2012-07-09

Design and Optimization of a Miniature Radiation Pattern Reconfigurable Antenna for 2.4 GHz Band and a Dual Tuned Birdcage Coil for Magnetic Resonance Imaging

Manoj Adhikari
Brigham Young University - Provo

Follow this and additional works at: https://scholarsarchive.byu.edu/etd
Part of the Electrical and Computer Engineering Commons

BYU ScholarsArchive Citation

Adhikari, Manoj, "Design and Optimization of a Miniature Radiation Pattern Reconfigurable Antenna for 2.4 GHz Band and a Dual Tuned Birdcage Coil for Magnetic Resonance Imaging" (2012). All Theses and Dissertations. 2917.
https://scholarsarchive.byu.edu/etd/2917

This Thesis is brought to you for free and open access by BYU ScholarsArchive. It has been accepted for inclusion in All Theses and Dissertations by an authorized administrator of BYU ScholarsArchive. For more information, please contact scholarsarchive@byu.edu, ellen_amatangelo@byu.edu.
Design and Optimization of a Miniature Radiation Pattern Reconfigurable Antenna for 2.4 GHz Band and a Dual Tuned Birdcage Coil for Magnetic Resonance Imaging

Manoj Adhikari

A thesis submitted to the faculty of Brigham Young University in partial fulfillment of the requirements for the degree of Master of Science

Karl F. Warnick, Chair
Neal K. Bangerter
Brian A. Mazzeo

Department of Electrical and Computer Engineering
Brigham Young University
August 2012

Copyright © 2012 Manoj Adhikari
All Rights Reserved
ABSTRACT

Design and Optimization of a Miniature Radiation Pattern Reconfigurable Antenna for 2.4 GHz Band and a Dual Tuned Birdcage Coil for Magnetic Resonance Imaging

Manoj Adhikari
Department of Electrical and Computer Engineering
Master of Science

This thesis describes development of a miniature reconfigurable antenna and optimization of a dual tuned birdcage coil. The design goals for the miniature reconfigurable antennas are resonance center frequency of 2.44 GHz, bandwidth of 2.4 GHz - 2.48 GHz, size of 0.8cm x 1.2cm, radiation efficiency of 70%, pattern correlation coefficient of 0.3 and input impedance of 50 Ω. The main goals to be achieved from the birdcage coil are the better homogeneity and higher signal to noise ratio than the existing coil. The design and optimization of both antenna and birdcage coil were done using simulation software and MATLAB.

Wireless communications have progressed rapidly in last decade and communication devices are becoming smaller and smaller. With miniaturization of devices, dimensions of antennas need to be reduced accordingly. In recent years engineers have not only focused on miniaturization but also on the reconfigurability of the antenna. The functionality and performance of an antenna can be greatly improved by a reconfigurable antenna. However, designing such an antenna can be a tricky task. This thesis addresses issues that are faced during design of such miniature reconfigurable antenna. It also describes design and optimization of such an antenna. The modeled and measured results for the miniature reconfigurable antennas were very close except the built antenna requires frequency tuning and better switching technique.

Magnetic resonance imaging (MRI) is an imaging modality that provides high quality images. Radio frequency (RF) coils play an important role in MRI. RF coils act like an antenna that transmits RF energy and receives energy as well. The most commonly-used RF coil for volume imaging is the birdcage coil. This thesis describes an optimization of a birdcage coil that is dual tuned for sodium and hydrogen frequencies. The modeled coil has better performance compared to the existing coil.

Keywords: radiation pattern reconfigurable antenna, dual tuned birdcage coil
ACKNOWLEDGMENTS

I would like to thank Dr. Karl Warnick and Dr. Neal Bangerter for their support, dedication and guidance. I am very grateful for their help and time to develop understanding of the projects. I would also like to thank Dr. Brian Mazzeo for giving me guidance on editing thesis. Finally, I would like to thank my Mom, Dad, sister and my friends for their support and encouragement.
Table of Contents

List of Tables vi

List of Figures vii

1 Introduction 1

1.1 Thesis Contributions .................................................. 2

1.1.1 Miniature Radiation Pattern Reconfigurable Antenna .......... 2

1.1.2 Birdcage Coil ....................................................... 3

1.2 Thesis Outline ......................................................... 3

2 Reconfigurable Antennas 4

2.1 Introduction ............................................................ 4

2.2 History of Reconfigurable Antennas .................................. 5

2.3 Antenna Parameters .................................................... 6

2.4 Challenges ............................................................... 9

2.5 Antenna Design ........................................................ 10

2.6 Y-shaped Design ......................................................... 12

2.6.1 Dimensions ......................................................... 13

2.6.2 Results ............................................................... 13

2.7 MTM Based Design ..................................................... 16

2.7.1 Dimensions .......................................................... 18
2.8 Results and Discussion ................................................. 19
  2.8.1 Antenna with Copper Bridges ................................. 19
  2.8.2 Antenna with RF Switches .................................... 20
  2.8.3 RF Switch .......................................................... 23
2.9 Design Challenges Encountered ................................... 28
2.10 Summary ............................................................. 31

3 Radio Frequency Coil for Magnetic Resonance Imaging ........ 33
  3.1 Introduction .......................................................... 33
  3.2 Radio Frequency Coil ............................................... 35
  3.3 Birdcage Coil .......................................................... 36
  3.4 Benchmark Model .................................................... 39
  3.5 Optimization ........................................................... 39
  3.6 Results ................................................................. 41
  3.7 Summary ............................................................... 43

4 Conclusion ............................................................... 48
  4.1 Future Work ........................................................... 48

Bibliography ............................................................... 50
List of Tables

2.1  Design goals for reconfigurable antenna. ........................................ 10
2.2  Dimension of Y-antenna. .............................................................. 14
2.3  Measured results for reconfigurable Y-antenna. ............................. 15
2.4  Dimension of MTM based antenna. ................................................... 18
2.5  Measured results for reconfigurable MTM antenna without switches. ... 20
2.6  Properties of different switch types. ............................................... 25
2.7  Control logic of switch RF1127. ...................................................... 25
2.8  Switch pin description. ................................................................. 26
2.9  Measured results for reconfigurable MTM antenna with switches. ....... 28
3.1  Dimension of the coil. ................................................................. 41
List of Figures

2.1  (a) The concept and (b) the cross section of MEMS reconfigurable Vee Antenna (From: Chiao et al.[10], IEEE 1999). ................................................................. 6

2.2  A seven-element circular array of reactively loaded parasitic dipoles for reconfigurable beam steering and beam forming (From: Harrington[12], IEEE 1978). ................................................................. 7

2.3  Prototype Y-shaped antenna with copper bridges. Left: Antenna with right branch attached to feed (Reconfigurable state A). Right: Antenna with left branch attached to feed (Reconfigurable state B). ................................. 11

2.4  Image of modeled Y-shaped antenna with adjusted room to fit switch and pad layout. ................................................................. 12

2.5  Top view of prototype Y-shaped antenna with switch. ......................... 13

2.6  Bottom view of prototype Y-shaped antenna showing decoupling capacitors and wires to power up the switch. ................................................................. 14

2.7  Input reflection coefficient of Y-shaped antenna. ................................ 15

2.8  Measured gain for Y-shaped reconfigurable state A antenna ............... 16

2.9  Measured gain for Y-shaped reconfigurable state A antenna ............... 17

2.10 Reconfigurable state A Model in HFSS. Left parasitic connected via a thin copper wire. ................................................................. 18

2.11 Reconfigurable state B Model in HFSS. Right parasitic connected via a thin copper wire. ................................................................. 19

2.12 Comparison between measured and simulated S11 for the two antenna states. ................................................................. 20

2.13 Measured and simulated radiation pattern of elevation cut for the reconfigurable antenna, showing the change in radiation pattern for the two antenna states. ................................................................. 21
2.14 Measured and simulated radiation pattern of azimuth cut. .......... 21
2.15 MTM based Reconfigurable Antenna. .............................. 22
2.16 Measured gain for MTM reconfigurable state A antenna ............ 23
2.17 Measured gain for MTM reconfigurable state B antenna ............ 24
2.18 RF 1127 switch. ................................................. 25
2.19 Top view of prototype MTM based antenna with RF switches. .... 27
2.20 Bottom view of prototype MTM based antenna showing decoupling capacitors and wires to power up the switch. ...................... 27
2.21 Return loss of two reconfigurable states of MTM based antenna after RF switches were incorporated. .......................... 28
2.22 Measured gain for MTM reconfigurable state A antenna after switches were added. ............................................. 29
2.23 Measured gain for MTM reconfigurable state A antenna after switches were added. ............................................. 30
2.24 Current distribution in the antenna structure showing high current density on the parasitic connected to the ground plane .......... 31

3.1 Magnetization in presence of static main field $B_0$. .................. 34
3.2 $B_1$ field applied in x-y plane that tips the magnetic vector away from z-axis. ......................................................... 34
3.3 Dual tuned birdcage coil. ............................................. 36
3.4 Magnetic field (A/m) in transverse plane at Sodium frequency (32.586 MHz). ......................................................... 37
3.5 Magnetic field (A/m) in sagittal plane at Sodium frequency (32.586 MHz). ......................................................... 37
3.6 Magnetic Field (A/m) in transverse plane at Hydrogen frequency (123 MHz). ......................................................... 38
3.7 Magnetic Field (A/m) in sagittal plane at Hydrogen frequency (123 MHz). ......................................................... 38
3.8 Two regions inside the coil. ............................................. 40
3.9 Simulated transverse (x-y) contour plot of magnetic field for birdcage coil at sodium frequency of 32.586 MHz. .................. 42
3.10 Simulated sagittal (x-z) contour plots of magnetic field for birdcage coil at sodium frequency (32.586 MHz)................................. 42
3.11 Magnetic field in transverse plane at sodium frequency showing linear magnetic field around the center of the coil...................... 43
3.12 Simulated 1D plot of magnetic field for birdcage coil at sodium frequency (32.586 MHz)............................................................ 44
3.13 Simulated contour plot of transverse (x-y) magnetic field at hydrogen frequency (123 MHz).................................................. 45
3.14 Simulated contour plots of sagittal (x-z) magnetic field at hydrogen frequency (123 MHz)...................................................... 46
3.15 Magnetic field in sagittal plane at hydrogen frequency (123 MHz)................. 46
3.16 Magnetic field in transverse plane at hydrogen frequency (123 MHz)........ 47
3.17 Comparison of electric and magnetic field......................................................... 47
Chapter 1

Introduction

Simulation is a valuable tool in early product design and development. It provides an opportunity to observe and understand behavior of the system with any changes made in a design. Combined with optimization, it can provide high quality results in a short amount of time. Simulation and optimization improves the performance of the design with user-selected parameters with respect to a final result of interest. Optimization tremendously helps users achieve the desired properties of a design. This thesis provides simulation and optimization of two different designs in the fields of communication and biomedical imaging.

The two designs are a miniaturized, pattern-reconfigurable antenna and a birdcage coil. Although they are completely different in design and are used for different purposes, the process of performing simulation and optimization is the same. Initially, a design is created with the basic structure and reasonable dimensions. The results are checked to see if the designs show any unexpected behavior. Once results are validated, the desired constraints or parameters are fed into the design. With good understanding of system, its properties and parameters, a cost function is formed which is given an additional input to the optimizing algorithm. After several iterations optimizer gives out optimal design dimension and/or shape that produces the optimal results. Once the optimal results are obtained, they are used to create a prototype. In this thesis, a miniature pattern reconfigurable antenna and birdcage coil were successfully designed and optimized to obtain desired results.

The performance of an antenna can be limited due to its inability to adapt to a new electromagnetic environment. A reconfigurable antenna helps overcome this adjustment inability and doesn’t let the performance degrade. The reconfiguration adds functionality to the antennas. Reconfigurability is the capacity to change an individual radiator’s fundamental operating characteristics through electrical, mechanical, or other means [1]. Several
works in [2], [3] and [4] deals with designing a reconfigurable antenna. These researches only provide the reconfigurability but not miniaturization.

The need for miniaturization of an antenna arose from the need to decrease the size of wireless devices. Miniature antenna helps reduce the size of wireless devices significantly. [5] provides design of a frequency reconfigurable miniature antenna but doesn’t provide pattern reconfigurability. The limited work in radiation pattern reconfigurable antenna motivated this project.

Birdcage coils are radio frequency coils that used in magnetic resonance imaging to send and receive RF signals. The desired properties of the birdcage coil are resonance at the desired frequency, good homogeneity, quadrature excitation and high signal to noise ratio. The existing coil is based on design by [6]. This coil was dual tuned at hydrogen and sodium frequency. Most of the coil designs are not done using simulation software. So, it is hard to tell if the design is optimal or not. Without sacrificing a lot of time and cost, simulation can predict if the design is performing at its optimal level. There is limited information regarding the design and optimization of a MRI coil in commercially available simulation software. Thus, this project was started in order to see how accurately we can model and create a coil with optimal dimensions that produces high signal to noise ratio and homogeneity.

1.1 Thesis Contributions

1.1.1 Miniature Radiation Pattern Reconfigurable Antenna

This thesis provides in detail the simulation and optimization of a miniature radiation pattern reconfigurable antenna. With reconfigurable antenna pattern, an antenna can perform well even in an undesired electromagnetic condition. Reconfigurable miniature antenna provides both reduction in size and reconfigurability which is highly desired for wireless devices.

Two different antennas were created using simulation software and optimized using MATLAB. One antenna was Y-shaped and another was modified antenna based on MTM design [7]. Once the optimal results were acquired, prototype antenna was built and antenna patterns were measured. The measured results were compared to the results from modeled
design. The measured results were in good agreement with the modeled results, which satisfied the design goals.

1.1.2 Birdcage Coil

The goal of this project was to study if the simulation software could accurately optimize the coil that provides high SNR and homogeneity compared to existing coil at the desired operating frequency. A birdcage coil was designed using simulation software and optimized using MATLAB. Birdcage coil was designed when optimal results were achieved. A prototype coil was built using optimal dimensions. Compared with old coil, the new coil was larger in diameter, with longer length of sodium portion and shorter length of hydrogen portion. Measurements are currently being done at Stanford University.

1.2 Thesis Outline

This thesis is organized as follows:

Chapter 2, Reconfigurable Antennas, gives a background to basic antenna theory and defines relevant antenna parameters. It describes developments that have been done in miniaturization of antenna and reconfiguration of antenna characteristics. The challenges faced by design engineers are explained in detail. It also provides design details of miniaturized pattern reconfigurable antenna. Modeled and measured results are compared and discussed.

Chapter 3, Birdcage Coil, gives a brief introduction to the background in magnetic resonance imaging. It also describes the different types of the radio frequency coils used in MRI with emphasis on birdcage coil. It gives the model optimization process and describes results obtained from simulation.

Chapter 4, Conclusion, summarizes the important points of this thesis. A short description of possible future work is also listed.
Chapter 2

Reconfigurable Antennas

2.1 Introduction

Antennas are important part of radar, wireless communication systems and anything else that requires exchange of information via electromagnetic waves. An antenna is a transducer that converts an electromagnetic energy in space to alternating current in conductor and vice versa. There are several fundamental types of antennas such as wire antenna such as dipoles and monopoles, aperture antennas such as horn and slot antennas, traveling wave antennas such as spiral and helical antennas, reflector antennas and microstrip antennas.

Reconfigurability can provide increased functionality and improved performance to any type of antenna. Reconfigurable antennas offer the possibility of changing antenna characteristics over time to maintain a high quality wireless communication link as the propagation environment changes. Reconfigurability can be obtained by changing frequency response, radiation pattern, polarization or the impedance bandwidth of an antenna [1]. Fundamentally, the reconfiguration of antenna is achieved through intentional redistribution of currents or equivalently, the electromagnetic fields of the antenna’s effective aperture, resulting in reversible changes in the antenna impedance and/or radiation properties [8].

To illustrate the importance of pattern reconfigurability, let us consider a situation when a cellphone antenna is present in a noisy electromagnetic condition. This will result in less than optimal antenna performance. If the radiation pattern of the antenna can be changed, it could be redirected to the base station resulting in better signal to noise ratio (SNR) performance as well as less transmit power usage resulting in better battery performance. This is only one example of usefulness of radiation pattern reconfigurability. Radiation pattern reconfigurability proves to be useful in various other situations in single antenna and array antenna system. We can manipulate the radiation pattern which enables
avoidance of noise sources, improves beam capability of phased array systems and increases diversity gain [9].

Reconfigurable antennas have been implemented in various ways over past 40 years. Reconfigurable microstrip antennas, in particular, have existed for almost as long as the microstrip antenna itself, dating back to early 1980s. Microstrip geometries are good choices for reconfigurability because their ground plane and planar structures are well defined, which facilitates addition of parasitic elements and its control circuitry. The structure and composition of microstrip antenna can be easily manipulated in various way to obtain desired reconfigurability [2].

Not only reconfigurability but antenna miniaturization also has been an interesting and significant topic in field of antenna design and theory. With decrease in size of communication devices like cell phones, PDAs, laptops etc, the need for small antennas is greater than ever. Not only size of communication devices has decreased but inclusion of multiple antenna is also desired. These days a cellular device not only has the cellular antenna but also antenna for bluetooth, GPS and Wi-Fi. The need to fit all these different antennas in already a small device has lead to increasing miniaturization of antennas. The continuing growth of wireless devices continues to push the size of antenna to be smaller and smaller.

### 2.2 History of Reconfigurable Antennas

Early design techniques to achieve reconfigurability includes the use of circuit elements or alteration of mechanical structure [1]. More recently, antenna designers have used electrically controlled switches like RF MEMS and PIN diodes to achieve reconfiguration [1]. All these various techniques and approaches have contributed significantly in evolution of reconfigurable antenna.

Chiao, et al.[10] used electrically-controlled microactuators in Vee antennas (Fig. 2.0) to change the shape of radiation pattern. The antenna arms were moved in opposite direction to change the angles in order to demonstrate the beam shaping capability. Nikolaou, et al.[11] used annular slot antenna using PIN diodes to create a radiation pattern reconfigurable antenna. Radiation pattern control was achieved by activating and deactivating shorts on the slot.
One of the widely used methods to change radiation pattern is the addition of the parasitic elements. In 1978, a reactively loaded parasitic dipole [12] was proposed by Harrington, which still continues to be utilized in various forms. Reactance was varied in each parasitic element, that changed the magnitude and phase of the signal on the array elements, resulting in beam pattern variation (Fig. 2.1).

2.3 Antenna Parameters

The following parameters are critical in defining the performance of an antenna:

Radiation pattern: Radiation pattern is the angular dependence of the field strength transmitted by an antenna. In most cases it is measured in the far field and is represented by a function of spherical coordinates. The average power density $S_{av}$ is given as follows:
Figure 2.2: A seven-element circular array of reactively loaded parasitic dipoles for reconfigurable beam steering and beam forming (From: Harrington[12], IEEE 1978).

\[ S_{av} = \frac{1}{2} \text{Re}(E \times H^*) \hat{r} \]

\[ = \frac{|E(r)|^2}{2\eta} \hat{r}. \]

If we lump all the angle dependence into a new term \( f(\theta, \phi) \), we can write the average power density as:

\[ S_{av} = f(\theta, \phi) S_{max}. \]

This angular dependency \( f(\theta, \phi) \) is called as radiation pattern of an antenna.

*Pattern correlation coefficient:* The pattern correlation coefficient is a numerical measure of how different the antennas are in terms of radiation pattern characteristics. The correlation coefficient is related to the diversity gain [13] and is closely related to the received signal correlation matrix for a propagation environment with a uniform angular distribution of multi-path arrival angles. With the lower correlation between diversity branches the
higher diversity gain is achieved. The correlation coefficient can be defined by the following equation [14].

\[ \rho_{12} = \frac{\int_{\Omega} E_{1\theta} E_{2\theta}^* d\Omega + \int_{\Omega} E_{1\phi} E_{2\phi}^* d\Omega}{\int_{\Omega} |E_{1\theta}|^2 + |E_{1\phi}|^2 d\Omega \ast \int_{\Omega} |E_{2\theta}|^2 + |E_{2\phi}|^2 d\Omega} \]

where \( \Omega \) is the solid angle \((\theta, \phi)\). \( E_{1\theta} \) and \( E_{2\theta} \) are vertical \((\theta)\) complex radiation patterns of reconfigurable state 1 and 2, respectively. \( E_{1\phi} \) and \( E_{2\phi} \) are horizontal \((\phi)\) complex radiation patterns of reconfigurable state 1 and 2 respectively. If the patterns are orthogonal, then the correlation coefficient is equal to zero, meaning they are completely uncorrelated. If the correlation coefficient is unity, the patterns are completely correlated and doesn’t provide any diversity. The pattern correlation coefficient of 0.5 provides better diversity gain but a coefficient of less than 0.8 can still provide good diversity gain.

**E-plane cut:** Radiation pattern in the plane that contains the electric field vector radiated and the direction of maximum directivity.

**H-plane cut:** Radiation pattern in the plane that contains the magnetic field vector radiated and the direction of maximum directivity.

**Radiation efficiency:** The ratio of the power radiated by the antenna to power supplied to the antenna. Although we would like efficiency to be close to one, ohmic loss and dielectric loss result in efficiency below one. It is expressed as

\[ \eta_{\text{rad}} = \frac{P_{\text{rad}}}{P_{\text{in}}} \]

Efficiency is often quoted in terms of percentage. A high efficiency antenna radiates most of the power and is very desirable. A low efficiency antenna does not radiate well and most power gets lost due to ohmic and dielectric loss.

**Gain Pattern:** Gain Pattern is defined as the ratio of radiated power density, in a given direction, to the radiation power density that would be obtained if power accepted by the antenna were radiating isotropically. The power density radiated by an isotropic antenna is

\[ S_{\text{iso}} = \frac{P_{\text{rad}}}{4\pi r^2} \]
The total radiating power can be calculated as

\[ P_{\text{rad}} = \int S_{\text{av}}(\theta, \phi) dS. \]

In equation form, gain pattern is expressed as

\[ G = \eta_{\text{rad}} \frac{S_{\text{av}}}{P_{\text{rad}}/(4\pi r^2)}. \]

**Radiation Resistance:** The input resistance of an antenna can be divided into radiation resistance \( R_{\text{rad}} \) and loss resistance \( R_{\text{loss}} \). The corresponding radiated power and dissipated power are

\[ P_{\text{rad}} = \frac{1}{2} |I_0|^2 R_{\text{rad}}, \]

\[ P_{\text{loss}} = \frac{1}{2} |I_0|^2 R_{\text{loss}} \]

where \( I_0 \) is the input current exciting the antenna.

In terms of antenna impedances, the antenna efficiency can be written as

\[ \eta_{\text{rad}} = \frac{R_{\text{rad}}}{R_{\text{rad}} + R_{\text{loss}}}. \]

### 2.4 Challenges

One of the biggest challenges any miniature antenna designer faces is to have the antenna perform well even with the size reduction. Reducing size of an antenna is one of the key constraints in miniature antenna design. The product of antenna efficiency and bandwidth is proportional to the volume of the antenna. As the antenna’s size gets smaller, the radiation resistance decreases. With smaller radiation resistance, larger input current is needed to get same amount of radiated power as before. An antenna is made of finite conductive material, so as the current increase, losses increase due to higher ohmic losses. When the loss resistance \( R_{\text{loss}} \) gets larger, the antenna efficiency, \( \eta_{\text{rad}} \) gets smaller which means most of power is lost and antenna does not radiate well.
Table 2.1: Design goals.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>2.4GHz-2.48GHz</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>2.44 GHz</td>
</tr>
<tr>
<td>Radiation Efficiency</td>
<td>70%</td>
</tr>
<tr>
<td>Size</td>
<td>0.8cm x 1.2cm</td>
</tr>
<tr>
<td>Pattern Correlation Coefficient</td>
<td>0.3</td>
</tr>
<tr>
<td>Substrate</td>
<td>FR-4</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>50 Ω</td>
</tr>
</tbody>
</table>

The physical size of antenna is proportional to the bandwidth. With electrically small antennas the bandwidth could get narrower than we desire. Thus, to achieve higher antenna efficiency and wider bandwidth, the size of antenna needs to be large which is not a luxury in miniature antenna design.

In addition to the challenges above, another challenge faced by antenna designers is that the changing one reconfiguration characteristic could alter another characteristics. For example, changing the radiation pattern may also change the frequency response or bandwidth of antenna, which could be undesired for certain applications. Thus, it is critical to consider many factors while designing a miniature reconfigurable antenna.

2.5 Antenna Design

The antenna design was done to meet goals shown in Table 2.0. It was designed to work for industrial, scientific and medical (ISM) radio bands, since this band is most commonly used for Wi-Fi communication. As the size of an antenna dictates the radiation efficiency, size could only be reduced to a limit such that we still achieve good radiation efficiency. As for our case, we wanted to achieve radiation efficiency of 70% while the size is 0.8 cm x 1.2 cm.

The substrate for the antenna was FR-4. FR-4 glass epoxy is the most commonly used material in PCBs. It is known to provide very good electrical isolation and is inexpensive. For our board, the dielectric constant of FR-4 was 4.4.
Since most of the microwave sources have impedance of 50 Ω, the input impedance of antenna was also matched to 50 Ω. This impedance matching minimizes the reflection from the antenna and hence the maximum power is transferred to antenna.

Two different designs were proposed to achieve the desired goals. One design was a Y-shaped antenna and other was a modified design of metamaterial (MTM) structures based on Rayspan MTM Technology™ [7]. The designs were done using finite element method (FEM) based high frequency structure simulator HFSS (ANSYS Inc). HFSS is a standard tool that performs full-wave electromagnetic simulation. The antennas were simultaneously optimized for small size, low return loss, efficiency and high pattern reconfigurability. The parametric optimization available in HFSS optimization package was implemented. This optimization helps to better understand changes in the antenna parameters due to the design variation. It also helps understand the limitation of cost function for further optimization. Using parametric optimization, a range of suitable geometric dimension of antenna was obtained, which gave us results within the range of antenna goals. For optimal results further optimization was required. A genetic algorithm and Quasi-Newton methods were used. The cost functions include the desired s11, radiation efficiency, pattern correlation coefficient and good impedance matching performance. The best design obtained from optimization process was used to build a prototype for purpose of testing antenna characteristics.
2.6 Y-shaped Design

Reconfigurability for a Y-shaped antenna (Fig. 2.2) is achieved by altering the way current flows in the antenna. The current arrangements in the structure of the antenna directly determine the spatial distribution of radiation from the structure [2]. The branches act as radiators with current flowing in either a left branch or a right branch. The switches are placed between feed and branch. For one instance the left switch is turned on while keeping right switch off, this causes current to flow in the left branch. For the second instance right switch is turned on while left is turned off, which causes the current to flow in the right branch.

The design was started with two quarter-wave length (0.25\(\lambda\), \(\lambda\) is 5.67 cm) arms. It is a commonly used length of a monopole that provides good radiation characteristics. Top-load was added to the end of monopole. By adding top loading the length of the monopole is decreased. Electrically small antennas have high quality factor (Q), which means a smaller impedance bandwidth. Top-loading of an antenna can lower its Q and improve the impedance
bandwidth. With an addition of top-load, the size of the monopole was reduced by more than a half.

The antenna optimization factors were: the length and the width of the arms and the top-load. The optimization process showed that a wide variety of results can be obtained. But each result was a compromise between different desired antenna criteria. Thus, the design with lower radiation pattern correlation was given higher preference, followed by radiation efficiency and impedance matching.

Before switches were integrated, a copper bridge was used to act as a switch. After the validation of modeled and measured results, the design was adjusted to fit switches. The model is shown in Fig. 2.3 and built prototype is shown in Fig. 2.4.

2.6.1 Dimensions

Table 2.1 shows the final dimensions of the designed Y antenna. To ensure frequency characteristics remain same between two states, the dimensions of left side and right side structures were symmetric.

2.6.2 Results

The measurements were done for Y-shaped antenna with copper bridges in place of real switches. The modeled and measured S11 in dB are shown in Fig. 2.6. The gain pattern
for both states are shown in Fig. 2.7 and Fig. 2.8. Fig. 2.7(a) and Fig. 2.8(a) show the far-field gain pattern versus space angles. Reconfigurable state A (Fig. 2.7(a)) shows the maximum gain of 1.56 dB at azimuth angles of 60° and 340° with an elevation angle of 50°. In reconfigurable state B (Fig. 2.8(a)) maximum gain moves to 150° in elevation angle.

The reconfigurable antenna B provides better gain at the space angles where reconfigurable antenna A was not able to achieve and vice versa. At the elevation cut for $\phi = 90^\circ$ (Fig. 2.7(b) and Fig. 2.8(b)), it is seen that between two states, the total gain pattern shifts by 20°. Looking at the elevation cut for $\phi = 0^\circ$ (Fig. 2.7(c) and Fig. 2.8(c)), it is seen that between two states, the total gain pattern shifts by 120°. Also, in azimuth cut for $\theta = 90^\circ$, (Fig. 2.7(d) and Fig. 2.8(d)), the total gain pattern shifts by 180°. These large shifts in the patterns between the two antenna reconfigurable states signify that this antenna has good pattern reconfigurability. The more different these patterns are the better pattern reconfigurability.
Table 2.3: Measured design results for Y-antenna.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>2.42 GHz-2.48 GHz</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>2.46 GHz</td>
</tr>
<tr>
<td>Radiation Efficiency</td>
<td>72%</td>
</tr>
<tr>
<td>Pattern Correlation Coef-</td>
<td></td>
</tr>
<tr>
<td>ficient</td>
<td>0.24</td>
</tr>
<tr>
<td>Input Impedance @ 2.46</td>
<td></td>
</tr>
<tr>
<td>GHz</td>
<td>48 Ω</td>
</tr>
</tbody>
</table>

Figure 2.7: Input reflection coefficient of Y-shaped antenna.

we can obtain. The measured pattern correlation coefficient was 0.24 and maximum radiation efficiency was 72%. The results are summarized in Table 2.2.

After successful demonstration of very low pattern correlation while maintaining high radiation efficiency, the next step was incorporation of switches in the antenna and adjustment of the resonance frequency. But the sponsor of this project, Rayspan Inc. wanted to prioritize development of design derived from the MTM based antenna. Thus, the final radiation pattern measurements of tuned Y antennas with switches were not done and MTM based design was initiated.
Figure 2.8: Measured gain for Y-shaped reconfigurable state A antenna. (a) Gain plot for elevation angle vs azimuthal angle. The maximum gain is 1.56 dB whereas average gain is -1.329 dB. (b) Elevation plot vs $\theta$ at x-z plane for $\phi = 90$. (c) Elevation plot vs $\theta$ at y-z plane for $\phi = 0$. (d) Azimuth plot vs $\phi$ at x-y plane for $\theta = 90$.

2.7 MTM Based Design

Reconfigurability in new modified reconfigurable MTM [7] based antenna is achieved through parasitic coupling. The changes in radiation pattern are achieved through changes in the coupling between the elements, which, in turn, change the effective source currents.
Figure 2.9: Measured gain for Y-shaped reconfigurable state B antenna. (a) Gain plot for elevation angle vs azimuthal angle. The maximum gain is 1.864 dB whereas average gain is -1.487 dB. (b) Elevation plot vs $\theta$ at x-z plane for $\phi = 90$. (c) Elevation plot vs $\theta$ at y-z plane for $\phi = 0$. (d) Azimuth plot vs $\phi$ at x-y plane for $\theta = 90$.

on the both driven and parasitic element. The benefit of achieving reconfigurability by parasitic tuning is that the reconfiguration elements are isolated from the radiating element. This results in parasitics having only a small effect on operating frequency and impedance bandwidth.
Table 2.4: Dimension of MTM based antenna.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board Area</td>
<td>60 mm x 43 mm x 28.6 mil</td>
</tr>
<tr>
<td>Parasitic Length</td>
<td>9 mm</td>
</tr>
<tr>
<td>Parasitic Width</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Parasitic Hat Length</td>
<td>5 mm</td>
</tr>
<tr>
<td>Parasitic Hat Width</td>
<td>5 mm</td>
</tr>
<tr>
<td>Total antenna electrical size</td>
<td>$0.19 \lambda \times 0.28 \lambda$</td>
</tr>
</tbody>
</table>

Figure 2.10: Reconfigurable state A Model in HFSS. Left parasitic connected via a thin copper wire.

2.7.1 Dimensions

The dimensions for the MTM-based antenna are summarized in Table 2.3.

As with the Y-antenna, to maintain the impedance bandwidth, the dimensions of the left and right parasitic were identical. For the purpose of simulation a thin copper wire was used to act as a switch. For reconfigurable state A, left parasitic element was connected to the ground plane, leaving the right parasitic disconnected. For reconfigurable state B, the right parasitic element was connected to the ground plane and left parasitic was disconnected.
2.8 Results and Discussion

2.8.1 Antenna with Copper Bridges

Before integrating actual RF switches, prototypes were fabricated with narrow short- ing trace of copper metal for the conducting closed state. The return loss obtained from measurements and simulations for both configurations are shown in Fig. 2.11. The measured resonance frequency was 2.47 GHz. The elevation and azimuthal angles are defined with the antenna axis as vertical. The measured antenna gain was 0.14 dB and 0.3 dB for configuration states A and B, respectively. The antenna efficiency was 50%. The results in Fig. 2.12 and Fig. 2.13 showed significant change in the radiation patterns between the two antenna states. The measured gain plots are show in Fig. 2.15 and Fig. 2.16. Fig. 2.15(a) and Fig. 2.16(a) show the far-field gain pattern versus space angles. Reconfigurable state A (Fig. 2.15(a)) shows the maximum gain of 0.14 dB at azimuth angle 180° with an elevation angle of 60°. In reconfigurable state B (Fig. 2.16(a)) maximum gain moves to 10° in azimuth angle. Looking at the elevation cut of $\phi = 90^\circ$ (Fig. 2.15(b) and Fig. 2.16(b)), it is seen that between two states, the total gain pattern shifts by 120°. This plot also shows that using reconfiguration state B we can get a good signal in the space angles where reconfiguration state A was not able to receive and vice versa. Fig. 2.15(d) and Fig. 2.16(d) show the shift of
Figure 2.12: Comparison between measured and simulated S11 for the two antenna states.

total gain pattern by 180°. These plots show that we have highly different gain patterns for two different antenna states. These differences in pattern suggest this antenna can provide a high pattern reconfiguration. Thus, we can expect very low radiation pattern correlation coefficient. The radiation pattern correlation coefficient measured was 7\text{e}-4. The results are summarized in Table 2.4.

![Image of Return Loss for MTM-Antenna]

Table 2.5: Measured design results for MTM reconfigurable antenna with copper bridges as switches.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>2.42 GHz-2.48 GHz</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>2.46 GHz</td>
</tr>
<tr>
<td>Radiation Efficiency</td>
<td>52%</td>
</tr>
<tr>
<td>Pattern Correlation Coefficient</td>
<td>0.0007</td>
</tr>
<tr>
<td>Input Impedance @ 2.46 GHz</td>
<td>48 , \Omega</td>
</tr>
</tbody>
</table>

2.8.2 Antenna with RF Switches

As the prototypes with copper bridges produced quality results, we implemented actual RF switches (Fig 2.18). Since there are lot of switches in the market we looked for the ones that are matched at 50 ohms, have low insertion loss, are easy to implement and
are small as possible. Low insertion loss is important because we do not want to lose the signal power due to the insertion of the device in the antenna.

Our first choice was a MEMS switch as they are known to have very low insertion loss and high isolation. We purchased MEMS switches from Radant MEMs. There were not a lot of vendors available who would sell MEMS switches in low quantity. We built a simple microstrip line board to check the performance of MEMS switch. The switch was connected to the board using epoxy and was connected to the microstrip line using gold bond wire. But,
Figure 2.15: MTM based reconfigurable antennas showing 2 different states. Antenna footprint is of length, $L_{ant} = 11\text{mm}$ and width, $W_{ant} = 16.24\text{mm}$. Ground plane is of length $L_{gnd} = 30\text{mm}$ and width $W_{gnd} = 60\text{mm}$ (a) Reconfigurable state A where switch 1 is open and switch 2 is closed. (b) Reconfigurable state B where switch 1 is closed and switch 2 is open.

we were unable to see any switching from MEMS switch. The on and off state didn’t change with supply voltage. These switches are highly static sensitive with ESD sensitivity of 100 and there were issues with wire bonder not bonding the wire to the board properly. This could have caused the problem with the switching. After unsuccessful multiple attempts to get MEMS switch to work, FET switches were tried because they are not as sensitive as MEMS and do not require high supply voltage.

We were able to see change in on and off states with the FET switches; which then were implemented in our prototype antennas. The greatest advantage of using FET switches is they are controlled by low voltage source of less than 3V and can be operated by batteries. Comparison Table 2.5 describes properties of the switches that were tried.
2.8.3 RF Switch

After trying different switches, RF1127 provided switching with low insertion loss and lower voltage. It is single pole double throw switch that works from low frequency to 3.5 GHz. The single pole single throw is better type to choose but we could not find a single
Figure 2.17: Measured gain for MTM reconfigurable state B antenna. (a) Gain plot for elevation angle vs azimuthal angle. The maximum gain is 0.14 dB whereas average gain is -2.835 dB. (b) Elevation plot vs $\theta$ at y-z plane for $\phi = 90$. (c) Elevation plot vs $\theta$ at x-z plane for $\phi = 0$. (d) Azimuth plot vs $\phi$ at x-y plane for $\theta = 90$.

pole single throw switch of reasonable size for our design. The control logic for this switch is shown in Table 2.6.

To obtain logic level of 1, control signal (V1) should be 1.8V-3.6V and for logic 0, V1 should be 0V-0.2V. In case of indeterminate states, both signal paths are ON with degraded
Table 2.6: Properties of different switch types.

<table>
<thead>
<tr>
<th></th>
<th>Radant (RMSW100)</th>
<th>RFMD (RF1127)</th>
<th>RFMD (RF1128)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>SPSR</td>
<td>SPDT</td>
<td>SPDT</td>
</tr>
<tr>
<td>Technology</td>
<td>MEMS</td>
<td>GaAs pHEMT</td>
<td>GaAs pHEMT</td>
</tr>
<tr>
<td>Control Voltage</td>
<td>+/- 100V</td>
<td>0/+1.8V</td>
<td>0/+2.85 V</td>
</tr>
<tr>
<td>(on/off)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Package(mm)</td>
<td>1.42x1.37x0.65</td>
<td>2x1.3x0.4 6pin</td>
<td>2x1.3x0.4 6pin</td>
</tr>
<tr>
<td>QFN</td>
<td></td>
<td>QFN</td>
<td>QFN</td>
</tr>
<tr>
<td>Insertion Loss @</td>
<td>0.16 dB</td>
<td>0.4 dB</td>
<td>0.45 dB</td>
</tr>
<tr>
<td>2.4 GHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Required External</td>
<td>Resistors or</td>
<td>Capacitors</td>
<td>Capacitors</td>
</tr>
<tr>
<td>Components</td>
<td>Inductors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESD</td>
<td>100V</td>
<td>250V</td>
<td>150 V</td>
</tr>
</tbody>
</table>

Table 2.7: Control logic of switch RF1127.

<table>
<thead>
<tr>
<th>Logic State</th>
<th>RF1-RFC</th>
<th>RF2-RFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td>0</td>
<td>OFF</td>
<td>ON</td>
</tr>
</tbody>
</table>

performance. To accommodate for addition of switches extra pads were created in the HFSS design. These switches needed decoupling capacitors, so capacitors were also modeled in simulation software. The capacitance of a decoupling capacitor was 100pF.

![Figure 2.18: RF 1127 switch.](image-url)
The top view of switch is shown in Table 2.7. For the purpose of open circuit, either RF port1 or RF port2 was left open depending on which arm we want to be disconnected. RFC pad was connected to the parasitic lines. The power supply voltage (VDD) was 3V.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF1</td>
<td>RF Port1</td>
</tr>
<tr>
<td>GND</td>
<td>Ground</td>
</tr>
<tr>
<td>RF2</td>
<td>RF Port2</td>
</tr>
<tr>
<td>VDD</td>
<td>Power Supply</td>
</tr>
<tr>
<td>RFC</td>
<td>Antenna</td>
</tr>
<tr>
<td>V1</td>
<td>Control Line</td>
</tr>
</tbody>
</table>

Table 2.8: Switch pin description.

After the switches and capacitors were added to the prototype MTM based antenna radiation pattern and return loss measurements were taken. The return loss plot is shown in Fig. 2.20 and gain patterns are shown in Fig. 2.21 and Fig. 2.22. Fig. 2.21(a) and Fig. 2.22(a) show the far-field gain pattern versus space angles. The plots do not show significant change in the gain pattern. The maximum gain in reconfigurable state A is 3.0 dB at azimuth angle of 280° and elevation angle of 150°. The gain in reconfigurable state B is 2.22 dB at azimuth angle of 320° and elevation angle of 150°. The elevation pattern cuts for φ = 90° (Fig. 2.21(c) and Fig. 2.21(b)) show minimal change in radiation pattern. The azimuth pattern cuts for θ = 90° (Fig. 2.21(d) and Fig. 2.22(d)) also are very much the same. These plots show that this antenna does not have very high pattern reconfigurability. Due to the lack of differences in pattern, we can predict the pattern correlation coefficient to be in higher side. As expected, the correlation coefficient was 0.8. The maximum radiation efficiency was 48%. The bandwidth was 600 MHz with center frequency of 2.4 GHz. The results are summarized in Table 2.8.
Figure 2.19: Top view of prototype MTM based antenna with RF switches.

Figure 2.20: Bottom view of prototype MTM based antenna showing decoupling capacitors and wires to power up the switch.
Table 2.9: Measured design results for MTM reconfigurable antenna with RF switches.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>2.38 GHz-2.44 GHz</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Radiation Efficiency</td>
<td>38%</td>
</tr>
<tr>
<td>Pattern Correlation Coefficient</td>
<td>0.8</td>
</tr>
<tr>
<td>Input Impedance @ 2.4 GHz</td>
<td>50 Ω</td>
</tr>
</tbody>
</table>

Figure 2.21: Return loss of two reconfigurable states of MTM based antenna after RF switches were incorporated.

2.9 Design Challenges Encountered

The impedance bandwidth of the fabricated MTM-based antenna was not very wide. Going back to simulation and changing the distance between radiator and parasitic element, it was observed that the bandwidth of the antenna was increasing with increase in distance. To understand more on this issue, we looked at the current distribution on the antenna Fig. 2.23. Looking at the current distribution, it can be seen that current distribution in parasitics are high, which led to higher mutual coupling between radiating element and parasitics. This must have caused significant perturbation on the radiator. So, to improve the bandwidth neither the structure nor dimension of parasitics needs to be changed but the
Figure 2.22: Measured gain for MTM reconfigurable state A antenna after switches were added. (a) Gain plot for elevation angle vs azimuthal angle. The maximum gain is 3.0 dB whereas average gain is -4.61 dB. (b) Elevation plot vs $\theta$ at y-z plane for $\phi=90$. (c) Elevation plot vs $\theta$ at x-z plane for $\phi=0$. (d) Azimuth plot vs $\phi$ at x-y plane for $\theta=90$.

distance needs to be wider. When the distance between the radiating element and radiating element was increased, the bandwidth was getting wider but the pattern correlation was not as good as we would like. Since our requirement was bandwidth from 2.4 – 2.48 GHz and bandwidth of designed antenna was already 2.4 – 2.46 GHz, we decided not to spend more time on trying to widen the bandwidth. Our primary goal was to produce a pattern
reconfigurable miniature antenna and since bandwidth was in close range of the design goal, preference was given to design with smaller footprint which gives a lower pattern correlation coefficient.

Antennas with incorporated FET switch showed decrease in the radiation efficiency and pattern correlation coefficient. Since the switch is lossy and not as conducting as a
Figure 2.24: Current distribution in the antenna structure showing high current density on the parasitic connected to the ground plane.

copper bridge, it makes sense than the radiation efficiency decreases. If provided with less lossy switch, the radiation efficiency wouldn’t have taken a hit. Also to power up the switch, there were wires connected to the antenna. Those hanging wires could have perturbed the radiation pattern during the measurements resulting in higher pattern correlation coefficient.

2.10 Summary

A reconfigurable miniature antenna was designed and built. The results were comparable to the desired design goals. The main goal of this project was to understand the possibility of reconfigurable miniature single antenna system with good radiation efficiency. The two different antenna were designed to fulfill the design goals.

For each design two different antennas were created, one with copper bridge acting as a switch and an actual FET switch. The best results obtained from optimization was
used to create prototypes. The radiation pattern measurements were done and pattern reconfigurability was calculated.

The results from prototype antenna with copper bridges were in good agreement with the simulation and were close to the design goals. But, with addition of actual switches, the results did not come out as expected. To accommodate for the switches, multiple discrete decoupling capacitor were added and to power up the switches, wires were also attached to the antenna. The addition of power supply wires, discrete capacitors and lossy switches degraded the performance of the antenna. The performance of antenna could have been improved if the switches did not require discrete capacitors and the power supply to the switch was isolated from the antenna. If better capacitors are not available, a better capacitor and solder models should be created in simulation and results should be reanalyzed.

Despite these issues, this project showed that a good performing antenna with pattern reconfigurability can be built in a given small space.
Chapter 3

Radio Frequency Coil for Magnetic Resonance Imaging

3.1 Introduction

Magnetic resonance imaging (MRI) is an imaging process which is used to produce detailed images of the inside of human body as well as a non biological object. It is widely used for detection of tumors, diagnosing joint or bone problems and imaging of internal organs. It is a powerful noninvasive imaging modality that has been growing rapidly for last decade. MRI is popular than X-rays or computed tomography as MRI does not introduce any ionizing radiation effects on human subject. Although MRI radiates RF, if human exposure to RF can be reduced, it could be the safest imaging modality.

The nature of magnetic resonance is based on interaction of the atomic magnetic moments with the magnetic fields. Atoms with an odd number of protons or neutrons possess a small magnetic moment. The interacting magnetic fields are main magnetic field $B_0$, radio frequency field $B_1$ and gradient field $G$. In absence of an external magnetic field, the nuclear spin angular momentum is oriented randomly with resultant magnetic moment being zero. Once an external field $B_0$ is applied (along the z-axis) the magnetic moments align in z-axis and a net magnetic moment is created along z-axis. The spin also exhibit resonance at their Larmor frequency. The Larmor frequency can be defined in terms of magnetic field as

$$\omega = \gamma B_0$$

where $\gamma$ is gyromagnetic ratio, which varies for different nuclei.

The RF magnetic field $B_1$ is applied perpendicular to $B_0$ field. This field forces the net magnetization vector towards x-y plane and applies a torque that causes the magnetization vector to rotate in the prescribed angle around the static magnetic field (Fig. 3.1). The angle...
is dependent on the strength and the applied duration of $B_1$. The frequency at which this rotation occurs is called as Larmor frequency.

Once the tipped magnetic vector reaches the x-y plane, the $B_1$ field is cut off, allowing magnetization to relax back to the z-axis. During this process RF energy is released. The
frequency of this RF signal is same as the precession frequency. The time constant that
describes the return of magnetization vector along the z-axis is $T_1$ and the time constant
describing the decay of magnetization vector in x-y plane is $T_2$.

The principle components of MRI are strong magnet, transmitting and receiving RF
coil and image processing software. Out of these components, RF coils will be discussed in
detail.

### 3.2 Radio Frequency Coil

The purpose of RF coils is to produce RF pulses at the Larmor frequency to excite
the nuclei of the the body part being imaged and to pick up the signal emitted by excited
nuclei at the same frequency. The coils that are used to transmit are called transmit coils
and ones that are used to receive are called receive coils. Some coils can act both as a
transmit and receive. The primary considerations while designing coils are: 1) it should be
able to produce high signal to noise ratio (SNR) and 2) have a field homogeneity around the
imaging area.

Various types of RF coils have been developed since MRI became a prominent imaging
technique. These can be categorized into volume coil or surface coil. Coils like birdcage coils,
Helmholtz, saddle etc are some of the examples of volume coil and loop coils fall into surface
coil category. The volume coils are known to produce better homogeneity and surface coils
are know for higher SNR. If the RF coils do not produce the homogeneous magnetic field
across region of interest, the flip angles, which tips the atoms of the object being imaged,
will vary with the position and create a image-shading artifact. Thus, homogeneity is a big
factor in creating good quality images.

Surface coils are placed closer to the imaging subject so higher signal is received. As
these coils don’t have bigger field of view (FOV) they pick up less noise resulting in higher
SNR. They are usually used as a receivers. References [15] and [16] describe the methods to
improve SNR in surface coils

Volume coils are usually used for purpose of both transmit and receive. The volume
coils have a broad field of view with high magnetic field homogeneity. Since the imaging
area is large, the coil picks up considerably higher noise, resulting in poor SNR.
3.3 Birdcage Coil

The birdcage coils are popular choice in MRI as they have high magnetic field homogeneity with acceptable SNR. The first birdcage coil was designed and fabricated by Hayes [17]. Hayes, et. al designed high pass and low pass birdcage coil. Birdcage coil consists of two circular end rings connected by $N$ equally spaced segments. Each segment included a distributed capacitor. A high-pass coil has capacitors on the end ring segments, while a low-pass coil has capacitors placed on the the legs and a band-pass coil has capacitors at the both legs and end ring segments.

The sodium imaging has been used in the assessment of cartilage health [18], detection of abnormal sodium levels in the kidneys [19] and assessment of tissue damage following stroke [20]. The dual tuned birdcage coil is of particular interest because of its capability to acquire images at both hydrogen and sodium frequencies without the need to move patient to change the coils.

The optimization was performed on the birdcage coil designed by [6]. This birdcage coil was a four ring coil that employs low pass structure for the middle sodium portion and the high pass for pair of half birdcages for the outer hydrogen portion. This structure is less lossy over traditional coils that employ frequency block traps. The optimized cage had the same structure as [6] but with new dimensions.
Figure 3.4: Magnetic field (A/m) in transverse plane at Sodium frequency (32.586 MHz).

Figure 3.5: Magnetic field (A/m) in sagittal plane at Sodium frequency (32.586 MHz).
Figure 3.6: Magnetic Field (A/m) in transverse plane at Hydrogen frequency (123 MHz).

Figure 3.7: Magnetic Field (A/m) in sagittal plane at Hydrogen frequency (123 MHz).
3.4 Benchmark Model

As a preliminary check to see if the coil designed will produce the results as expected, we modeled an existing dual tuned birdcage coil (Fig. 3.2). The existing coil consists of 16 rungs which are 0.5 inch wide copper strips. The inner coil lengths of both sodium and hydrogen were 2.65 inches. The inner radius of the coil was 3.65 inch. The capacitors for the sodium were 80pF and hydrogen were 40pF. There were three variable caps in the sodium coil as well as hydrogen for the purpose of tuning. Matching capacitor of 200pF was used.

The simulated results produced the magnetic field that as expected. Fig. 3.3 and Fig. 3.4 show magnetic field in transverse and sagittal plane of this coil at frequency of 32.586 MHz. The fields distribution is not homogeneous at the center of the coil. The magnetic strength varies from 2 A/m to 8 A/m at the ROI. This shows that there is room for improvement in the linearity of the magnetic field. Fig. 3.5 and Fig. 3.6 show magnetic field in transverse and sagittal plane at frequency 32.586 MHz. In case of hydrogen as well, there is high variation in the magnetic field at the center of the coil.

3.5 Optimization

The goal of this optimization was to obtain higher SNR and better field homogeneity for both sodium and hydrogen. Measure of homogeneity was computed using the root mean square deviation (RMSD).

\[
\text{RMSD} = \sqrt{\frac{\sum_{n} (H_n - H_{av})^2}{N}}
\]

where, \(H_n\) is the magnetic field at the \(n^{th}\) location, \(H_{av}\) is the average magnetic field in region of interest and \(N\) is the total number of \(n\) locations. The lower RMSD denotes lesser difference between the magnetic field at each point in coil and the average magnetic field, which ultimately results in better homogeneity. We used following equation as a figure of merit for optimization of SNR

\[
S = \frac{|E[E(r_1)_{\text{Sig}}]|^2}{|E[E(r_2)_{\text{Noise}}]|^2}
\]

where, \(E(r_1)_{\text{Sig}}\) is a field inside the region of interest and \(E(r_2)_{\text{Noise}}\) is a field outside the region of interest. The regions \(r_1\) and \(r_2\) are shown in Fig. 3.7. We used electric fields in the figure of merit as it is very common in antenna systems to work with electric fields.
Figure 3.8: Two regions defined inside the coil.

The region of interest (ROI) is the area where we want to maximize SNR and homogeneity. The ROI for our design was a cylinder of diameter 16 cm and length 12 cm.

The parameters used in optimization process were width of copper tape, the lengths of both sodium and hydrogen coil and the diameter of the coil. The small changes in copper tape width did not have big influence in the cost function result. So, standard sized copper tape of 0.5 inch was used. The cost function included homogeneity and S of both sodium and hydrogen. Higher preference was given to the homogeneity and S of the sodium followed by the homogeneity and S of the hydrogen. Since optimetrics available in HFSS does not provide a way of optimizing fields, we had to use MATLAB to perform the optimization. Magnetic fields and electric fields were extracted from HFSS and imported to the MATLAB. MATLAB would then compute RMSD and S. If they were not optimal, MATLAB called a script that would start a HFSS simulation with updated coil dimension. This process was repeated until optimal result was achieved. A genetic algorithm was used for this optimization.
3.6 Results

Optimal RMSD achieved for sodium and hydrogen were 1.58 and 3.2 respectively. This was significant improvement over existing coil with RMSD 7.9 for sodium and 5.3 for hydrogen. The optimal S obtained for sodium and hydrogen were 2.1 and 1.6 respectively. The existing coil had S of 1.6 and 1.2. These numbers tell us that this coil performs much better than the existing coil. The optimal dimension of the coil is given in Table 3.0

<table>
<thead>
<tr>
<th>Table 3.1: Dimensions of the coil.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
</tr>
<tr>
<td>Sodium Inner length</td>
</tr>
<tr>
<td>Hydrogen Inner length</td>
</tr>
</tbody>
</table>

The simulation results for sodium frequency obtained from modeled birdcage are shown in Fig. 3.8 and Fig. 3.9. The magnetic field is seen to be homogeneous in the center of the coil with in the ROI. The simulated 1D plot of normalized magnetic field (Fig. 3.11) helps look into the homogeneity clearly. We can see the the linear homogeneous region extends from -5 cm to 5 cm in both X and Y axes. Since, the field near a conductor is stronger, we can see the magnetic field at the ends to be higher. Fig. 3.11(c) shows the hump in the middle with decreased field at the ends. This is due to the standing wave created in the rungs. The contour magnetic fields for hydrogen frequency is shown in Fig. 3.12 and Fig. 3.13. These plots show good homogeneity at the center of coil at hydrogen frequency. The image plots Fig. 3.14 and Fig. 3.15 show the magnetic field distribution in the coil. It is seen that in sagittal plane the field is linear along the center of coil and in transverse plane the field is also linear in the ROI. As expected the magnetic fields are higher at the ends and decrease as we move towards the center.

The optimal dimensions were used to built a prototype coil. The experimental studies with the coil to determine the performance are underway in collaboration with Stanford.
Figure 3.9: Simulated transverse (x-y) contour plot of magnetic field for birdcage coil at sodium frequency of 32.586 MHz.

Figure 3.10: Simulated sagittal (x-z) contour plots of magnetic field for birdcage coil at sodium frequency of 32.586 MHz.
3.7 Summary

A dual tuned birdcage coil was optimized and built, with experimental result underway. The simulation results showed better homogeneity and SNR compared to existing coil. It is possible that a disagreement exists between results from modeled and measured coil. If that happens there may be several reasons for the discrepancies. The cost function included electric fields, so the next thing to try would be use of magnetic fields instead. Looking at Fig.3.16, we can see that electric field is very low at the coil center compared to the ends. The magnetic field at the center of the coil doesn’t drop as low as the electric field. Thus, one can expect different results with the use of magnetic field in calculating figure of merit. Also, a better cost function may be developed.

Studies have shown that at low frequencies most of the coil resistance comes from conductor resistance and lumped components. In our experience, modeling software had issues with accurately predicting the behavior of capacitors. Since there are multiple capacitors present in the design, the effect could have been magnified and hence disagreement between modeled data and measurements. The errors may also be due to the inaccurate model or the excitation source that was used to excite the coil. The modeled coil was simulated devoid of any external noise sources, so adding some external noise in model could help predict the results better. In future, the designs should be tried in different simulation software and

Figure 3.11: Magnetic field in transverse plane at sodium frequency showing linear magnetic field around the center of the coil.
Figure 3.12: Simulated 1D plot of normalized magnetic field for birdcage coil at sodium frequency of 32.586 MHz. (a) Normalized B field along the transverse line (Y=0, Z=0). (b) Normalized B field along the transverse line (X=0, Z=0). (c) Normalized B field along the sagittal line (X=0, Y=0).

Results should be compared to that of HFSS. This would help depict the accuracy of model designed in HFSS. It might be useful to add coaxial cables on the design and see if any significant change occurs.
Figure 3.13: Simulated contour plot of transverse (x-y) magnetic field magnetic field at hydrogen frequency of 123 MHz.
Figure 3.14: Simulated contour plots of sagittal (x-z) magnetic field at hydrogen frequency of 123 MHz.

Figure 3.15: Magnetic field in sagittal plane at hydrogen frequency (123 MHz).
Figure 3.16: Magnetic field in transverse plane at hydrogen frequency (123 MHz).

Figure 3.17: Comparison of electric and magnetic field.
Chapter 4

Conclusion

This thesis has described the design and optimization of a miniature radiation pattern reconfigurable antenna and a dual tuned birdcage coil to achieve desired results. The pattern reconfigurable antenna was built and tested using the optimal dimension. The experimental results for the birdcage coil are underway. The dimensions and results for reconfigurable antenna and birdcage coil are described in Chapters 2 and 3 respectively.

Y-shaped and MTM based antennas were created and analyzed. In both structures, the initial design was created using short copper bridge instead of actual switches. Both of those designs performed well and were in close agreement with the model. When actual switches were implemented instead of short copper bridges the results were still good but not as good as the design goals. The addition of lossy switches, lossy capacitors and wires are described as most likely culprits. Still, we showed that a miniature reconfigurable antenna is possible and with better switches and less lossy capacitors, best results can be achieved.

A birdcage coil based on design [6] was created in simulation software and optimized. MRI coils perform well when it provides homogeneity and high SNR at operating frequency. This coil was optimized to perform well for resonant frequencies of sodium (32.586 MHz) and hydrogen (132 MHz). The optimal length and diameter was used to build a prototype coil. The prototype coil is now being tested in collaboration with Stanford University.

4.1 Future Work

The next step for the miniature pattern reconfigurable antenna would be to integrate the nano switches. Nano switches are smaller in size and do not have high insertion loss. These switches do not require decoupling capacitors; and could significantly improve the performance of the antenna. This antenna can also be integrated to form a phased ar-
ray. Phased array enhances signal strength, decreases the interference and ultimately better coverage.

In the case of the birdcage coil, experimental results need to be compared with modeled results. If they are in good agreement, we can try changing the shape of the coil from cylinder to flared ends. If there are disagreements a better model needs to be created. Model should try to add external noises to make sure that the modeled coil will experience same environment as the coil under test. A different simulation software should be utilized to check the validity of the results of the current simulation software. A software that can accurately model at low frequencies should be chosen. These implements definitely should help debug the discrepancies between modeled and measured data.
Bibliography


