Full-Wave Analyses of Nano-Electromechanical Systems Integrated Multifunctional Reconfigurable Antennas

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FULL-WAVE ANALYSES OF NANO-ELECTROMECHANICAL SYSTEMS
INTEGRATED MULTIFUNCTIONAL RECONFIGURABLE ANTENNAS

by

Xiaoyan Yuan

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Electrical Engineering

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Logan, Utah

2009
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Abstract

Full-Wave Analyses of Nano-Electromechanical Systems Integrated Multifunctional Reconfigurable Antennas

by

Xiaoyan Yuan, Master of Science
Utah State University, 2009

Major Professor: Dr. Bedri A. Cetiner
Department: Electrical and Computer Engineering

This thesis work builds upon the theoretical studies and full-wave analysis of radio frequency micro- and nano-electromechanical systems (RF M/NEMS) integrated multifunctional reconfigurable antennas (MRAs). This is a part of the overall M/NEMS research efforts performed in the RF μNcMS Laboratory at USU, which includes design, microfabrication, test, and characterization of M/NEMS integrated cognitive wireless communication systems (fig. A.1).

The thesis work focuses on two MRAs. 1) A triple bands patch antenna which can operate at 800, 2400, and 4900 MHz in response to public safety wireless communication systems. 2) A multi-frequency multi-polarization MRA for wireless personal area networking applications (WPAN) operating at 57-64 GHz frequency range.

(48 pages)
To my father Houqiang, my mother Suli, my grandfather Kun, and my friend Xing;
  I can’t do it without your love...
Acknowledgments

My upmost gratitude goes to my major advisor, Dr. Bedri A. Cetiner, for allowing me to join his group, for his expertise, kindness, and support and guidance throughout the project. I believe that one of the main gains of this program was working with Dr. Cetiner and gaining his trust and friendship. My thanks and appreciation go to my committee members, Dr. Jacob Gunther and Dr. Huifang Dou. I owe a lot to my friends and colleagues, Yasin Damgaci and others in our research team. Our conversations and work together have greatly helped me on the research work.

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Xiaoyan Yuan
Contents

Page

Abstract ........................................................................................................ iii
Acknowledgments ...................................................................................... v
List of Tables .............................................................................................. viii
List of Figures ............................................................................................ ix
Acronyms .................................................................................................. xi

1 Introduction .............................................................................................. 1

2 Triple Bands MRA Patch ........................................................................ 3
  2.1 Introduction ....................................................................................... 3
  2.2 Reconfigurable Antenna Design ....................................................... 3
    2.2.1 Basic Characteristics .................................................................. 3
    2.2.2 Feeding Method–Microstrip Line Feed ...................................... 5
    2.2.3 Shorting Plane ........................................................................... 7
  2.3 Operation ............................................................................................. 8
  2.4 Simulation Results and Conclusions ................................................... 9

3 Multi-Frequency Multi-Polarization MRA ............................................... 14
  3.1 Introduction and Background ............................................................ 14
  3.2 Reconfigurable Antenna Design ....................................................... 15
    3.2.1 Basic Characteristics .................................................................. 15
    3.2.2 Dual-Frequency Slits .................................................................. 15
    3.2.3 Dual-Polarization Truncated Corners ........................................ 17
    3.2.4 Feeding Methods-Coaxial Feed/Probe Coupling ....................... 17
  3.3 Operation ............................................................................................. 18
  3.4 Simulation Results and Conclusions ................................................... 19

4 Conclusions and Future Work .................................................................. 28

References .................................................................................................. 29

Appendices .................................................................................................. 32
  Appendix A Overall Research Flow at RF μNeMS Lab ........................... 33
  Appendix B List of Fundamental Parameters of Antennas .................... 34
    B.1 Permittivity .................................................................................... 34
    B.2 Impedance ..................................................................................... 34
    B.3 Full-Wave Analysis ....................................................................... 35
    B.4 Reflection Coefficient($S_{11}$) .................................................... 35
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>9</td>
</tr>
<tr>
<td>3.1</td>
<td>19</td>
</tr>
</tbody>
</table>

2.1 Operation mechanism of frequency reconfigurable antenna.

3.1 Reconfigurable modes of operation of the MRA truncated patch.
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Frequency reconfigurable MRA patch.</td>
<td>4</td>
</tr>
<tr>
<td>2.2</td>
<td>Single segment structure of frequency MRA.</td>
<td>6</td>
</tr>
<tr>
<td>2.3</td>
<td>Schematic DC-contact double-arm cantilever type M/NEMS switch with dimen-</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>sions: cantilever width=15µm, cantilever length=50µm, $t_{metal}=2µm$,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$t_{cantilever}=0.4-1µm$, $t_{biaselectrode}=0.2µm$, $t_{biasline}=0.2µm$,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$t_{dielectric}=0.2µm$.</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>Reflection coefficient of MRA patch at 800 MHz.</td>
<td>10</td>
</tr>
<tr>
<td>2.5</td>
<td>Reflection coefficient of MRA patch at 2400 MHz.</td>
<td>11</td>
</tr>
<tr>
<td>2.6</td>
<td>Reflection coefficient of MRA patch at 4900 MHz.</td>
<td>11</td>
</tr>
<tr>
<td>2.7</td>
<td>Radiation pattern of total gain of MRA patch at 800 MHz.</td>
<td>12</td>
</tr>
<tr>
<td>2.8</td>
<td>Radiation pattern of total gain of MRA patch at 2400 MHz.</td>
<td>12</td>
</tr>
<tr>
<td>2.9</td>
<td>Radiation pattern of total gain of MRA patch at 4900 MHz.</td>
<td>13</td>
</tr>
<tr>
<td>3.1</td>
<td>Multi-frequency multi-polarization MRA patch.</td>
<td>16</td>
</tr>
<tr>
<td>3.2</td>
<td>Single-feed square patch antenna with posts for obtaining different polariza-</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>tions.</td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>Reflection coefficient of MRA on 57 GHz with LP.</td>
<td>20</td>
</tr>
<tr>
<td>3.4</td>
<td>Reflection coefficient for MRA on 57 GHz with CP.</td>
<td>20</td>
</tr>
<tr>
<td>3.5</td>
<td>Reflection coefficient for MRA on 64 GHz with LP.</td>
<td>21</td>
</tr>
<tr>
<td>3.6</td>
<td>Reflection coefficient for MRA on 64 GHz with CP.</td>
<td>21</td>
</tr>
<tr>
<td>3.7</td>
<td>Radiation pattern of total gain of MRA on 57 GHz with LP.</td>
<td>22</td>
</tr>
<tr>
<td>3.8</td>
<td>Radiation pattern of total gain of MRA on 57 GHz with CP.</td>
<td>22</td>
</tr>
<tr>
<td>3.9</td>
<td>Radiation pattern of total gain of MRA on 64 GHz with LP.</td>
<td>23</td>
</tr>
<tr>
<td>3.10</td>
<td>Radiation pattern of total gain for MRA on 64 GHz with CP.</td>
<td>23</td>
</tr>
</tbody>
</table>
**Acronyms**

- RF: radio frequency
- RA: reconfigurable antenna
- MRA: multi-functional reconfigurable antenna
- MIMO: multi input multi output
- MEMS: micro-electromechanical systems
- NEMS: nano-electromechanical systems
- BW: bandwidth
- WPAN: wireless personal area network
- WLAN: wireless local area network
- BCB: benzocyclobutene polymer
- LP: linear polarization
- CP: circular polarization
- CPW: coplanar wave guide
- RL: return loss
- AR: axial ratio
Chapter 1

Introduction

The multi-functional reconfigurable antenna (MRA) concept [1, 2] has gained significant interest as a result of two main factors. First, a single MRA can perform multiple functions by dynamically changing its properties (operating frequency, polarization, and radiation pattern). This can result in a significant reduction in the overall size of multi-mode multi-band wireless communication systems and replace multiple single-function legacy antennas. Second, the reconfigurable antenna properties of a MRA can be used as important additional degrees of freedom in an adaptive system (first proposed in the paper of multi-functional reconfigurable MEMS integrated antennas for adaptive MIMO systems) [3, 4]. In particular it was shown that a MRA equipped adaptive multiple-input multiple-output (MIMO) wireless communication system can provide gains up to 30 dB as compared to conventional fixed antenna MIMO systems [4]. These additional gains result from the joint optimization of dynamically reconfigurable antenna properties with adaptive space-time modulation techniques [5] in response to the changes in the propagation environment.

In order to dynamically change the properties of a MRA, the current distribution over the volume of the antenna needs to be changed, where each distribution corresponds to a different mode of operation. To this end, one can change the geometry and feed line of the antenna by switching on and off various geometrical segments that make up the MRA and the feed circuitry. Micro/nano-electromechanical systems (M/NEMS) integrated multifunction reconfigurable antenna (MRA) concept enables an antenna to dynamically change its properties, thereby introducing important additional degrees of freedom in adaptive system parameters as is evident from recent research and development results [4, 6, 7].

For successful implementation of MRAs, there are a couple of issues that need to be addressed. These issues are mainly related to on-wafer hermetic packaging and low-loss
compact DC bias circuitry for MRAs which does not compromise the performances of an MRA [8]. In a typical MRA design, such as MRA patch which is studied in this thesis research, EM interactions within the antenna architecture occur in two fashions. The first one is the EM mutual coupling that takes place between active and passive (disconnected) parts of the MRA [9]. As is well known when a parasitic element is placed in close proximity to an active element, a current is induced in the parasitic element by mutual coupling that in return changes the input impedance and radiation characteristics of the antenna. Second interaction occurs between monolithically integrated RF M/NEMS and antenna segments [10–12]. Strong understanding on the combination of these two interaction mechanisms will allow us to design MRAs with optimum dimensions and architectures resulting in enhancement in the performance of the MRA, i.e., higher gain and increased operational bandwidth [13–15].

To this end, full wave electromagnetic analysis tools based on the finite element method (Ansoft HFSS) and method of moment (ADS momentum) are used to carry out EM simulations. The designs of MRAs using M/NEMS switches as building blocks including the bias circuitry will be performed through these simulations. The results from the simulations will be used to optimize the position and amount of the switches for optimal performances, i.e., gain and S-parameters.
Chapter 2

Triple Bands MRA Patch

2.1 Introduction

Modern and future wireless communications systems are placing greater demands on antenna designs. Many systems now operate in two or more frequency bands, requiring dual- or triple-band operation of fundamentally narrowband antennas [13, 14]. These include cellular systems, satellite navigation systems, and many other communications and sensing applications, in which it is highly desirable to have a single antenna that could be automatically reconfigured to satisfy the frequency band and gain requirements.

Multifrequency modes sometimes are implemented by stacked patches [16], arrays [17], or a single patch but complex structures or slow-speed operations [18]. A novel multi-band patch antenna (MRA patch) with simple structure and fast-speed operation is presented in this thesis work, of which operation frequency can be tuned over 800MHz, 2.4GHz, and 4.9GHz in response to public safety communications applications [19]. Frequency reconfiguration is achieved through Micro/nano-electromechanical systems (M/NEMS) switches [20], which are monolithically integrated within the antenna architecture. These are a new type of DC-contact double-arm cantilever type M/NEMS switches. The switches exhibit excellent RF performances with typical actuation voltages of 6 volts and switching speed of 50 nano-second.

2.2 Reconfigurable Antenna Design

2.2.1 Basic Characteristics

A frequency reconfigurable antenna is designed on RT/duroid substrate with a relative permittivity of 2.2 and the thickness of 1.57 mm, as shown in fig. 2.1. The MRA patch
consists of three radiating segments, which are connected to each other through strategically locating M/NEMS switches. Each segment is excited by activating and deactivating the proper switches, thereby three different modes of operation is achieved. The concept of permittivity is explained in Appendix B.1.

In the design procedure, each segment could follow the outline of practical designs of rectangular microstrip antenna. And then, combine three design into one MRA. Single segment structure is shown in fig. 2.2. The procedure assumes that the specified information includes the dielectric constant of the substrate ($\epsilon_r$), the resonant frequency ($f_r$), and the thickness of the substrate $h$. The procedure is as follows [21]:

Specify: $\epsilon_r, f_r$ (in Hz), and $h$

Determine: $W, L$
Design procedure:

1. For an efficient radiator, a practical width that leads to good radiation efficiency is

\[ W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}} \sqrt{\frac{2}{\epsilon_r + 1}}, \quad (2.1) \]

where \( \mu_0 \) is the free-space magnetic permeability, \( \epsilon_0 \) is the free-space dielectric constant.

2. Determine the effective dielectric constant of the microstrip antenna using

\[ \epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[ 1 + 12\frac{h}{W} \right]^{-\frac{1}{2}}. \quad (2.2) \]

3. Once \( W \) is found using (2.1), determine the extension of the length \( \Delta L \) using

\[ \frac{\Delta L}{h} = 0.412 \frac{(\epsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\epsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)}. \quad (2.3) \]

4. The actual length of the patch can now be determined by

\[ L = \frac{1}{2f_r\sqrt{\epsilon_{reff}\sqrt{\mu_0\epsilon_0}}} - 2\Delta L. \quad (2.4) \]

2.2.2 Feeding Method–Microstrip Line Feed

After selecting the patch dimensions \( L \) and \( W \) for a given substrate, the next task is to determine the feed point so as to obtain a good impedance match between the generator and the antenna. There are many configurations that can be used to feed rectangular microstrip antennas. The four most popular are the microstrip line, coaxial probe, aperture coupling, and proximity coupling [21].

The MRA patch here is fed by a microstrip line, which is also a conducting strip, usually of much smaller width compared to the patch for \( Z_c=50 \) ohms. Single segment structure is shown in fig. 2.2. It is observed that the change in feed location gives rise to a change in the input impedance, and hence provides a simple method for impedance matching [22].
The procedure to calculate the position of the inset feed point is as follows [21].

Specify: $W, L, \varepsilon_r, f_r$ (in Hz), and $h$

Determine: $y_0$, the inset feed point distance

Calculation procedure:

1. 

$$\lambda_0 = \frac{c}{f_r} \quad (2.5)$$

2. 

$$G_1 = \frac{1}{120} \frac{W}{\lambda_0} \quad (2.6)$$

3. 

$$G_{12} = \frac{1}{120\pi^2} \int_0^\pi \left[ \sin\left(\frac{k_0W}{2 \cos \theta} \right) \right]^2 J_0(k_0L\sin \theta) \sin^3 \theta d\theta, \quad (2.7)$$

where $J_0$ is the Bessel function of the first kind of order zero and $k_0$ is the wave number in free space,

$$k_0 = \frac{2\pi}{\lambda_0}. \quad (2.8)$$
4. The input impedance at the leading radiating edge of the patch $R_{\text{in}}$,

$$R_{\text{in}} = \frac{1}{2(G_1 - G_{12})}.$$  \hfill (2.9)

5. $R_{\text{in}(y=y_0)} = R_{\text{in}(y=0)}\cos^2\left(\frac{\pi}{L}y_0\right)$ \hfill (2.10)

While the desired impedance is $R_{\text{in}(y=y_0)}=50$ ohms, the inset feed point distance $y_0$ could be obtained. The impedance of antenna is explained in Appendix B.2.

In addition, as the impedance of feed point is 50 ohms, the width of the feed line could be determined by

$$Z_c = \frac{120\pi}{\sqrt{\epsilon_{\text{reff}}} \left[\frac{W_0}{h} + 1.393 + 0.667\ln\left(\frac{W_0}{h} + 1.444\right)\right]}.$$ \hfill (2.11)

When the antenna is matched to generator, the input impedance does not depend on the length of the feed line.

The microstrip-line feed is easy to fabricate, simple to match by controlling the inset position and rather simple to model. It is very clear in formula (2.10) that different feed points are accompanied with different effective length. Therefore, three different inset feed length are required for three bands (800, 2400, and 4900MHz) in MRA.

### 2.2.3 Shorting Plane

While patch width has a minor effect on the resonant frequency and radiation pattern of the antenna, actually it affects the input resistance and bandwidth to a larger extent, patch length determines the resonant frequency, and is a critical parameter in design because of the inherent narrow bandwidth of the patch. To a zeroth-order approximation, the patch
length $L$ for $TM_{10}$ mode is given by [22]

$$L = \frac{c}{2f_r\sqrt{\varepsilon_r}}. \quad (2.12)$$

The MRA consists of three radiating segments, which behaves like an inset-fed microstrip antenna. Due to a large separation between the lowest, $f_l = 800$ MHz, and highest, $f_h = 4.9$ GHz, operation frequencies, the electrical lengths are also largely separated, i.e., by a factor of 6. Therefore, in order to achieve a compact design, the MRA segment that operates at 800 MHz operation is realized by using a shorting plane, which reduces a rectangular patch to half by placing a short circuit at the zero electric field line [22]. The introduction of shorts does not load the antenna because they are being placed at the zero electric field position. The field disturbances produced by a short are very complex in nature and cannot be described simply as a perturbation effect. However, the effect by applying a shorting plane at the edge of patch is remarkable and gives rise to the maximum reduction in the size of the antenna.

2.3 Operation

The most challenging part of this design is to maintain the required input impedance for each mode of operation. To overcome this problem, M/NEMS switches indicated as group S3 and group S4 in fig. 2.1 are strategically located on both sides of the inset microstrip feed line, which has 50 Ohm characteristic impedance. These switches enable to change the penetration length of the inset microstrip; thereby required input impedance is maintained for each mode of operation. Basically, the MRA patch has a reconfigurable matching network.

The operation mechanism is shown in Table 2.1. S1, S2, S3, and S4 represent groups of switches that are either closed (down-state) or (up-state) in response to the desired reconfigurable mode of operation. For example, in the case of Mode 1, the MRA patch operates at 800 MHz frequency band, which requires switches of group S4 to be open for proper impedance matching, while all other switches belonging to groups S1, S2, and S3
Table 2.1: Operation mechanism of frequency reconfigurable antenna.

<table>
<thead>
<tr>
<th>Switch Group Status</th>
<th>Reconfigurable Mode of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1, S2 down-state</td>
<td>Mode 1: $f_l=800$ MHz</td>
</tr>
<tr>
<td>S3, S4 up-state</td>
<td></td>
</tr>
<tr>
<td>S2, S3 down-state</td>
<td>Mode 2: $f_m=2400$ MHz</td>
</tr>
<tr>
<td>S1, S4 up-state</td>
<td></td>
</tr>
<tr>
<td>S3, S4 down-state</td>
<td>Mode 3: $f_h=4900$ MHz</td>
</tr>
<tr>
<td>S1, S2 up-state</td>
<td></td>
</tr>
</tbody>
</table>

are brought to down-state. The status of the M/NEMS switches for the other modes of operation is shown in Table 2.1.

2.4 Simulation Results and Conclusions

The full-wave analyses of the MRA patch monolithically integrated with M/NEMS switches have been performed by Ansoft HFSS v.11 [23]. The concept of full-wave analyses is explained in Appendix B.3. The models for all the simulation are with real-switch geometry and biaslines which control the actions of the switch. A schematic of a M/NEMS switch including high DC resistance bias line, which is used in this MRA patch design, as shown in fig. 2.3.

The simulated reflection coefficient corresponding to three reconfigurable modes of operation are shown in figs. 2.4, 2.5, and 2.6. For 800 MHz, the bandwidth (BW) is 0.4%; for 2.4 GHz, the BW is 0.8%; for 4.9 GHz, the BW is 1%. The concept of reflection coefficient is explained in Appendix B.4.

The radiation patterns of the MRA patch for the total gain in the $X-Z$ plane, i.e., $\phi=0$ plane, for each frequency bands are shown in figs. 2.7, 2.8, and 2.9. The MRA patch exhibit similar gain patterns for each mode of operation with maximum gain values at around 6 dB. The concept of gain pattern is explained in Appendix B.5. In summary, MRA patch has very similar gain and well-behaved radiation patterns at all frequency bands, which is a required antenna property for public safety multi-mode multi-band mobile wireless communication applications.
Fig. 2.3: Schematic DC-contact double-arm cantilever type M/NEMS switch with dimensions: cantilever width=15µm, cantilever length=50µm, $t_{metal}=2\mu m$, $t_{cantilever}=0.4-1\mu m$, $t_{biaselectrode}=0.2\mu m$, $t_{biasline}=0.2\mu m$, $t_{dielectric}=0.2\mu m$.

Fig. 2.4: Reflection coefficient of MRA patch at 800 MHz.
Fig. 2.5: Reflection coefficient of MRA patch at 2400 MHz.

Fig. 2.6: Reflection coefficient of MRA patch at 4900 MHz.
Fig. 2.7: Radiation pattern of total gain of MRA patch at 800 MHz.

Fig. 2.8: Radiation pattern of total gain of MRA patch at 2400 MHz.
Fig. 2.9: Radiation pattern of total gain of MRA patch at 4900 MHz.
Chapter 3
Multi-Frequency Multi-Polarization MRA

3.1 Introduction and Background

A wireless personal area network (WPAN) system, i.e., IEEE 802.15 [24], is designed to provide short-range (<10m), very-high-speed (>2Gb/s) multi-media data services to computer terminals and consumer appliances located in rooms, office space, and kiosks. These WPANs will provide higher data rates, but shorter range, than comparable wireless local area networks (WLANs) [25] such as the popular 802.11a/b/g Wi Fi systems. Presently available unlicensed frequency band for USA and Canada is 57.05-64.0 GHz.

IEEE 802.15 standard relates to broadband antennas, and more specifically, to broadband antennas of compact size [26] which are capable of receiving or transmitting multi-polarized electromagnetic radiation. Antennas were often required to receive or transmit electromagnetic radiation over wide band while maintaining uniform radiation pattern and impedance characteristics within the operating band. However, the polarization of the received EM signal is unknown and a conventional log periodic or spiral antenna may not respond to the sense of polarization being transmitted [21]. The problem of responding to transmitted signals over a broad band for any sense of polarization (i.e., linear, circular, or elliptical) could be solved by MRAs [27,28].

One of the implementations could be in the form of two or more patches placed side-by-side or stacked on top of each other [17], or simultaneous excitation of natural modes of the antenna. But for most applications, it is desirable to have one input port and an arbitrary separation of the frequency bands, which impose severe constraints on the use of natural modes. Here, loading the slits achieve dual frequency operation by modifying the natural modes [29].

A multi-frequency multi-polarization MRA patch antenna for WPAN with slits and
truncated corners on benzocyclobutene (BCB) polymer substrate is presented [30]. BCB was chosen due to its high performance RF characteristics and compatibility with microfabrication processes. This MRA is capable of providing dual frequency (57 GHz and 64 GHz) and dual polarization operation (linear and circular polarizations) with such a simple structure, which is also achieved through micro/nano-electromechanical systems (M/NEMS) switches [20] strategically located in each slit gap.

3.2 Reconfigurable Antenna Design

3.2.1 Basic Characteristics

The multi-frequency and multi-polarization MRA is designed on a benzocyclobutene (BCB) polymer with a relative permittivity of 2.6 and the thickness of 0.1 mm. As shown in fig. 3.1, MRA patch is fed by a coaxial probe and consists of four inserted slits and a pair of truncated corners. While multi-frequency operation is achieved by changing the length of the slits, the polarization is changed from linear to circular by introducing a pair of truncated corners.

The procedure for designing the MRA patch given in Chapter 2 could also be followed to determine the effective length and width of the patch for the parameters of $\epsilon_r=2.6$, resonant frequency $f_r=57$ GHz, and the thickness of substrate $h=0.1$ mm. As patch width has a minor effect on the resonant frequency and radiation pattern of the antenna, it affects the input resistance and bandwidth to a larger extent. The patch length determines the resonant frequency. In this design, a square patch is used where $L=W$ after the effective length is determined.

3.2.2 Dual-Frequency Slits

Due to the inserted slits, the electrical length of the patch traveled by the fundamental-mode patch surface current increases, which in turn lowers the resonant frequency, thereby enabling smaller patch size [22]. Simultaneous activation and deactivation of four double-arm M/NEMS switches [20] strategically located into each slit gap enables changing the
Fig. 3.1: Multi-frequency multi-polarization MRA patch.
length of the slits, thereby providing two different slit lengths corresponding to 64 GHz and 57 GHz band operations, respectively.

### 3.2.3 Dual-Polarization Truncated Corners

In general, the polarization characteristics of an antenna can be represented by its polarization pattern whose one definition is the spatial distribution of the polarizations of a field vector excited (radiated) by an antenna taken over its radiation sphere [21]. When describing the polarizations over the radiation sphere, we could get two orthogonal components ($E_\theta$ and $E_\phi$) of each point on the radiation sphere with orthogonal decomposition on the electric-field vector. When the time-phase difference between $E_\theta$ and $E_\phi$ is $n\pi$, which means one is accompanied with the other, it is linear polarization (LP). When the magnitudes of $E_\theta$ and $E_\phi$ are the same and the time-phase difference between them is odd multiples of $\pi/2$, it is circular polarization (CP).

As we could see clearly, another case is more common, in which time-phase difference between two components is odd multiples of $\pi/2$ and their magnitudes are not the same or the time-phase difference between the two components is not equal to multiples of $\pi/2$. We define it as elliptical polarization.

Microstrip patch antenna, which consists of a single patch, could simultaneously support two orthogonal modes in phase quadrature [22]. But it is usually designed for single-mode operation that radiates mainly linear polarization. For a circular polarized radiation, a patch must support orthogonal fields of equal amplitude but in-phase quadrature. The MRA here with a single-point feed generally radiates linear polarization, however, circular polarization could still be accomplished by slightly perturbing the patch at appropriate locations with respect to the feed location. Thus, two truncated corners are implemented as proper perturbation segments to achieve the required phase difference.

### 3.2.4 Feeding Methods-Coaxial Feed/Probe Coupling

Coupling of power through a probe is also one of the basic mechanisms for the transfer of microwave power. For coaxial feeds, the inner conductor of the coaxial probe is attached
to the radiation patch while the outer conductor is connected to the ground plane. The coaxial probe feed is also easy to match and fabricate. The impedance of the coaxial probe is determined by the relative permittivity $\epsilon_r$ of the substrate and the radius of the inner and outer conductor as [31]

$$Z = \frac{60}{\sqrt{\epsilon_r}} \ln \left( \frac{b}{a} \right), \quad (3.1)$$

where $a$ is the radius of inner conductor and $b$ is the radius of outer conductor. As 50 ohms characteristic impedance is desired, the radius of inner and outer conductor could be fixed reversely. Actually, the ratio of the radius of inner and outer conductor ($\frac{b}{a}$) is important and the absolute values of two radius can be chosen properly with the patch size.

Special feed locations for common perturbation are provided in fig. 3.2 [22]. The distance $d$ between the feed location and the center of the patch is determined following the same steps as microstrip line feed formulas [21].

### 3.3 Operation

The operation mechanism of this MRA is shown in Table 3.1. $S_1, S_2$ represent group of switches which are either closed (down-state) or opened (up-state) in response to the desired
Table 3.1: Reconfigurable modes of operation of the MRA truncated patch.

<table>
<thead>
<tr>
<th>Switch Status</th>
<th>Frequency</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 up-state, S2 down-state</td>
<td>57 GHz</td>
<td>LP</td>
</tr>
<tr>
<td>S1 up-state, S2 up-state</td>
<td>57 GHz</td>
<td>CP</td>
</tr>
<tr>
<td>S1 down-state, S2 down-state</td>
<td>64 GHz</td>
<td>LP</td>
</tr>
<tr>
<td>S1 down-state, S2 up-state</td>
<td>64 GHz</td>
<td>CP</td>
</tr>
</tbody>
</table>

reconfigurable mode of operation as shown in fig. 3.1. For example, when the MRA operates at 57 GHz with linear polarization, the switches of group $S_1$ are opened for frequency shift, while $S_2$ are closed for changing polarization pattern.

3.4 Simulation Results and Conclusions

The full-wave analyses of this multi-frequency multi-polarization MRA integrated with M/NEMS switches have been performed by Ansoft HFSS v.11 [23]. The concept of full-wave analyses is explained in Appendix B.3. The simulated reflection coefficient corresponding to four modes of operation are shown in figs. 3.3, 3.4, 3.5, and 3.6. For 57 GHz in LP, BW is 1.4%; for 57 GHz in CP, BW is 2.3%; for 64 GHz in LP, BW is 1.9%; for 64 GHz in CP, BW is 1.4%. The concept of reflection coefficient is explained in Appendix B.4.

The gain pattern are shown in figs. 3.7, 3.8, 3.9, and 3.10. The concept of gain pattern is explained in Appendix B.5. They also exhibit similar gain patterns for each mode of operation with maximum gain values at around 7 dB. Besides, the polarization pattern could be recognized from axial ratio data combined with comparison shapes of $E_\theta$ and $E_\phi$ ($E_\theta$ and $E_\phi$ are the two orthogonal components of a electric vector), which are shown in figs. 3.11, 3.12, 3.13, 3.14, and figs. 3.15, 3.16, 3.17, 3.18. The concept of axial ratio is explained in Appendix B.6.
Fig. 3.3: Reflection coefficient of MRA on 57 GHz with LP.

Fig. 3.4: Reflection coefficient for MRA on 57 GHz with CP.
Fig. 3.5: Reflection coefficient for MRA on 64 GHz with LP.

Fig. 3.6: Reflection coefficient for MRA on 64 GHz with CP.
Fig. 3.7: Radiation pattern of total gain of MRA on 57 GHz with LP.

Fig. 3.8: Radiation pattern of total gain of MRA on 57 GHz with CP.
Fig. 3.9: Radiation pattern of total gain of MRA on 64 GHz with LP.

Fig. 3.10: Radiation pattern of total gain for MRA on 64 GHz with CP.
Fig. 3.11: Axial ratio of MRA on 57 GHz with LP.

Fig. 3.12: Axial ratio of MRA on 57 GHz with CP.
Fig. 3.13: Axial ratio of MRA on 64 GHz with LP.

Fig. 3.14: Axial ratio of MRA on 64 GHz with CP.
Fig. 3.15: The maximum rE-field in the $\theta$ and $\phi$ direction of MRA on 57 GHz with LP.

<table>
<thead>
<tr>
<th>Name</th>
<th>Theta</th>
<th>Ang</th>
<th>Mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>m1</td>
<td>90.00</td>
<td>-0.00</td>
<td>1.276</td>
</tr>
<tr>
<td>m2</td>
<td>90.00</td>
<td>-0.00</td>
<td>0.986</td>
</tr>
</tbody>
</table>

Fig. 3.16: The maximum rE-field in the $\theta$ and $\phi$ direction of MRA on 57 GHz with CP.
Fig. 3.17: The maximum rE-field in the $\theta$ and $\phi$ direction of MRA on 64 GHz with LP.

Fig. 3.18: The maximum rE-field in the $\theta$ and $\phi$ direction of MRA on 64 GHz with CP.
Chapter 4
Conclusions and Future Work

The design and full-wave analyses of two MRAs have been presented. One can be tuned to operate at 800 MHz, 2.4GHz, and 4.9 GHz frequencies in response to public safety communities’ mobile wireless communications applications. The other one is capable of providing dual frequencies 57 GHz and 64 GHz for WPAN and dual polarization operation LP and CP. Both MRA patch exhibits good gain and well-behaved radiation patterns at each band.

The design and microfabrication of a new type of reduced size MEMS switches, which are called NEMS switches, are in progress. Currently, I am integrating NEMS-type switches into the architecture of MRA patch for fabrication and test/characterization.
References


Appendices
Appendix A

Overall Research Flow at RF $\mu_N\epsilon$MS Lab

Fig. A.1: Over research flow at RF $\mu_N\epsilon$MS lab.
Appendix B

List of Fundamental Parameters of Antennas

B.1 Permittivity

Permittivity is a property of a medium or a region of space, which is given in units of Farads/meter; since Farads relates to capacitance, a material with a higher permittivity can be thought of as storing more electrical energy. For example, RT/duroid and BCB are used as dielectric medium in thesis design. The permittivity describes how an electric field is affected within a medium. The total E-field in medium is always less than in a vacuum. This effect is quantized in terms of the permittivity. In antenna, the permittivity affects the speed of propagation of a wave through a medium and also its wavelength, which is defined as relative permittivity [22]:

\[ \epsilon_r = \frac{\epsilon}{\epsilon_0}, \]

(B.1)

and wavelength:

\[ \lambda = \frac{\lambda_0}{\sqrt{\epsilon_r}}. \]

(B.2)

B.2 Impedance

Impedance of antenna relates the voltage to the current at the input to the antenna, which is a real number. The voltage is in-phase with the current. The real part of an antenna’s impedance represents power that is either radiated away or absorbed within the antenna. The imaginary part of the impedance represents power that is stored in the near field of the antenna (non-radiated power). An antenna with a real input impedance (zero imaginary part) is said to be resonant. Note that an antenna’s impedance will vary with frequency.
B.3 Full-Wave Analysis

There are many methods of analysis for microstrip antennas. The most popular models are the transmission − line, cavity, and fullwave. In general when applied properly, the full-wave models are the best one. Some of the features of the full-wave techniques include these [22]:

1. **Accuracy.** Full-wave techniques generally provide the most accurate solution for the impedance and radiation characteristics.
2. **Completeness.** Full-wave solutions are complete for the most part; that is, they include the effects of dielectric loss, conductor loss, space wave radiation, surface waves, and external coupling.
3. **Versatility.** Full-wave techniques can be used for arbitrarily shaped microstrip elements and various types of feeding techniques.
4. **Computation cost.** Full-wave techniques are numerically intensive, and therefore require careful programming to reduce computation cost.

B.4 Reflection Coefficient \((S_{11})\)

S-parameters describe the input-output relationship between ports (or terminals) in an electrical system. For instance, if we have two ports (intelligently called Port 1 and Port 2), then \(S_{12}\) represents the power transferred from Port 1 to Port 2. \(S_{21}\) represents the power transferred from Port 2 to Port 1.

In practice, the most commonly quoted parameter in regards to antennas is \(S_{11}\). \(S_{11}\) represents how much power is reflected from the antenna. If \(S_{11}=0\) dB, then all the power is reflected from the antenna and nothing is radiated. If \(S_{11}=-10\) dB, this implies that if 3 dB of power is delivered to the antenna, -7 dB is the reflected power. The rest was accepted by the antenna. This accepted power is either radiated or absorbed as losses within an antenna. Since antennas are typically designed to be low loss, the majority of the power delivered to the antenna is radiated.
B.5 Antenna Efficiency and Gain Pattern

[t] The efficiency of an antenna relates the power delivered to the antenna and the power radiated or dissipated within the antenna. A high-efficiency antenna has most of the power present at the antenna’s input radiated away. A low-efficiency antenna has most of the power absorbed as losses within the antenna.

The losses associated within an antenna are typically the conduction losses (due to finite conductivity of the antenna) and dielectric losses (due to conduction within a dielectric which may be present within an antenna).

The efficiency can be written as the ratio of the radiated power to the input power of the antenna:

\[ e = \frac{P_{\text{radiated}}}{P_{\text{input}}} \]  \hspace{1cm} (B.3)

The term Gain describes how much power is transmitted in the direction of peak radiation to that of an isotropic source. Gain is more commonly quoted in a real antenna’s specification sheet because it takes into account the actual losses that occur. A gain of 3 dB means that the power received far from the antenna will be 3 dB (twice as much) higher than what would be received from a lossless isotropic antenna with the same input power.

An antenna radiation pattern or antenna pattern is defined as a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates. In most cases, the radiation pattern is determined in the far-field region and is represented as a function of the directional coordinates.

B.6 Axial Ratio

The ratio of the magnitudes of two orthogonal components, \( E_\theta \) and \( E_\phi \), of electric-field vector is defined as the Axial Ratio (AR).

\[ AR = \frac{|E_\theta|}{|E_\phi|} \]  \hspace{1cm} (B.4)
1. $AR=0$ or $\infty$ (either $E_\theta$ or $E_\phi$ is zero), the field is linear polarization.

2. $AR=1$, the field is circular polarization.

Otherwise, the elliptical polarization.

As above, *Axial Ratio* is often quoted for antennas in which the desired polarization is circular. The ideal value for CP is 0 dB. For a real case, $AR<3$ dB could indicates CP.