools and the polar coordinate systems used in the orientation of the plane waves. Finally, Figure 119(c) depicts the bandwidth of the EBG metamaterial for the same varying $\varphi$ and $\theta$ values. It is apparent from this graph that while the bandwidth does vary for extreme cases of angular phase angle it is within a 10% error for plane waves incident at a $\sim30^\circ$
angle. This is a very encouraging result for the use of EBG metamaterials below radiating surfaces, as they can be used beneath antennas with medium to wide scan angles without degrading the performance of the antenna designs.

Figure 119: Results of the incident angle vs. EBG metamaterial bandwidth study. (a) Depicts the induced currents in the EBG substrate for various incidences of plane wave. (b) Shows the orientation of each of the studied cases. (c) Shows the bandwidth of the EBG metamaterial for each case studied.
9.3 Discussion of Co-Site Interference

In order to determine the co-site mitigation capabilities in the L-band (GPS) frequencies via limiting surface currents, FEM tools have been used. In Figure 120(a and b), the current induced on an EBG metamaterial surface from a stripline is compared to that of a standard perfect electric conductor (PEC) of the same size. The effect of the EBG metamaterial on the current flow is readily apparent.

Figure 120: Depiction of the currents induced by a microstrip above a ground plane for the case of dielectric substrate compared to that of an EBG metamaterial, the ability to reduce currents in the plane is quite apparent.
In Figure 121(a) the effect of a plane wave on a plane of patches is examined. Here the patches were simulated as 17μm thick copper patches with accurate losses. In Figure 121(b) the currents excited on an EBG metamaterial ground plane from an Archimedes spiral antenna (ASA) at 1.6 GHz can be seen. The radial current distribution is due to the currents in the spiral antenna above the EBG plane, and the limits on current flow are readily apparent.

Figure 121: (a) Current sheet plots for an EBG metamaterial slab. (b) Depiction the effect of a near field spiral radiating aperture placed 1.0 mm above the EBG surface on currents produced in the EBG metamaterial during a normal mode of operation.

### 9.4 Design of Dielectric Material EBGs

As noted in the previous sections there are many characteristics to keep in mind while designing an appropriate EBG metamaterial for a given situation. The first and perhaps the most important design parameters are the material parameters of the
substrate. In this section the use of common dielectrics will be examined with $\varepsilon_r$ ranging from 3 to 9.8. It will be demonstrated that while higher values of permittivity lower the operating frequency, they also limit the bandwidth which is in agreement with the theory provided in the previous sections. Secondly, the height requirements of the application need to be considered as the height of the EBG has been shown to affect both the operating range and overall bandwidth. Finally, if the height is restricted, the only method for reducing the operating frequency is to increase the patch size and gap spacing which also negatively affect the bandwidth. It should be noted that unless otherwise stated the gap size was set to 0.15 times the patch size for the following EBG simulations, this was due to the fact that decreasing the gap size further would severely limit the bandwidth.

9.4.1 Standard Dielectric Material EBG Design

The first dielectric EBG design that will be introduced was simulated on an $\varepsilon_r = 3$ Rodgers/RT Duroid 3003 substrate and is pictured in Figure 122. The goal of this design was a 50% bandwidth in the L-Band. This EBG was designed with a height of $\lambda_0/10$, which is 2.1 cm at the center frequency of 1.6 GHz. The specific EBG metamaterial geometric parameters are a patch width of 7.25 mm, a spacing of 1.09 mm, and via radius of 0.25 mm. It should be noted that while this EBG is quite thick compared to those that will be presented in the future, it is in fact much thinner than a $\lambda_0/4$ cavity which would be the standard design for these antennas. To quantify this result, utilizing a 10 cm by 10 cm substrate, this EBG metamaterial reduces the volume to 45% of the case with a ground plane spaced at $\lambda_0/4$, a reduction in $\sim 12\%$ over a standard $\lambda_{\text{sub}}/4$ cavity with a similar permittivity value. It should be noted that this EBG's height has been specifically
designed to allow for increased bandwidth, for more strict spacing concerns the height can be decreased by sacrificing bandwidth. However, for this application a bandwidth of 50% of the L-band was desired so $\lambda_0/10$ was the thinnest possible EBG which could be used.

Figure 122: Dielectric EBG design on a $\varepsilon_r=3$ substrate, the center frequency of the design is 1.6 GHz. The approximate bandwidth is shown to be 50% of the L-band.

The second dielectric EBG design that will be introduced was simulated on an $\varepsilon_r=6.6$ Rodgers/RT Duroid 6006 substrate and is pictured in Figure 123. This EBG was designed with a height of 4.1 mm, at the center frequency of 2.05 GHz. The specific EBG parameters are a patch width of 1.25 cm, a spacing of 1.0 mm, and via radius of 0.25 mm. The reason that this EBG design is much wider than the preceding design in Figure 122 was that the height is much smaller, therefore to achieve the low frequency operation
desired for this EBG application the patch width had to be increased. To get this EBG to operate over the same frequency range as the EBG in Figure 122 would be extremely difficult as the patch size would be huge. Also, as a direct result of this patch width increase, the bandwidth of the EBG metamaterial has decreased significantly. Here a bandwidth of only approximately 7.5% is shown. These simulation results fit quite well with the theory and previous works presented in the previous sections of this dissertation, and further outline how difficult it is to optimize dielectric EBGs for low frequency operations if the height restrictions are severe.

![Graph](image)

**Figure 123**: Dielectric EBG design on a $\varepsilon_r = 6.6$ substrate with a center frequency of $\sim 2.05$ GHz. The approximate bandwidth is 7.5%.

The third and final dielectric EBG design to be introduced was simulated on an $\varepsilon_r = 9.8$ Alumina ($\text{Al}_2\text{O}_3$) substrate and is pictured in Figure 124. This EBG was designed
with a height of 1.3 cm, at the center frequency of 1.0 GHz. The specific EBG parameters are a patch width of 1.6 cm, a patch spacing of 0.1 cm, and via radius of 0.5 mm. For this design the high $\varepsilon_r$ material was used in order to try and produce a low frequency EBG design. This low frequency operation; however; comes at the expense of bandwidth (<5%). This result again matches what is to be expected of dielectric EBG designs at low frequencies. It shows the importance of developing technologies to circumvent these limitations, otherwise these technologies are impractical for commercial and defense applications due to their size and inherently narrow operating bandwidths.

Figure 124: Dielectric EBG design on substrate with a $\varepsilon_r = 9.8$, and a center frequency of 1 GHz. The approximate bandwidth is <5%.

In the following section magnetic materials will be introduced into the design of EBG metamaterials to address the limitations which dielectric EBG metamaterials have
in terms of bandwidth and operating frequencies. These EBG metamaterials will utilize realistic parameters of materials which have been previously presented in this dissertation in Chapters 3 through 5 for a variety of operating frequencies. These EBG metamaterials will allow for this technology to be used in a variety of cases that are not practical for dielectric EBG metamaterials such as low frequency applications in the UHF through L and S-Bands.

**9.5 Design of Magnetic Material EBGs**

9.5.1 Introducing $\mu$ in EBG Metamaterial Design

As shown in the theoretical bandwidth section of EBG metamaterials in this dissertation (9.2.1), it is important to incorporate materials which have high values of $\mu_r$ and low values of $\varepsilon_r$. This section will outline the materials which have been presented in the proceeding chapters (3-5), and show the potential operating bands of each with respect to potential EBG and antenna applications. It will be shown how large bandwidths (50-75%) of the L-band can be achieved for these materials.

9.5.2 Spinel Ferrites

As previously introduced, spinel ferrites are materials which operate with high permeabilities and low permittivities and are optimal for EBG device design. Unfortunately, the spinel ferrites as a material class have very low ferromagnetic resonance values, on the order of 20-30 MHz. This makes them impractical for antenna applications at anything other than very low frequencies, and very difficult to simulate utilizing FEM tools. This is due to the inherently large apertures needed to radiate at
these frequencies. For example a square slot spiral antenna (SSSA) operating with a center frequency of 30 MHz would need a radiating aperture of 2.5 m. However, if there is significant demand for antennas in these frequency ranges, then this technology would be very much in demand. It is because of these frequency limitations, also provided in Table 2, that the discussion of EBG materials utilizing practical ferrites will be limited in scope to Co$_2$Z hexaferrite materials which have an intrinsic zero field FMR value of ~1 GHz, allowing for a larger variety of antenna applications.

![Diagram](image)

Figure 125: Magnetodielectric EBG design on a $\varepsilon_r = 10$, $\mu_r = 16$ textured Co$_2$Z substrate with a center frequency of 300 MHz. The approximate bandwidth is 40%.

9.5.3 Hexaferrites

The first magnetodielectric EBG design that will be introduced is a low frequency design intended to operate in the lower UHF band (.3 to 3 GHz) which is below the zero
field ferromagnetic resonance value of the Co$_2$Z hexaferrite material. This EBG metamaterial was simulated via FEM tools on an $\varepsilon_r=10$, $\mu_r=16$ textured Co$_2$Z substrate and is pictured in Figure 125. This EBG was designed with a height of $\lambda_o/125$, which is .8 cm at the center frequency of 300 MHz ($\lambda_o=1$ m). The specific EBG parameters are patch with a width of 2.3 cm and a spacing of 3.45 mm. It should be noted that because this EBG is made out of a high $\mu_r$ material there is no need to utilize vias for inductance. Therefore this material is easier to fabricate than the dielectric case. To compare this antenna to a $\lambda_o/4$ cavity, utilizing a 10 cm by 10 cm substrate, this EBG metamaterial reduces the volume to 3.2% of the original case. Also, since this device operates below the zero field FMR value of the ferrite bias magnets will not need to be used.
To understand the effect of magnetic loss on the operating frequency of the magnetodielectric EBG metamaterials, and therefore increase their operating regions, a study was run on a material which had a center frequency of 500 MHz. The geometric parameters of this design were a height = \( \lambda_0/60 \) (1.0 cm), a width = 0.55 cm, and spacing = 0.825 mm. The material parameters used in the FEM simulation were \( \varepsilon_r = 10 \), \( \tan(\delta_\varepsilon) = 0.0025 \), \( \mu_r = 12.5 \), and \( \tan(\delta_\mu) \) varying from 0.01 to 2.5. Here it is shown that higher magnetic losses shift the lowest operating frequency downward, but only at values
greater than $\tan(\delta_\mu)=1$, otherwise the effect of the magnetic loss is negligible [14]. This is very important as the material parameters of the Co$_2$Z which have been introduced in the previous chapters have magnetic loss tangents which roll upwards near their FMR values (1 GHz).

The third magnetodielectric EBG design that will be introduced is intended to demonstrate the effect of the magnetodielectric substrates vs. a more standard dielectric design approach. This EBG metamaterial has been designed to operate in L-band (1 to 2 GHz), with the same frequency range and bandwidth (50%) as the dielectric EBG pictured in Figure 123. This EBG metamaterial was simulated via FEM tools on an $\varepsilon_r=10$, $\mu_r=12.5$ textured Co$_2$Z substrate and is pictured in Figure 127. This EBG was designed with a height of $\sim\lambda_o/95$, which is 0.24 cm at the center frequency of 1.4 GHz ($\lambda_o=21.4$ cm). This is almost a factor of ten smaller in size than the previous EBG design. The specific EBG parameters for this design are a patch with a width of 4.0 mm and a spacing of 0.6 mm.
The fourth and final magnetodielectric EBG design that will be introduced is a low frequency design intended to operate in L-band (1 to 2 GHz). This EBG metamaterial was simulated via FEM tools on an $\varepsilon_r = 7.5$, $\mu_r = 16$ textured Co$_2$Z substrate and is pictured in Figure 128. This EBG was designed with a height of $\lambda_o/75$, which is 0.4 cm at the center frequency of 1 GHz ($\lambda_o=30$ cm). The specific EBG parameters are patch with a width of 1.0 mm and a spacing of 0.15 mm. To compare this antenna to a $\lambda_o/4$ cavity, utilizing a 10 cm by 10 cm substrate, this EBG metamaterial reduces the volume to 5.3% of the original case.
Figure 128: (a) Design of an EBG surface for RF device applications. (b) Depiction of a single EBG element employing a Co$_2$Z hexaferrite substrate and a metallic patch. (c) Simulated bandwidth of an EBG sheet.

It is important to note that for the third and fourth magnetodielectric EBG metamaterial designs this material is operating in the L-band. Therefore, bias magnets will need to be used which increase the ferromagnetic resonance (FMR) frequency and decrease the magnetic losses due to Snoek's limit. This has been shown in literature where the operating range of Co$_2$Z hexaferrites can be extended to cover the entire L-
band (1 - 2 GHz) by applying a low magnetic bias field (200-300 Oe) in the plane of the substrate while maintaining \( \mu_r \geq 12.5 \) at L-Band [15]. This bias field can be supplied by small permanent magnets positioned at the perimeter of the substrate. As such, operation of the EBG metamaterial in the 1 to 2 GHz band can be achieved using material properties presented in the previous section.

**9.6 Conclusions**

In this chapter the design and implementation of various EBG metamaterials have been investigated. In particular, parameters of EBG metamaterial structures have been discussed with respect to increasing their bandwidths at low frequencies in the UHF through L and S-Bands. These methods included changing the permittivity and the permeability of the substrates, changing the height of the substrates, changing the patch widths, and changing the gaps of the metallic patches. It has been shown that by utilizing standard dielectric materials it is difficult to achieve wide bandwidths in the UHF to L and S-bands. While bandwidths on the order of 50% can be achieved for dielectric EBG designs, they can only be achieved with profile heights on the order of \( \lambda_o/10 \), and while this is a significant volumetric reduction over a standard cavity it is insufficient for truly low profile antenna designs. To solve this problem, EBG metamaterials based on high permeability magnetodielectric materials were investigated. It was shown that a EBG metamaterial with an equivalent bandwidth (50%) in the L-band can be achieved for a Co\(_2\)Z ferrite substrate with a height of \( \lambda_o/95 \). Furthermore, it has been shown that these novel magnetodielectric substrates are much more practical to fabricate in today's
materials fabrication facilities due to the reduction of vias. Finally, it was shown that utilizing textured materials it is possible to achieve 100% bandwidths in the L-band for these metamaterials, making them practical for use in many microwave devices. In the following chapter these EBG materials, both magnetic and dielectric will be applied to a variety of antenna apertures to determine effective uses for both designs.

9.7 References


Chapter 10: *EBG Metamaterials in Antenna Design*

The focus of Chapter 10 will be the application of the electromagnetic band gap (EBG) metamaterials which have been introduced in Chapter 9. The antenna simulations in this chapter will employ both dielectric and magnetic EBG metamaterials, the goal of these studies will be to determine the optimal case for using each of the prospective EBG designs. In doing so it will be shown that both dielectric and magnetic EBG metamaterials can be used to suit a variety of different commercial and defense related antenna applications. Elements to be studied in this chapter including wide and narrow band square slot spiral antenna (SSSA) elements and Archimedean spiral antenna (ASA) elements.

**10.1 Introduction to Previous Works**

In recent years applications of EBG metamaterials in antenna designs have been gaining popularity [1-9]. Most of the designs revolve around narrow band and high frequency dielectric applications [1-3]. In cases where the frequency is low, high permittivity materials have been used further reducing bandwidth [4-5]. Recently, in order to enhance the potential bandwidth of these designs, ferrite materials have been incorporated into these designs as a ground plane treatment functioning as absorbers [5-9]. In these metamaterial systems the ferrite layers allow for better antenna impedance matching over a wider bandwidth than standard dielectric designs; however, the ferrite materials absorb the low frequency gain. While these results are promising, they are not practical for antennas which operate in the ultra high frequency (UHF) to L-bands due to
the reduced gains over these frequency regions. As described in depth in the previous chapter (Chapter 9) dielectric EBG designs are prohibitively large and have inherently low bandwidths in these frequency ranges. Therefore in this chapter, dielectric EBG metamaterials will be constrained to low bandwidth applications and applications above 1 GHz. Ferrite EBG metamaterial antenna assemblies will be shown to be superior to dielectric designs at frequencies in the lower UHF and L-bands.

10.2 Dielectric EBG Substrates in Antenna Designs

10.2.1 Introduction to a Dielectric EBG SSSA Design

In this section the effect of a low bandwidth EBG is shown utilizing a square slot spiral antenna. This EBG has been designed to operate with a ~10% bandwidth in the S-Band utilizing standard commercially available dielectric materials. The complete outline of this metamaterial is given in Chapter 9 (Figure 123) of this dissertation. The geometries of the antenna element, a square slot spiral design, have been previously outlined in Chapter 6 (Figure 70) of this dissertation. This design has been utilized due to its circular polarization, and high gain over the desired EBG bandwidth. Figure 129 depicts the combination of this element and the EBG, in these simulations the element has been placed at a height of 1.0 mm from the EBG surface, and a low dielectric material (Rodgers Ultralam ε=1.7) has been utilized as the spacer. The total height of the antenna assembly used is $\lambda_{\text{LoF}}/30$. 

269
Figure 129: Depiction of a SSSA element over a low bandwidth dielectric EBG metamaterial for operation in the S-band.

10.2.2 Effect of Dielectric EBG on Spiral Performance

In order to determine the effectiveness of the EBG metamaterial on antenna miniaturization the return loss of the antenna element has been examined as a function of height in Figure 130. In this figure, the first three data sets are for dielectric cavity antenna designs of decreasing height; 5 cm, 3 cm, and 0.61 cm respectively. From this data it is apparent that as the height decreases from 5 cm to 0.61 cm the return loss of the antenna suffers, which is to be expected due to destructive interference. In the case of a 0.61 cm cavity the antenna is no longer matched over the desired frequency bands. In addition to these cavity measurements, two EBG measurements are provided. Here it is
apparent that over the bandwidth of the EBG (highlighted in green in the figure) the return loss of the low profile antenna EBG combination is below -10 dB, indicating good matching. This figure shows that the EBG can be used to reduce the height of the antenna element while at the same time maintaining the matching parameters of a $\lambda_{\text{sub}}/4$ cavity design.

Figure 130: Effect of antenna assembly height on return loss. A comparison of various antenna heights above a ground plane with and without dielectric EBG metamaterials is shown.

The next step in order to determine the effectiveness of the dielectric EBG metamaterial on antenna miniaturization was to examine the efficiency of the antenna element as a function of height. The results of this study are shown in Figure 131. It is important to note that this efficiency plot includes both mismatch loss, and dielectric loss. These values were calculated via a finite element method (FEM) technique, based off the
ratio of the input power to the device to the radiated power. In this figure, the first three data sets, are for dielectric cavity antenna designs. From this data it is apparent that as the cavity height decreases from 5 cm to 0.61 cm the efficiency decreases accordingly. This is partially due to the fact that the return loss of the antenna suffers as the element is placed closer and closer to the ground plane, and further and further away from its optimal $\lambda_{sub}/4$ cavity design. In the case of a 0.61 cm cavity the antenna is no longer matched and the efficiency of the element is severely decreased.

![Effect of EBG on Efficiency](image)

Figure 131: Effect of antenna assembly height on efficiency. A comparison of various antenna heights above a ground plane with and without dielectric EBG metamaterials is shown.

In addition to these standard cavity efficiency measurements two EBG measurements are provided. Here it is apparent that over the bandwidth of the EBG (highlighted in green in the figure) the efficiency of the low profile antenna EBG
combination is very close to that of the standard cavity designs at around 70%. It is technically lower than the optimal design as the EBG material itself is not lossless and utilizes capacitive and inductive elements. This figure does a very good job of showing that the EBG can be used to reduce the height of the antenna element while at the same time maintaining the efficiency parameters of a $\lambda_{sub}/4$ cavity design. This is very important as inefficient antennas are not practical for commercial or defense related applications.

![Effect of EBG on Gain](image)

**Figure 132**: Effect of antenna assembly height on broad side gain. A comparison of various antenna heights above a ground plane with and without dielectric EBG metamaterials is shown.

The next step in order to determine the effectiveness of the EBG metamaterial on antenna miniaturization was to examine the gain of the antenna element as a function of
height this is pictured in Figure 132. As in the previous figures in this section, the first three data sets are for dielectric cavity antenna designs of various heights. In these designs a significant reduction in gain from the case of the 3 cm antenna to that of the 0.61 cm case is shown. This again can be attributed to the changes in efficiency and return loss and the closeness of the antenna element to the ground plane. This closeness makes it so the reflected electromagnetic energy is not in phase with the energy radiated from the element as would be the case in a standard $\lambda_{sub}/4$ cavity design. It is important to note that there is a small dip in the gain of the 5cm cavity design of this antenna, this has been attributed to a resonance in the original design. As these antennas were first developed for wideband operation, this antennas gain is significantly higher <2.5 GHz this was not addressed.

In addition to these standard cavity efficiency measurements two EBG measurements are provided. Here it is apparent that over the bandwidth of the EBG (highlighted in green in the figure) the gain of the low profile antenna EBG combination very close to that of the standard cavity designs at around 7 dB. It should be noted that outside of the operating ranges of the EBG the gain plummets. This result reiterates the discussion in the previous chapter of the limitations of dielectric EBGs and the importance of determine a way to increase the bandwidth of the EBG material in the following section this concern has been addressed utilizing ferrite substrates instead of the more standard dielectric designs.
The final study on the effect of the dielectric EBG metamaterial on the SSSA element was to examine the radiation patterns of the element over the operating range of the EBG metamaterial. The results of this study are given in Figure 133, where good omnidirectional performance is shown in both the $\phi = 0^\circ$ and $\phi = 90^\circ$ planes.

![Figure 133](image)

**Figure 133**: (a) Effect of frequency on radiation patterns of the SSSA above a dielectric EBG metamaterial with $\phi = 0^\circ$. (b) Effect of frequency on radiation patterns of the SSSA above a dielectric EBG metamaterial with $\phi = 90^\circ$.

### 10.3 Ferrite EBG Substrates

#### 10.3.1 Low Frequency SSSA Element

The goal of this section will be to utilize the wide band and low frequency magnetic EBG designs pictured in Chapter 9 in realistic antenna applications. This will allow for low profile antenna technologies which will allow the radiating elements to operate while reducing size, cost, and weight over standard cavity designs. The preliminary spiral antenna design (SSSA element) calculated using FEM tools is shown in Figure 134(a). Also shown is the 3-D radiation pattern simulated at the antennas center frequency of 300 MHz (Figure 134 (b)) which shows good omnidirectional performance.
This antenna has been designed to be ultra thin with a height of $\lambda_0/100$, and a planar size of $\lambda_0/4$. This was done by utilizing an EBG ground plane (Figure 125) with $\varepsilon_r=10 \mu_r=16$, which according to literature and those produced in this dissertation are realizable (Chapter 5). The preliminary antenna design offers a narrow operating bandwidth of $\sim 8\%$ in the UHF band. The realized gain over this bandwidths is $\sim 3$ dB. The spiral antenna produces circular to slightly elliptical polarization with an axial ratio in the $\sim 1.3$ range in its current configuration. An axial ratio of 1, equivalent to circular polarization can be achieved through further design optimization such as the implementation of a Klopfenstein taper.

![Figure 134: (a) Depiction of a SSSA element above a low frequency Co$_2$Z Ferrite EBG metamaterial designed to operate with a center frequency of 300 MHz and a total height of $\lambda_0/100$. (b) 3-D radiation pattern of element at the center frequency, 3.5 dB of gain is observed.](image)

The performance metrics of the preliminary spiral antenna design calculated using FEM tools are shown in Figure 135. Here the broad side gain of the SSSA element
compared to that of Chu's Limit over the operating range of the EBG metamaterial is shown, indicating radiation parameters close to Chu's Limit. Also plotted are the return loss measurements, indicating good performance over the antennas operating frequencies. The efficiency of the antenna element is shown to be 50-70%. Finally, the axial ratio of the proposed SSSA element is shown to be elliptical to slightly circular which can be optimized as mentioned earlier.
Figure 135: (a) Broad side gain of the SSSA element compared to that of Chu's Limit over the operating range of the EBG metamaterial. (b) Return loss measurement. (c) Efficiency of the antenna element. (d) Axial ratio of the proposed SSSA element.
Figure 136: (a) 3-D radiation pattern of an Archimedean spiral antenna designed on a magnetic EBG substrate at a center frequency of 2 GHz. (b) Top view of the spiral element design. (c) Radiating properties including gain, return loss, and efficiency.

Figure 136 depicts a second ferrite EBG metamaterial ASA element designed utilizing a textured ferrite material with a substrate with $\varepsilon_r \approx \mu_r$ similar to the design in Figure 127. This EBG has been designed to operate over 50% of the L-Band. Figure 130(b) depicts the radiation pattern of this antenna near the GPS frequency range at 1.6 GHz. This antenna has been designed to specifically operate in the L to S-Band region.
and boasts a height of $\lambda_{0}/40$, and a bandwidth of $>30\%$. It should be noted that for this design bias magnets will need to be used to increase the FMR value, and due to the size of the substrate this may be problematic. One potential solution is to section the substrate and bias each section independently.

As previously mentioned, electrically small antenna performance limitations are set by the theoretical Chu's limit. This value denotes the maximum realizable gain as a function of frequency for an antenna which can be inscribed in a sphere with radius $a$, $a$ being the maximum dimension of the antenna element. In Figure 136(c), the gain of the ASA antenna was plotted against Chu's limit. At the low frequency end the realized gain of the antenna is very close to the theoretical limit. Some design refinement is necessary at the high frequency end to produce optimal realized gain across the entire operating band as well as to increase the operating bandwidth of the antenna. This can be achieved through an optimization of spiral geometry parameters, such as the width and the spacing of the lines, as well as using different EBG substrate materials which have inherently more bandwidth.

10.3.2 Conformal Antenna Designs

The technologies presented in the previous EBG metamaterial inspired antenna designs lend themselves well to applications in conformal antennas. In particular, these antennas need to conform to a variety of circumferences in defense and commercial applications. Their inherent low profile nature ($\lambda_{0}/40$ to $\lambda_{0}/100$) allow these designs to
work without adding excess drag and weight to a variety of applications. Prospective conformal designs are shown in Figure 137 with and without superstrates.

Figure 137: Conformal antenna assemblies utilizing EBG metamaterials with superstrates (a) and without superstrates (b).

10.3.3 Realistic Antenna Fabrication

Due to current limitations on the production size of the textured materials presented in Chapter 5, and in order effectively utilize the Co$_2$Z hexaferrite materials in antennas and EBG metamaterials without bias fields, an antenna has been designed to operate below ferromagnetic resonance of these materials (pictured in Figure 82) on a commercially available non-oriented Co$_2$Z EBG metamaterial substrate. The potential ASA element itself has been designed on a thin piece of Rodgers Duroid$^{\text{TM}}$ with $\varepsilon_r = 2.2$ to operate with a lowest operating frequency of 400 MHz, this correlates to $\sim$23 cm based off of the design tool $D=\lambda_d/\pi$. The Co$_2$Z materials which will be utilized to make the
substrate have been purchased from Trans Tech materials (Skyworks inc.) and their parameters are given in Figure 138.

Figure 138: Material parameters of the Co$_2$Z hexaferrite materials provided by Trans Tech including the permittivity and permeability as well as the loss tangents associated.
It should be noted that these material parameters do not meet the specifications of the materials provided in Chapters 5 and 6, this is due to the fact that commercially available materials are not textured, and therefore the $\mu$ and $\varepsilon$ values have not been optimized for antenna and EBG metamaterial performance. An EBG metamaterial designed on these substrates has been depicted in Figure 139, this EBG has been designed to operate below the ferromagnetic resonance of the unbiased Co$_2$Z hexaferrite. This result shows that the maximum achievable bandwidth using conventional commercially available materials is 50% (given a height of $\lambda_{LoF}/75$). Textured designs in chapter 9 have shown upwards of 100% bandwidths, depicting the versatility and potential of the technologies presented in this dissertation.

**Tiled Hexaferrite EBG Substrate Design**

Figure 139: EBG designed to operate below the ferromagnetic resonance of the unbiased unoriented Co$_2$Z hexaferrite provided by Trans Tech.
10.4 Conclusions on EBG Designs

The focus of this chapter has been on the implementation of the previous chapters dielectric and magnetic EBG metamaterial designs, in doing so the practical implementation of each design has been shown. Namely, that for narrow band somewhat low profile designs ($\lambda_0/20$), dielectric EBGs are sufficient. However; if the frequency of operation is below 1 GHz, the needed bandwidths are greater than 5%, and the required heights are ($<\lambda_0/40$) dielectric EBG inspired antenna elements are not sufficient. To suit applications of this sort, magnetic EBG inspired antenna elements have been designed. these materials allow for wider bandwidths of operation over the lower frequency bands. It has been shown that ultra thin antennas ($\lambda_0/100, \lambda_0/60$), can operate with gains close to that of Chu's limit with bandwidths between 10% and 30%. As a final discussion these textured designs have been compared to those of commercially available materials, depicting the versatility and potential of the oriented technologies presented in this dissertation.

10.5 References


Chapter 11: Thesis Conclusions

In this dissertation common and novel antenna miniaturization techniques have been thoroughly examined. The common techniques, such as dielectric loading and superstrate design were shown to be mildly successful in the development of miniaturized antennas (Chapter 2) by increasing the low frequency gain of the elements and shifting their lowest operating frequencies downward. However, these techniques have not achieved the sizes and radiation parameters desired in many commercial and defense related applications (heights < $\lambda_0/40$). Towards this end, other novel techniques have been studied/employed to reduce the size of these antenna elements even further without overly affecting their radiation properties such as the gain and return loss.

The first novel technique employed was the use of ultra high permittivity materials for antenna miniaturization. This miniaturization technique was approached through a materials fabrication perspective with the goal of developing a material which could operate as low loss substrate for miniaturized antenna designs. Following this discussion a patch antenna GPS element was proposed for this material. This antenna boasted a height of $\lambda_0/40$ as well as functional radiation parameters; however, due to the high permittivity of the substrate the bandwidth of the antenna was only 4-5 MHz. In this study it became readily apparent that the utilization of high permittivity materials alone would not be the design goals of this dissertation. Therefore other novel miniaturization techniques were employed in the subsequent chapters.
The second novel miniaturization technique employed was the use of magnetodielectric materials for antenna substrates, the belief was that the permeability in these materials would lower the profile ($< \lambda_0/40$) and at the same time increase their bandwidths due to the better wave impedance matching of materials with $\varepsilon_r \approx \mu_r$. In particular the structural, morphological, and magnetodielectric properties of various ferrites was examined. The first of these ferrites were spinel ferrites formed through polyol and aqueous co-precipitation methods. These materials were shown to be suitable for antenna applications below 100MHz (Chapter 3).

Following the study of these low frequency materials, cobalt substituted barium Y-Type hexaferrite ($\text{Ba}_2\text{Co}_2\text{Fe}_{12}\text{O}_{22}$) particles were synthesized utilizing an aqueous co-precipitation chemical synthesis method followed by a single step sintering at or above 900 °C (Chapter 4). These materials were characterized for structure, morphology, and magnetodielectric properties. All measured properties, including lattice constants, magnetic moment, permittivity, permeability, and coercive field, were determined to be in close numerical agreement with bulk reference values. To improve the magnetodielectric properties of these materials, the concept of texturing was introduced, allowing for a significant (>60%) increase in the materials permeability. These materials have shown to be suitable for antenna and designs up to 1 GHz due to their moderate permeability values, and low magnetic loss tangents $\approx 0.01$.

The final material introduced for use as antenna substrates was a cobalt substituted barium Z-Type hexaferrite material (Chapter 5). This material was introduced
through a modified co-precipitation of elements technique, and has been thoroughly characterized with regard to its in-plane orientation and magnetic properties. Optimization studies have been performed to maximize the permeability and minimize the magnetic losses below ferromagnetic resonance (1 GHz) for unbiased antenna applications. In addition, the effect of bias fields on this material has been studied to show that with fields on the order of 200-300 Oe, these materials can be used well into the L and S bands with permeabilities >5. Finally, the tunability of this material has been examined as a function of applied field, allowing for tunable devices to be fabricated.

Following the materials discussion presented in this dissertation, a series of antenna elements were proposed through a standard dielectric approach (Chapter 6). In doing so, it has been shown that these elements can achieve wide bandwidths and a variety of different polarizations ranging from linear to elliptical and circular. Special care was spent to make sure these elements operated in the frequency ranges of the magnetodielectric materials introduced in the previous chapters. In particular antennas with small radiating apertures compared to their operating frequencies such as spiral antennas and square slot spirals were investigated due to their inherent small sizes and potential for miniaturization. While these results were promising it should be noted that due to the standard \( \lambda_{\text{sub}}/4 \) cavity beneath these elements required to enhance the gain, the antennas presented on dielectric substrates are bulky and not cost effective.

In the following chapter (Chapter 7) the use of cobalt substituted barium Z-Type hexaferrites as antenna substrates to reduce the profile of antenna designs and increase
their operating bandwidths has been thoroughly examined. Utilizing standard Archimedean spiral designs (ASA) as well as more novel square slot spirals (SSSA) it has been shown that these substrates can reduce the height of the antennas to $\lambda_0/40$ or even $\lambda_0/60$. This reduction in height significantly reduces the weight and associated drag of these elements. However, due to the high losses of these materials gains $>0$ dB are difficult to achieve. Efficiency has also shown to be a problem when utilizing these materials as they show only about 20% radiation efficiency for these designs. Therefore, in addition to utilizing these materials as antenna substrates they were also introduced as absorber layers, along with spinel ferrites, to increase low frequency matching of wideband antennas. It was shown that utilizing realistic ferrite parameters the loss in gain can be minimized to the ferromagnetic resonance frequency of the ferrites used, while concurrently increasing the low frequency S11 response of these designs. The use of these absorbers has been shown as an effective way to use these materials in antenna designs where large bandwidths are required such as S and X-band antenna designs.

Utilizing the elements produced in the previous chapters the concept of phased arrays of elements was introduced utilizing circularly polarized antenna elements (Chapter 8). This concept was examined through the use of both dielectric and magnetic antenna elements. The results of the dielectric antennas resulted in gains on the order of 20 dB for 4x4 element arrays spaced at $\lambda_0/2$. However; as these antennas require large cavities on the order of 4-5 cm to maintain these operational gains, it makes them heavy and hard to work with. For this reason, and for applications where profile is more of a
design constraint such as mounted phased arrays, which need to minimize drag, phased antenna arrays utilizing magnetic materials have also been proposed. These elements have intrinsically lower gains due to the magnetic losses in the substrate as well as the more standard dielectric losses. Utilizing a 5×5 element array of these antennas spaced at $\lambda_{\text{CE}}/4$, gains on the order of 13-20 dB have been shown. In addition to these gains, studies have been performed which examine the beam widths of these designs as well as their applicability towards steering. It has been shown that these phased arrays have 3 dB scan angles on the order of 70°.

The next approach to minimize the planar height of the proposed antenna elements was through the use of EBG metamaterial structures (Chapter 9). In this chapter these metamaterials have been discussed with respect to increasing their bandwidths and reducing their heights for potential antenna applications. Towards this end both dielectric and magnetic EBG metamaterials have been introduced for a variety of different applications. It has been shown that by utilizing standard dielectric materials it is difficult to achieve wide bandwidths in the UHF to L and S-bands. While bandwidths on the order of 50% can be achieved for dielectric EBG designs, they can only be achieved with profile heights on the order of $\lambda_0/10$, and while this is a significant volumetric reduction over a standard $\lambda_0/4$ cavity it is insufficient for truly low profile antenna designs. To solve this problem, EBG metamaterials based on high permeability magnetodielectric materials were investigated. It was shown that a EBG metamaterial with an equivalent bandwidth (50%) in the L-band can be achieved for a Co$_2$Z ferrite substrate with a height of $\lambda_0/95$. Furthermore, it has been shown that these novel magnetodielectric substrates are much
more practical to fabricate in today's materials fabrication facilities due to the reduction of vias. Finally, it was shown that utilizing textured materials it is possible to achieve 100% bandwidths in the L-band for these metamaterials, making them practical for use in many microwave devices.

The focus of the final chapter (Chapter 10) of this dissertation, was the application of the previous chapter's EBG metamaterials towards different dielectric and magnetic antenna designs. The goal of this discussion was to determine the optimal case for using each of the prospective EBG designs. It was shown that for narrow band somewhat low profile designs ($\lambda_0/20$) dielectric EBGs are sufficient. However; if the frequency of operation is below 1 GHz, the needed bandwidths are greater than 5%, and the required heights are ($<\lambda_0/40$) dielectric EBG inspired antenna elements are not sufficient. To suit applications of this sort, magnetodielectric EBG inspired antenna elements have been designed. these materials allow for wider bandwidths of operation over the lower frequency bands. It has been shown that ultra thin antennas ($\lambda_0/100$, $\lambda_0/60$), can operate with gains close to that of Chu's limit with bandwidths between 8% and 30%.

In conclusion, in order to achieve a significant reduction in volume over standard dielectric $\lambda_0/4$ cavity antenna designs while concurrently maintaining usable gains > 3 dB, realizable high permeability oriented Co$_2$Z hexaferrite materials have been introduced through a modified aqueous synthesis technique both as magnetic substrates and as electromagnetic band gap (EBG) metamaterial ground planes. Significant
volumetric reduction of the antenna elements (92%) due to magnetic and dielectric loading has been achieved via tailoring the permittivity and permeability of the ferrite material through an orientation process over standard dielectric $\lambda_o/4$ cavity designs. Further reduction (94% of $\lambda_o/4$ cavity design) is achieved via combining a realizable high permeability Co$_2$Z hexaferrite ($\varepsilon_r=16 \mu_r=14$) with a periodic array of metallic Sivenpiper Structures to create an EBG metamaterial. The thickness of the investigated EBG metamaterial is $>\lambda_o/65$ at the lowest operation frequency and the bandwidth, investigated in terms of realizable fabrication techniques is determined from the phase of the reflected wave to be 100% of the L-Band (1 GHz - 2 GHz). Gains of -2.5 to 3 dBi have been achieved for both magnetic substrates and EBG ground planes, with VSWR <2. Indicating that these designs are practical for commercial and defense applications which call for low profile miniaturized antenna designs which do not suffer from reduced gain.