NONLINEAR CHARACTERISATION OF RECONFIGURABLE ANTENNAS

BY

SHAHARIL MOHD SHAH

A thesis submitted to
the University of Birmingham
for the degree of
DOCTOR OF PHILOSOPHY

School of Electronic, Electrical and Systems Engineering
College of Engineering and Physical Sciences
University of Birmingham
March 2016
ABSTRACT

The lack of references on nonlinearity issue faced in reconfigurable antennas has motivated the work described in this thesis. The nonlinear behaviour is caused by active switches introduced on the radiating structure of the reconfigurable antennas. Depending on the type of active switches deployed on the antenna, the nonlinearity could be severe, which could have serious implications for antenna operation. Thus, the issue of nonlinearity in reconfigurable antennas should not be ignored and nonlinearity measurements should be performed to ensure the nonlinear performance is within an acceptable level. A set of nonlinearity measurements has been identified and performed on the proposed reconfigurable PIFAs. Prototypes are presented with PIN diode and E-PHEMT switches. For the purpose of comparison, measurements were also made with the active switch replaced with a copper bridge for linear interconnection. The nonlinearity performance can be evaluated from the measurement values of third-order intermodulation distortion (IMD3) products, ratio of IMD3 products to carrier, IMD3 products asymmetry, third-order input intercept point (IIP3) and 1-dB gain compression point (P1-dB). The measurements are performed when the antenna is transmitting signals. All measurements are performed on the state-of-the-art, 4-port ZVA67 Rohde & Schwarz VNA. Based on the nonlinearity measurements, it can be concluded that the presence of active switches has compromised the nonlinearity of the reconfigurable antennas. This is evident from the appearance of strong IMD3 products at the frequency of interest. In addition, the power-series-based approximation of 10 dB difference between the measured P1-dB and IIP3 is shown to be reasonable. Moreover, this work has demonstrated that the ratio of the IMD3 products to carrier does not vary significantly with radiation angles.
ACKNOWLEDGMENTS

I would like to express my immense and sincerest gratitude to my supervisor; Professor Peter Gardner for without his continuous support and careful guidance, this thesis would not have been possible. His vast knowledge has enabled me to develop a thorough understanding on the subject matter. His kindness and motivation, on the other hand, have helped me to overcome multiple obstacles and low periods during the whole research process until completion.

I also wish to thank my laboratory technician; Mr. Alan Yates for sharing his technical skills and knowledge. It was hard initially, but as time goes by, I have managed to pick up the required skills necessary to fabricate my own devices. The whole experience has taught me to have patience and keep moving forward.

I am indebted to my many colleagues who have supported me through thick and thin over the years. Their presence has made the whole journey to be more exciting and memorable.

I owe my deepest appreciation to my parents and siblings for their continuous love and care. A special thank you reaches out to my mother for all the late night calls and her strong encouragement words.

I also acknowledge the provision of Modelithics™ models utilised under the University License Program from Modelithics, Inc., Tampa, FL, USA.

Last but not least, to my sponsor and employee; Ministry of Education (MOE) Malaysia and Universiti Tun Hussein Onn Malaysia (UTHM), I am truly grateful for the funding and financial assistance.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xxi</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xxiii</td>
</tr>
<tr>
<td>PUBLICATIONS IN PREPARATION</td>
<td>xxv</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Background</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Aim</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Problem Statement</td>
<td>3</td>
</tr>
<tr>
<td>1.4 Objectives</td>
<td>5</td>
</tr>
<tr>
<td>1.5 Scope</td>
<td>5</td>
</tr>
<tr>
<td>1.6 Contribution to Knowledge</td>
<td>7</td>
</tr>
<tr>
<td>1.7 Thesis Outline</td>
<td>8</td>
</tr>
<tr>
<td>2. BACKGROUND AND LITERATURE REVIEW</td>
<td>10</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>10</td>
</tr>
<tr>
<td>2.2 Software Defined Radio (SDR) Architecture</td>
<td>11</td>
</tr>
<tr>
<td>2.3 Fixed Multiband Antenna</td>
<td>13</td>
</tr>
<tr>
<td>2.4 Reconfigurable Antenna</td>
<td>14</td>
</tr>
<tr>
<td>2.5 Reconfigurable Performance Metrics</td>
<td>17</td>
</tr>
<tr>
<td>2.5.1 Frequency Reconfigurable</td>
<td>17</td>
</tr>
<tr>
<td>2.5.2 Radiation Pattern Reconfigurable</td>
<td>19</td>
</tr>
<tr>
<td>2.5.3 Polarization Reconfigurable</td>
<td>19</td>
</tr>
<tr>
<td>2.6 Reconfiguration Mechanisms</td>
<td>21</td>
</tr>
<tr>
<td>2.7 Reconfiguration Technologies</td>
<td>21</td>
</tr>
</tbody>
</table>
2.7.1 Electromechanical Devices................................................................. 22
  2.7.1.1 Packaged RF MEMS and NEMS............................................... 23
  2.7.1.2 In Situ Fabricated RF MEMS and NEMS................................. 23
  2.7.1.3 Structurally Reconfigurable Electromechanical Systems ......... 24
  2.7.2 Ferroic Materials........................................................................ 24
  2.7.3 Solid State Devices...................................................................... 25
  2.7.4 Fluidic Reconfiguration............................................................... 27
2.8 Switching Speed .............................................................................. 27
2.9 Comparative Analysis of Switches based on PIN Diodes and FETs ... 28
  2.9.1 System-on-Chip Integrability...................................................... 28
  2.9.2 Control Current.......................................................................... 29
  2.9.3 Operating Frequency .................................................................. 29
  2.9.4 Switching Speed ....................................................................... 29
  2.9.5 Nonlinear Distortions .................................................................. 30
2.10 Antennas for Multi-radio Wireless Platforms............................... 30
  2.10.1 Patch Antennas ........................................................................ 30
  2.10.2 Wire Antennas ......................................................................... 33
  2.10.3 Planar Inverted F Antennas (PIFAs).......................................... 33
2.11 Antenna for Smartphones.................................................................. 35
2.12 Third-Order Intermodulation Distortion (IMD) Products.............. 36
  2.12.1 Model of Intermodulation Distortion (IMD) Products................. 38
  2.12.2 Measuring Linearity of Reconfigurable Antennas ..................... 43
2.13 Previous Work on Nonlinearity Performance Measurements ......... 46
2.14 Conclusion....................................................................................... 60
3. RECONFIGURABLE PIFA WITH BAR50-02V PIN DIODE ............... 61
  3.1 Introduction...................................................................................... 61
    3.1.1 Fundamentals of PIN Diodes.................................................... 61
  3.2 Preliminary Investigation................................................................... 64
3.2.1 Preliminary Study - Antenna Design with Copper Bridge ........................................ 64
  3.2.1.1 Reflection Coefficient ................................................................. 66
  3.2.1.2 Current Distribution ................................................................. 68
  3.2.1.3 Radiation Pattern .......................................................................... 70
  3.2.1.4 Realized Gain, Directivity and Efficiency ........................................ 72
3.2.2 Antenna Design with Only the Main Radiating Plane ........................................ 73
  3.2.2.1 Reflection Coefficient ................................................................. 73
  3.2.2.2 Current Distribution ................................................................. 75
  3.2.2.3 Radiation Pattern .......................................................................... 76
  3.2.2.4 Realized Gain, Directivity and Efficiency ........................................ 77
3.3 Reconfigurable PIFA with BAR50-02V PIN Diode ............................................... 78
  3.3.1 Antenna Geometry and Dimensions ...................................................... 81
  3.3.2 Reflection Coefficient ......................................................................... 84
  3.3.3 Current Distribution ............................................................................ 87
  3.3.4 Radiation Pattern ................................................................................. 88
  3.3.5 Realized Gain, Directivity and Efficiency ............................................. 90
3.4 Antenna Fabrication and Measurement ................................................................ 94
  3.4.1 Reflection Coefficient Measurement .................................................... 97
3.5 Active Switch Performance and Antenna Analysis ............................................. 98
  3.5.1 Further Investigation on the Appearance of the New Resonant Frequency .... 100
3.6 Reconfigurable PIFA with BAR50-02V PIN Diode (Gap, \textbf{G}_1 = 5 \text{ mm}) .......... 106
  3.6.1 Reflection Coefficient ......................................................................... 107
  3.6.2 Current Distribution ............................................................................ 109
  3.6.3 Radiation Pattern ................................................................................. 110
  3.6.4 Realized Gain, Directivity and Efficiency ............................................. 112
3.7 Antenna Fabrication and Measurement ................................................................ 116
  3.7.1 Reflection Coefficient Measurement .................................................... 117
3.8 Active Switch Performance and Antenna Analysis ............................................. 118
3.9 Conclusion ......................................................................................................................... 120

4. RECONFIGURABLE PIFA WITH ATF 54143 E-PHEMT SWITCH ...................... 121
4.1 Introduction ....................................................................................................................... 121
        4.1.1 Characteristics of Switching Transistors ......................................................... 122
4.2 Low Noise Pseudomorphic Enhancement Mode High-Electron Mobility Transistor (E-PHEMT) by Avago Technologies ......................................................... 124
4.3 Antenna Geometry and Dimensions ................................................................................. 131
4.4 Antenna Design and Configuration .................................................................................. 131
        4.4.1 Reflection Coefficient ....................................................................................... 132
        4.4.2 Current Distribution .......................................................................................... 134
        4.4.3 Radiation Pattern ............................................................................................... 135
        4.4.4 Realized Gain, Directivity and Efficiency ......................................................... 137
4.5 Antenna Fabrication and Measurement .......................................................................... 141
        4.5.1 Reflection Coefficient Measurement ................................................................ 143
4.6 Conclusion ....................................................................................................................... 146

5. PIFA WITH COPPER BRIDGE AS REFERENCE ANTENNA ............................ 147
5.1 Introduction ....................................................................................................................... 147
5.2 PIFA with 2 × 1 mm$^2$ Copper Bridge ........................................................................ 148
        5.2.1 Antenna Geometry and Dimensions ................................................................ 148
        5.2.2 Reflection Coefficient ....................................................................................... 148
        5.2.3 Current Distribution .......................................................................................... 150
        5.2.4 Radiation Pattern ............................................................................................... 150
        5.2.5 Realized Gain, Directivity and Efficiency ......................................................... 151
        5.2.6 Antenna Fabrication and Measurement .............................................................. 153
        5.2.7 Reflection Coefficient Measurement ................................................................ 154
5.3 PIFA with 5 × 1 mm$^2$ Copper Bridge ........................................................................ 156
        5.3.1 Antenna Geometry and Dimensions ................................................................ 156
5.3.2 Reflection Coefficient................................................................. 156
5.3.3 Current Distribution................................................................. 158
5.3.4 Radiation Pattern ................................................................. 158
5.3.5 Realized Gain, Directivity and Efficiency ................................. 159
5.3.6 Antenna Fabrication and Measurement ..................................... 161
5.3.7 Reflection Coefficient Measurement ........................................ 162
5.4 Conclusion .................................................................................... 164

6. NONLINEARITY MEASUREMENTS OF RECONFIGURABLE PIFAs WITH ACTIVE SWITCHES AND PIFAs WITH COPPER BRIDGES ................................................................. 165

6.1 Introduction .................................................................................... 165

6.2 Methodology ................................................................................... 165

6.2.1 Measurement of Third-Order Intermodulation Distortion (IMD3) Products ...... 166
  6.2.1.1 Experimental Setup in Transmit Mode ........................................ 166

6.2.2 Simplified Experimental Setup to Measure IMD3 Products ............. 169
  6.2.2.1 Simplified Experimental Setup in Transmit Mode ....................... 170

6.2.3 Measurement of Ratio of IMD3 Products to Carrier ........................ 171

6.2.4 Measurement of Third-Order Input Intercept Point (IIP3) .................. 172

6.2.5 Measurement of 1-dB Gain Compression Point (P_{1-dB}) ............... 172

6.3 Nonlinearity Measurements of Reconfigurable PIFAs with Active Switches........ 173

6.3.1 Reconfigurable PIFA with BAR50-02V PIN Diode (Gap, G_1 = 2 mm) .......... 178
  6.3.1.1 PIN Diode in ON State ....................................................... 179
  6.3.1.2 PIN Diode in OFF State ..................................................... 184

6.3.2 Reconfigurable PIFA with BAR50-02V PIN Diode (Gap, G_1 = 5 mm) .......... 192
  6.3.2.1 PIN Diode in ON State ....................................................... 193
  6.3.2.2 PIN Diode in OFF State ..................................................... 197

6.3.3 Reconfigurable PIFA with ATF 54143 E-PHEMT Switch .................... 206
  6.3.3.1 E-PHEMT Switch in ON State ........................................... 206
  6.3.3.2 E-PHEMT Switch in OFF State ........................................... 211

6.4 Nonlinearity Measurements of PIFAs with Copper Bridges ................. 215
LIST OF FIGURES

Figure 2.1: Possible software defined radio (SDR) architecture [10] ........................................ 12
Figure 2.2: Cognitive radio architecture [10] .............................................................................. 13
Figure 2.3: Multiple frequency bands achieved in frequency reconfigurable antenna in [20] when two PIN diodes are switched; (a) OFF - ON (b) ON - OFF (c) ON - ON ......................... 18
Figure 2.4: The radiation pattern in different states of PIN diodes in [25];
(a) Mode 1 (PIN diodes ON - OFF) (b) Mode 2 (PIN diodes OFF - ON) ................................. 19
Figure 2.5: Polarization reconfigurable antenna [27]...................................................................... 20
Figure 2.6: Optically reconfigurable CPS dipole antenna [52] ....................................................... 26
Figure 2.7: Geometry of a patch antenna with a switchable slot (PASS) [60] ............................... 31
Figure 2.8: Simulated reflection coefficient for each mode of the switch in [60] ......................... 32
Figure 2.9: Variation of resonant frequencies with slot lengths [60] ............................................ 32
Figure 2.10: Antenna geometry of MEMS-based L-shaped slot PIFA in [70] ................................. 35
Figure 2.11: The locations of IMD products with respect to their fundamental frequencies [79] 40
Figure 2.12: Crucial parameters in nonlinearities measurement [82] ........................................... 41
Figure 2.13: Output spectrum of a nonlinear circuit with two-tone input signal at \( f_1 \) and \( f_2 \) [66]. 43
Figure 2.14: Combination of two generator signals;
(a) Power divider (b) Directional coupler [80] ............................................................................. 45
Figure 2.15: Experimental arrangement for measurement of IMD products [85] ......................... 47
Figure 2.16: Measured received spectrum in the transmit mode in [85] ................................. 47
Figure 2.17: Harmonic radiated power for measurement setup in [87] ......................................... 48
Figure 2.18: Radiation patterns for a varactor loaded quarter-wavelength antenna at second
harmonic with bias voltage of -2.5 V along; (a) E-plane (b) H-plane [87] ................................. 49
Figure 2.19: Radiation patterns for a varactor loaded half-wavelength antenna at second
resonance with bias voltage of -2.5 V along; (a) E-plane (b) H-plane [87] ................................. 49
Figure 2.20: Experimental setup for IIP3 measurement in [88] .................................................... 51
Figure 2.21: Measured reflection coefficient when \( V_b = 2 \) V at three different power levels: the
small signal region (-20dBm) and the 1 and 3 dB compression points (1.2 and 5.4 dBm) [88] ... 51
Figure 2.22: Measured realized gain along E-plane at 1.175 GHz with varying input power of reconfigurable antenna in [89]........................................................................................................ 52
Figure 2.23: Co- and Cross-polar radiation patterns at 1.175 GHz with varying input power for reconfigurable antenna in; (a) Along E-plane  (b) Along H-plane [89].............................................. 53
Figure 2.24: Experimental setup for; (a) $P_{1-dB}$ measurement  (b) IIP3 measurement, both in [90] .................................................................................................................................................. 54
Figure 2.25: Circuit schematic of two reconfigurable omni-directional antennas which emulates coupling in 2 x 2 MIMO antenna system in [91] .................................................................................................................................................. 55
Figure 2.26: Harmonic balance simulation with both antennas in omni-directional mode: (a) Low coupling, $k = 0.1$  (b) High coupling, $k = 0.5$  (c) Very high coupling, $k = 0.9$ [91]................. 56
Figure 2.27: Reconfigurable UWB monopole antenna in; (a) Top view  (b) Bottom view [97]. 57
Figure 3.1: PIN diode construction [99]........................................................................................................... 62
Figure 3.2: PIN diode cross-section [55]........................................................................................................... 63
Figure 3.3: Schematic of PIN diode in forward biased ......................................................................................... 64
Figure 3.4: Structure of reconfigurable PIFA;...................................................................................................... 66
Figure 3.5: Reflection coefficient of reconfigurable PIFA with copper bridge (ON state) and without (OFF state) copper bridge........................................................................................................ 68
Figure 3.6: Current distribution on the radiating structure of reconfigurable PIFA with copper bridge to represent ON state at; (a) 2.01 GHz  (b) 4.03 GHz ............................................................. 69
Figure 3.7: Current distribution on the radiating structure of reconfigurable PIFA without copper bridge to represent OFF state at; (a) 2.01 GHz  (b) 5.65 GHz ............................................................. 69
Figure 3.8: Co-polar radiation patterns in xy-, xz- and yz- planes of PIFA with copper bridge (ON state) at; (a) 2.01 GHz  (b) 4.03 GHz and without copper bridge (OFF state) at; (c) 2.01 GHz  (d) 5.65 GHz ........................................................................................................ 72
Figure 3.9: The main radiating plane of reconfigurable PIFA; (a) Front view (b) Side view ...... 73
Figure 3.10: Reflection coefficient of the reconfigurable antenna with the main radiating plane 74
Figure 3.11: Reflection coefficient comparison between reconfigurable PIFAs with only the main radiating plane and the main radiating plane with an additional plane (but without copper bridge) .................................................................................................................................................. 75
Figure 3.12: Current distribution of reconfigurable PIFA with only a main radiating plane at:
(a) 2.01 GHz  (b) 5.74 GHz

Figure 3.13: Co-polar radiation patterns in xy-, xz- and yz- planes of reconfigurable PIFA with a main radiating plane at; (a) 2.01 GHz  (b) 5.74 GHz

Figure 3.14: PIN diode lumped element equivalent circuit in; (a) ON state  (b) OFF state [48]

Figure 3.15: Reconfigurable PIFA with metal rod to represent feed-through capacitor

Figure 3.16: Top view of reconfigurable PIFA with a discrete port connecting the radiating planes

Figure 3.17: Schematic view of reconfigurable PIFA with PIN diode in;
(a) ON state  (b) OFF state

Figure 3.18: Detailed dimensions of reconfigurable PIFA with PIN diode which is represented by a discrete port;
(a) Radiating planes  (b) Top view  (c) Front view  (d) Side view

Figure 3.19: Reflection coefficient comparison of reconfigurable PIFA with PIN diode in ON and OFF states

Figure 3.20: Current distribution of reconfigurable PIFA with PIN diode in ON state at;
(a) 2.01 GHz  (b) 3.67 GHz

Figure 3.21: Current distribution of reconfigurable PIFA with PIN diode in OFF state at;
(a) 2.01 GHz  (b) 5.16 GHz

Figure 3.22: Co-polar radiation patterns in xy-, xz- and yz- planes of reconfigurable PIFA with PIN diode in ON state at; (a) 2.01 GHz  (b) 3.67 GHz and OFF state at; (c) 2.01 GHz  (d) 5.16 GHz

Figure 3.23: Gain of reconfigurable PIFA with PIN diode in ON state within;
(a) Lower frequency band  (b) Upper frequency band

Figure 3.24: Efficiency of reconfigurable PIFA with PIN diode in ON state within;
(a) Lower frequency band  (b) Upper frequency band

Figure 3.25: Gain of reconfigurable PIFA with PIN diode in OFF state within;
(a) Lower frequency band  (b) Upper frequency band

Figure 3.26: Efficiency of reconfigurable PIFA with PIN diode in OFF state within;
(a) Lower frequency band  (b) Upper frequency band

xii
Figure 3.27: Fabricated reconfigurable PIFA with PIN diode; .............................................. 95
Figure 3.28: DC bias setup for reconfigurable PIFA measurement; ......................................... 96
Figure 3.29: Biasing circuit of BAR50-02V PIN diode .............................................................. 97
Figure 3.30: ZX85-12G+ Coaxial Bias Tee from Mini-Circuits .................................................. 97
Figure 3.31: Measurement setup of reconfigurable PIFA with PIN diode .......................... 98
Figure 3.32: Measured reflection coefficient of reconfigurable PIFA with PIN diode in ON state ................................................................. 99
Figure 3.33: Measured reflection coefficient of reconfigurable PIFA with PIN diode in OFF state ........................................................................................................ 99
Figure 3.34: Comparisons of simulated and measured reflection coefficient of reconfigurable PIFA with PIN diode ................................................................................. 100
Figure 3.35: Schematic view of the new simulation of reconfigurable PIFA with PIN diode in; (a) ON state  (b) OFF state ................................................................................................. 101
Figure 3.36: New simulation of reflection coefficient of reconfigurable PIFA with PIN diode and comparison with the measurement result in; (a) ON state  (b) OFF state .......................................................... 103
Figure 3.37: Radiation patterns of reconfigurable PIFA with PIN diode (include the bias RF choke inductor and feed-through capacitor) in ON state at; (a) 2.05 GHz  (b) 3.65 GHz ................................................................. 104
Figure 3.38: Radiation patterns of reconfigurable PIFA with PIN diode (include the bias RF choke inductor and feed-through capacitor) in OFF state at; (a) 1.4 GHz  (b) 2.1 GHz  (c) 4.75 GHz ................................................................. 105
Figure 3.39: Top view of reconfigurable PIFA with PIN diode (Gap, $G_1$ is increased from 2 mm to 5 mm) ........................................................................................................ 107
Figure 3.40: Reflection coefficient of reconfigurable PIFA with PIN diode (Gap, $G_1 = 5$ mm) in ON and OFF states ........................................................................................................ 108
Figure 3.41: Reflection coefficient comparison of reconfigurable PIFAs with PIN diode (variations in Gap, $G_1$ of 2 and 5 mm) .................................................................................. 109
Figure 3.42: Current distribution on the radiating planes of reconfigurable PIFA with PIN diode (Gap, $G_1 = 5$ mm) in ON state at; (a) 1.825 GHz  (b) 3.13 GHz .................................................. 110
Figure 3.43: Current distribution on the radiating plane of reconfigurable PIFA with PIN diode (Gap, G1 = 5 mm) in OFF state at; (a) 1.825 GHz  (b) 4.705 GHz .......................... 110
Figure 3.44: Co-polar radiation patterns in xy-, xz- and yz- planes of reconfigurable PIFA with PIN diode (Gap, G1 = 5 mm) in ON state at; (a) 1.825 GHz  (b) 3.13 GHz and OFF state at; (c) 1.825 GHz  (d) 4.705 GHz ................................................................. 112
Figure 3.45: Gain of reconfigurable PIFA with PIN diode (Gap, G1 = 5 mm) in ON state within; (a) Lower frequency band  (b) Upper frequency band ......................................................... 114
Figure 3.46: Efficiency of reconfigurable PIFA with PIN diode (Gap, G1 = 5 mm) in ON state within; (a) Lower frequency band  (b) Upper frequency band ......................................................... 114
Figure 3.47: Gain of reconfigurable PIFA with PIN diode (Gap, G1 = 5 mm) in OFF state within; (a) Lower frequency band  (b) Upper frequency band ......................................................... 115
Figure 3.48: Efficiency of reconfigurable PIFA with PIN diode (Gap, G1 = 5 mm) in OFF state within; (a) Lower frequency band  (b) Upper frequency band ......................................................... 115
Figure 3.49: Fabricated reconfigurable PIFA with PIN diode (Gap, G1 = 5 mm); (a) Front view  (b) Top view  (c) Side view ................................................................. 117
Figure 3.50: DC bias setup for reconfigurable PIFA measurement; (a) 1200-pF feed-through capacitor and 1.1-kΩ resistor  (b) 16-nH chip inductor ...................... 117
Figure 3.51: Measurement setup of reconfigurable PIFA with PIN diode (Gap, G1 = 5 mm) .... 118
Figure 3.52: Measured reflection coefficient of reconfigurable PIFA with PIN diode (Gap, G1 = 5 mm) in ON state ............................................................................... 119
Figure 3.53: Measured reflection coefficient of reconfigurable PIFA with PIN diode (Gap, G1 = 5 mm) in OFF state ............................................................................... 119
Figure 4.1: Cross section of a Field Effect Transistor (FET) [81] ........................................... 122
Figure 4.2: FET equivalent circuit in the; (a) ON state  (b) OFF state .................................... 123
Figure 4.3: Voltage-Current characteristic when FET is in ON and OFF states .................. 123
Figure 4.4: ATF 54143 E-PHEMT; (a) Surface mount package  (b) Pin connections and package marking ................................................................. 124
Figure 4.5: Circuit diagram of E-PHEMT switch in ON state. In OFF state, a bias voltage of -1 V is applied to the gate of the transistor ................................................................. 126
Figure 4.6: Simulated reflection loss, $S_{11}$ and insertion loss, $S_{21}$ of E-PHEMT switch in;
(a) ON state (b) OFF state ................................................................. 127
Figure 4.7: Lumped element equivalent circuit of E-PHEMT switch in;
(a) ON state (b) OFF state .................................................................... 128
Figure 4.8: $S_{11}$ and $S_{21}$ of lumped element equivalent circuit and $S_{11}$ and $S_{21}$ of simulated
ATF 54143 E-PHEMT switch in; (a) ON state  (b) OFF state...................... 130
Figure 4.9: Location of a discrete port to represent the ATF 54143 E-PHEMT switch .......... 131
Figure 4.10: Schematic view of reconfigurable PIFA with E-PHEMT switch in;
(a) ON state (b) OFF state .................................................................... 132
Figure 4.11: Reflection coefficient comparison of reconfigurable PIFA with E-PHEMT switch
in ON and OFF states ............................................................................. 133
Figure 4.12: Current distributions on the radiating structure of reconfigurable PIFA with
E-PHEMT switch in ON state at; (a) 1.825 GHz  (b) 3.38 GHz....................... 135
Figure 4.13: Current distributions on the radiating structure of reconfigurable PIFA with
E-PHEMT switch in OFF state at; (a) 1.825 GHz  (b) 4.06 GHz ..................... 135
Figure 4.14: Co-polar radiation patterns in xy-, xz- and yz- planes of reconfigurable PIFA with
E-PHEMT switch in ON state at; (a) 1.825 GHz  (b) 3.38 GHz  and  OFF state at;
(c) 1.825 GHz  (d) 4.06 GHz .................................................................... 137
Figure 4.15: Gain of reconfigurable PIFA with E-PHEMT switch in ON state within;
(a) Lower frequency band  (b) Upper frequency band .............................. 138
Figure 4.16: Efficiency of reconfigurable PIFA with E-PHEMT switch in ON state within;
(a) Lower frequency band  (b) Upper frequency band .............................. 139
Figure 4.17: Gain of reconfigurable PIFA with E-PHEMT switch in OFF state within;
(a) Lower frequency band  (b) Upper frequency band .............................. 140
Figure 4.18: Efficiency of reconfigurable PIFA with E-PHEMT switch in OFF state within;
(a) Lower frequency band  (b) Upper frequency band .............................. 141
Figure 4.19: Fabricated reconfigurable PIFA with E-PHEMT switch;
(a) Front view  (b) Top view (c) Side view .............................................. 142
Figure 4.20: Biasing circuit of ATF 54143 E-PHEMT switch.......................... 143
Figure 4.21: Measurement setup of reconfigurable PIFA with E-PHEMT switch .......... 144
Figure 4.22: Measured reflection coefficient of reconfigurable PIFA with E-PHEMT switch in ON state ................................................................. 145
Figure 4.23: Measured reflection coefficient of reconfigurable PIFA with E-PHEMT switch in OFF state ................................................................. 145
Figure 5.1: Top view of PIFA with 2 × 1 mm$^2$ copper bridge ................................................................. 148
Figure 5.2: Reflection coefficient comparison between PIFA with 2 × 1 mm$^2$ copper bridge and reconfigurable PIFA with PIN diode (Gap, $G_1 = 2$ mm) in ON state ................................................................. 149
Figure 5.3: Current distribution of PIFA with 2 × 1 mm$^2$ copper bridge at;
(a) 2.01 GHz  (b) 4.03 GHz ......................................................................................................................... 150
Figure 5.4: Co-polar radiation patterns in xy-, xz- and yz- planes of PIFA with 2 × 1 mm$^2$
copper bridge at; (a) 2.01 GHz  (b) 4.03 GHz ......................................................................................................................... 151
Figure 5.5: Gain of PIFA with 2 × 1 mm$^2$ copper bridge in;
(a) Lower resonant frequency band  (b) Upper resonant frequency band ................................................................. 152
Figure 5.6: Efficiency of PIFA with 2 × 1 mm$^2$ copper bridge in;
(a) Lower resonant frequency band  (b) Upper resonant frequency band ................................................................. 153
Figure 5.7: PIFA with 2 × 1 mm$^2$ copper bridge;
(a) Front view  (b) Top view  (c) Side view ......................................................................................................................... 154
Figure 5.8: Reflection coefficient measurement of PIFA with 2 × 1 mm$^2$ copper bridge .......... 155
Figure 5.9: Comparison of reflection coefficient from measurement and simulation of PIFA with 2 × 1 mm$^2$ copper bridge ......................................................................................................................... 155
Figure 5.10: Dimensions of PIFA with 5 × 1 mm$^2$ copper bridge ................................................................. 156
Figure 5.11: Reflection coefficient comparison of PIFA with 5 × 1 mm$^2$ copper bridge and reconfigurable PIFA with PIN diode (Gap, $G_1 = 5$ mm) and E-PHEMT switch in ON state .... 157
Figure 5.12: Current distribution of PIFA with 5 × 1 mm$^2$ copper bridge at;
(a) 1.825 GHz  (b) 3.33 GHz ......................................................................................................................... 158
Figure 5.13: Co-polar radiation patterns in xy-, xz- and yz- planes of PIFA with 5 × 1 mm$^2$
copper bridge at; (a) 1.825 GHz  (b) 3.33 GHz ......................................................................................................................... 159
Figure 5.14: Gain of PIFA with 5 × 1 mm$^2$ copper bridge in;
(a) Lower resonant frequency band  (b) Upper resonant frequency band ................................................................. 160
Figure 5.15: Efficiency of PIFA with $5 \times 1 \text{ mm}^2$ copper bridge in;
(a) Lower resonant frequency band (b) Upper resonant frequency band ........................................ 161
Figure 5.16: PIFA with $5 \times 1 \text{ mm}^2$ copper bridge;
(a) Front view (b) Top view (c) Side view ...................................................................................... 162
Figure 5.17: Experimental setup to measure reflection coefficient of reconfigurable PIFA with $5 \times 1 \text{ mm}^2$ copper bridge ........................................................................................................ 163
Figure 5.18: Comparison of reflection coefficient from measurement and simulation of PIFA with $5 \times 1 \text{ mm}^2$ copper bridge ........................................................................................................ 163
Figure 6.1: Block diagram for measurement of IMD3 products when the antenna is transmitting signals ........................................................................................................................................ 167
Figure 6.2: Components involved in experimental setup to measure IMD3 products;
(a) ZVA67 vector network analyzer (b) ZN2PD2-63-S+ power combiner
(c) ZHDC-16-63-S+ Directional coupler (d) Top-hat dipole ................................................................ 169
Figure 6.3: The configuration of nonlinear measurements from operating manual of ZVA67 R&S VNA [80] ........................................................................................................................................ 170
Figure 6.4: Simplified experimental setups of IMD3 products measurement in transmit mode 171
Figure 6.5: Experimental setup to measure ratio of IMD3 products to carrier in transmit mode ........................................................................................................................................ 172
Figure 6.6: Experimental setup for 1-dB gain compression measurement in transmit mode .... 173
Figure 6.7: Experimental setup for nonlinearity measurements .................................................................. 174
Figure 6.8: IMD3 frequencies variation with tone distance of reconfigurable PIFA with PIN diode (Gap, $G_1 = 2 \text{ mm}$); (a) ON state (b) OFF state ................................................................. 176
Figure 6.9: IMD3 frequencies variation with tone distance of reconfigurable PIFA with PIN diode (Gap, $G_1 = 5 \text{ mm}$); (a) ON state (b) OFF state ................................................................. 177
Figure 6.10: IMD3 frequencies variation with tone distance of PIFA with copper bridge;
(a) $2 \times 1 \text{ mm}^2$ (b) $5 \times 1 \text{ mm}^2$ ........................................................................................................... 178
Figure 6.11: Transmitted IMD3 products of reconfigurable PIFA with PIN diode (Gap, $G_1 = 2 \text{ mm}$) in ON state at 2 GHz ........................................................................................................ 180
Figure 6.12: Ratio of IMD3 products to carrier in transmit mode of reconfigurable PIFA with PIN diode (Gap, $G_1 = 2 \text{ mm}$) in ON state at 2 GHz ........................................................................................................ 180
Figure 6.13: Intermodulation asymmetry of reconfigurable PIFA with PIN diode (Gap, G₁ = 2 mm) in ON state at 2 GHz ................................................................. 182
Figure 6.14: IIP3 of reconfigurable PIFA with PIN diode (Gap, G₁ = 2 mm) in ON state at 2 GHz for; (a) Fundamental and lower tones (b) Fundamental and upper tones .......... 183
Figure 6.15: Transmission loss compression plot of reconfigurable PIFA with PIN diode (Gap, G₁ = 2 mm) in ON state at 2 GHz ................................................................................. 184
Figure 6.16: Transmitted IMD3 products of reconfigurable PIFA with PIN diode (Gap, G₁ = 2 mm) in OFF state at; (a) 1.4 GHz (b) 2 GHz ................................................................. 186
Figure 6.17: Ratio of IMD products to carrier in transmit mode of reconfigurable PIFA with PIN diode (Gap, G₁ = 2mm) in OFF state at; (a) 1.4 GHz (b) 2 GHz ................................................................. 187
Figure 6.18: Intermodulation asymmetry of reconfigurable PIFA with PIN diode (Gap, G₁ = 5 mm) in OFF state at; (a) 1.4 GHz (b) 2 GHz ................................................................. 188
Figure 6.19: IIP3 of reconfigurable PIFA with PIN diode (Gap, G₁ = 2 mm) in OFF state at 1.4 GHz for; (a) Fundamental and lower tones (b) Fundamental and upper tones .......... 190
Figure 6.20: IIP3 of reconfigurable PIFA with PIN diode (Gap, G₁ = 2 mm) in OFF state at 2 GHz for; (a) Fundamental and lower tones (b) Fundamental and upper tones .......... 191
Figure 6.21: Transmission loss compression plot of reconfigurable PIFA with PIN diode (Gap, G₁ = 2 mm) in OFF state at; (a) 1.4 GHz (b) 2 GHz ................................................................. 192
Figure 6.22: Transmitted IMD3 products of reconfigurable PIFA with PIN diode (Gap, G₁ = 5 mm) in ON state at 1.85 GHz .................................................................................. 193
Figure 6.23: Ratio of IMD products to carrier in transmit mode of reconfigurable PIFA with PIN diode (Gap, G₁ = 5 mm) in ON state at 1.85 GHz ................................................................................. 194
Figure 6.24: Intermodulation asymmetry of reconfigurable PIFA with PIN diode (Gap, G₁ = 5 mm) in ON state at 1.85 GHz .................................................................................. 195
Figure 6.25: IIP3 of reconfigurable PIFA with PIN diode (Gap, G₁ = 5 mm) in ON state at 1.85 GHz for; (a) Fundamental and lower tones (b) Fundamental and upper tones .......... 196
Figure 6.26: Transmission loss compression plot of reconfigurable PIFA with PIN diode (Gap, G₁ = 5 mm) in ON state at 1.85 GHz .................................................................................. 197
Figure 6.27: Transmitted IMD products of reconfigurable PIFA with PIN diode (Gap, G₁ = 5 mm) in OFF state at; (a) 1.35 GHz (b) 1.85 GHz ................................................................. 199
Figure 6.28: Ratio of IMD products to fundamental tones of reconfigurable with PIN diode (Gap, $G_1 = 5$ mm) in OFF state at; (a) 1.35 GHz  (b) 1.85 GHz

Figure 6.29: IMD3 products asymmetry of the reconfigurable PIFA with PIN diode (Gap, $G_1 = 5$ mm) in OFF state at; (a) 1.35 GHz  (b) 1.85 GHz

Figure 6.30: IIP3 of reconfigurable PIFA with PIN diode (Gap, $G_1 = 5$ mm) in OFF state at 1.35 GHz for; (a) Fundamental and lower tones  (b) Fundamental and upper tones

Figure 6.31: IIP3 of reconfigurable PIFA with PIN diode (Gap, $G_1 = 5$ mm) in OFF state at 1.85 GHz for; (a) Fundamental and lower tones  (b) Fundamental and upper tones

Figure 6.32: Transmission loss compression plot of reconfigurable PIFA with PIN diode (Gap, $G_1 = 5$ mm) in OFF state at; (a) 1.35 GHz  (b) 1.85 GHz

Figure 6.33: Transmitted IMD3 products of reconfigurable PIFA with E-PHEMT switch in ON state at 1.85 GHz

Figure 6.34: Ratio of IMD3 products to carrier of reconfigurable PIFA with E-PHEMT switch in ON state at 1.85 GHz

Figure 6.35: IMD3 products asymmetry of reconfigurable PIFA with E-PHEMT switch in ON state at 1.85 GHz

Figure 6.36: IIP3 of reconfigurable PIFA with E-PHEMT switch in ON state at 1.85 GHz for; (a) Fundamental and lower tones  (b) Fundamental and upper tones

Figure 6.37: Transmission loss compression plot of reconfigurable PIFA with E-PHEMT switch in ON state at 1.85 GHz

Figure 6.38: Transmitted IMD3 products of reconfigurable PIFA with E-PHEMT switch in OFF state at 1.85 GHz

Figure 6.39: Ratio of IMD3 products to carrier of reconfigurable PIFA with E-PHEMT switch in OFF state at 1.85 GHz

Figure 6.40: IMD3 products asymmetry of reconfigurable PIFA with E-PHEMT switch in OFF state at 1.85 GHz

Figure 6.41: IIP3 of reconfigurable PIFA with E-PHEMT switch in OFF state at 1.85 GHz for; (a) Fundamental and lower tones  (b) Fundamental and upper tones

Figure 6.42: Transmission loss compression plot of reconfigurable PIFA with E-PHEMT switch in OFF state 1.85 GHz
Figure 6.43: Transmitted IMD3 products of PIFA with 2 × 1 mm² copper bridge ................. 217
Figure 6.44: Ratio of IMD3 products to carrier of PIFA with 2 × 1 mm² copper bridge .......... 217
Figure 6.45: IMD3 products asymmetry of PIFA with 2 × 1 mm² copper bridge ................. 218
Figure 6.46: IIP3 of PIFA with 2 x 1 mm² copper bridge at 2 GHz for;
   (a) Fundamental and lower tones   (b) Fundamental and upper tones .......................... 219
Figure 6.47: Transmission loss compression plot of PIFA with
   2 x 1 mm² copper bridge at 2 GHz ................................................................................. 220
Figure 6.48: Transmitted IMD3 products of PIFA with 5 × 1 mm² copper bridge ............... 221
Figure 6.49: Ratio of IMD3 products to carrier of PIFA with 5 × 1 mm² copper bridge .......... 221
Figure 6.50: Intermodulation asymmetry of PIFA with 5 × 1 mm² copper bridge ............... 222
Figure 6.51: IIP3 of PIFA with 5 x 1 mm² copper bridge at 1.85 GHz for;
   (a) Fundamental and lower tones   (b) Fundamental and upper tones .......................... 223
Figure 6.52: Transmission loss compression plot of PIFA with
   5 × 1 mm² copper bridge at 1.85 GHz ............................................................................. 224
## LIST OF TABLES

Table 2.1: A review of switchable reconfigurable antennas .......................................................... 15
Table 2.2: Comparison of antenna solutions for wireless mobile platforms .................................. 16
Table 2.3: Performance comparison of FET, PIN diode and RF MEMS switches ....................... 28
Table 2.4: Intermodulation (IMD) products .................................................................................. 39
Table 2.5: Cellular network linearity requirements from Intel Mobile Corporation (2012) .......... 42
Table 2.6: Previous work on nonlinearity measurements of reconfigurable antennas .............. 58
Table 3.1: Resonant frequency performance of reconfigurable PIFA with and without copper bridge .................................................................................................................. 68
Table 3.2: Realized gain, directivity and efficiency of reconfigurable PIFA with copper bridge (ON state) and without copper bridge (OFF state) ............................................................ 72
Table 3.3: Resonant frequency performance comparison of reconfigurable PIFAs with a single and two radiating planes ........................................................................................................... 75
Table 3.4: Realized gain, directivity and efficiency of reconfigurable PIFA with respect to the radiating planes .................................................................................................................. 78
Table 3.5: Lumped element values of BAR50-02V PIN diode in ON and OFF states .............. 80
Table 3.6: Dimensions of the whole structure of reconfigurable PIFA with PIN diode .......... 84
Table 3.7: Resonant frequency performance of reconfigurable PIFA with PIN diode in ON and OFF states ............................................................................................................................. 86
Table 3.8: Realized gain, directivity and efficiency of reconfigurable PIFA with PIN diode in ON and OFF states .................................................................................................................. 91
Table 3.9: Resonant frequency performance of reconfigurable PIFA with PIN diode (include the 16-nH RF choke inductor and 1200-pF feed-through capacitor) .............................. 103
Table 3.10: Realized gain, directivity and efficiency of reconfigurable PIFA with PIN diode in ON and OFF states .................................................................................................................. 106
Table 3.11: Changes in dimensions of reconfigurable PIFA with PIN diode (Gap, G₁ = 5 mm) 107
Table 3.12: Resonant frequency performance of reconfigurable PIFA with PIN diode (Gap, G₁ = 5 mm) .......................................................................................................................... 108
Table 3.13: Realized gain, directivity and efficiency of reconfigurable PIFA with PIN diode (Gap, G₁ = 5 mm) ................................................................................................................................. 113
Table 4.1: Comparison of MESFET and PHEMT in switching configurations ........................................... 121
Table 4.2: The lumped element values of ATF 54143 E-PHEMT switch in ON and OFF states ................................................................................................................................................ 129
Table 4.3: Resonant frequency performance of reconfigurable PIFA with E-PHEMT switch ....................................................................................................................................................... 133
Table 4.4: Realized gain, directivity and efficiency of reconfigurable PIFA with E-PHEMT switch in ON and OFF states ............................................................................................................................................... 137
Table 4.5: Biasing components of ATF 54143 E-PHEMT switch .................................................................. 143
Table 5.1: Resonant frequency performance of PIFA with 2 × 1 mm² copper bridge and reconfigurable PIFA with PIN diode in ON state .................................................................................................. 149
Table 5.2: Realized gain, directivity and efficiency of PIFA with 2 × 1 mm² copper bridge (Gap, G₁ = 2 mm) ............................................................................................................................................... 152
Table 5.3: Resonant frequency performance of PIFA with 5 × 1 mm² copper bridge and reconfigurable PIFA with PIN diode (Gap, G₁ = 5 mm) and E-PHEMT switch in ON state ............................................................................................................................................... 157
Table 5.4: Realized gain, directivity and efficiency of PIFA with 5 × 1 mm² copper bridge ............................................................................................................................................... 160
Table 6.1: List of components in IMD3 product measurements ................................................................ 168
Table 6.2: Comparison of nonlinearity measurement results ................................................................ 225
Table 7.1: Proposed reconfigurable PIFAs in this work ............................................................................... 229
### LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3GPP</td>
<td>Third Generation Partnership Project</td>
</tr>
<tr>
<td>AC</td>
<td>Alternate Current</td>
</tr>
<tr>
<td>CPW</td>
<td>Co-Planar Waveguide</td>
</tr>
<tr>
<td>CR</td>
<td>Cognitive Radio</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DVB-H</td>
<td>Digital Video Broadcasting - Handheld</td>
</tr>
<tr>
<td>EM</td>
<td>Electro Magnetic</td>
</tr>
<tr>
<td>FET</td>
<td>Field Effect Transistor</td>
</tr>
<tr>
<td>GaAs FET</td>
<td>Gallium Arsenide Field Effect Transistor</td>
</tr>
<tr>
<td>HB</td>
<td>Harmonic Balance</td>
</tr>
<tr>
<td>IIP3</td>
<td>Input Third-Order Intercept Point</td>
</tr>
<tr>
<td>IMD</td>
<td>Inter Modulation Distortion</td>
</tr>
<tr>
<td>IMD3</td>
<td>Third-Order Inter Modulation Distortion</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific and Medical</td>
</tr>
<tr>
<td>MESFET</td>
<td>Metal Semiconductor Field Effect Transistor</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
</tr>
<tr>
<td>m-WiMAX</td>
<td>Microwave Worldwide Interoperability for Microwave Access</td>
</tr>
<tr>
<td>OIP3</td>
<td>Output Third-Order Intercept Point</td>
</tr>
<tr>
<td>PHEMT</td>
<td>Pseudomorphic High Electron Mobility Transistor</td>
</tr>
<tr>
<td>PIFA</td>
<td>Planar Inverted F Antenna</td>
</tr>
<tr>
<td>PIN DIODE</td>
<td>Positive-Intrinsic-Negative Diode</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RF MEMS</td>
<td>Radio Frequency Micro Electro Mechanical Systems</td>
</tr>
<tr>
<td>RF NEMS</td>
<td>Radio Frequency Nano Electro Mechanical Systems</td>
</tr>
<tr>
<td>RLC</td>
<td>Resistance, Inductance and Capacitance</td>
</tr>
<tr>
<td>SDR</td>
<td>Software-Defined Architecture</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>SMA</td>
<td>SubMiniature version A</td>
</tr>
<tr>
<td>SMD</td>
<td>Surface Mount Device</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication System</td>
</tr>
<tr>
<td>UNII</td>
<td>Unlicensed National Information Infrastructure</td>
</tr>
<tr>
<td>USPCS</td>
<td>United States Personal Communication Services</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra-Wideband</td>
</tr>
<tr>
<td>VNA</td>
<td>Vector Network Analyzer</td>
</tr>
<tr>
<td>VSWR</td>
<td>Voltage Standing Wave Ratio</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
</tbody>
</table>
PUBLICATIONS IN PREPARATION


CHAPTER 1

1. INTRODUCTION

1.1 Background

The recent and continuing growth of wireless communication these days has inspired the design and production of multifunctional antennas that are able to cover the increasing number of wireless bands [1]. Second Generation (2G) as the first digital cellular standard used quad-band solutions while the Third Generation (3G) standard has already supported up to 8 frequency bands. Fourth Generation (4G) which is dominated by the need for global roaming and wider frequency bandwidth has introduced over 40 bands allocated to Long Term Evolution (LTE) applications.

For this reason, attention has been diverted into reconfigurable multiband antennas. Reconfigurable antennas are realized by altering the current distributions on the radiating planes of the antennas or altering the current paths. This is being made possible by using radio frequency (RF) switches such as positive-intrinsic-negative (PIN) diodes or field-effect transistors (FETs) and other devices for instance, varactors, mechanically movable parts, phase shifters or attenuators [2].

Solid state RF switches is a mature technology and steadily advancing. However, they still exhibit some degree of nonlinear behaviour under certain operating conditions at high frequencies which may cause signal distortion in the antenna systems. Signal distortion will cause an undesired change in an input signal waveform as the signal passes through the communication
network. This in return will introduce frequency components that do not exist in the input waveform. The nonlinear behaviour of a reconfigurable antenna can be described in terms of intermodulation distortion (IMD) products and gain compression. In the industry, Third Generation Partnership Project (3GPP) has determined the degree of RF switch linearity which is required to avoid an interference with other devices in mobile communication systems. This is done by specifying the third-order input intercept point (IIP3) [3].

Radio frequency microelectromechanical system (RF MEMS) switches, on the other hand, offer significant advantage in terms of linearity performance [4]. RF MEMS switches are well-known for their excellent linearity. This is due to the mechanical passive nature of the device.

In general, reconfiguration mechanisms or control devices of reconfigurable antennas can be divided into four technologies [5]. They are solid state devices, electromechanical mechanisms, ferroic materials and fluidic reconfiguration. From these four technologies, solid state device technology is fully developed technology but still progressively advancing, while fluidic reconfiguration, at the extreme end, has not yet attained the level of maturity required to be applied on commercial antennas.

1.2 Aim

The aim of this project is to investigate the nonlinearity issues faced in active reconfigurable antennas. From the reviewed literature, references discussing linearity performance and nonlinearity measurements on reconfigurable antennas are still lacking. In addition, the related works that study the nonlinear behaviour of active devices mostly are being performed on other RF devices such as power amplifiers, filters and phase shifters but very few on reconfigurable
antennas. Furthermore, even though there are references found on nonlinearity measurements of reconfigurable antennas, majority of them are using varactors instead of active switches as discussed in Chapter 2.

In order to successfully complete this research work, a careful study has been conducted to choose the most appropriate type of antenna and the suitable reconfiguration technology. The first step is to choose the type of switching involved whether an electronic, mechanical or optical switching. In terms of efficiency and reliability, electronic switching is frequently used as compared to others. The next step is to determine which antenna is widely used in wireless applications and have been the popular choice of reconfiguration capability.

For this research work, two types of active switches were selected and each of them was implemented on a reconfigurable antenna. Theoretically, PIN diodes and E-PHEMT switches suffer from nonlinear behaviour at high frequencies and were chosen for nonlinearity measurements. For comparison purpose, reference antennas with copper bridges to replace the active switches were fabricated. The copper bridge serves as a linear interconnection. A comprehensive study on the nonlinear behaviour of the reconfigurable antennas was then conducted and in-depth analysis was performed to investigate the nonlinear properties of the active switches.

1.3 Problem Statement

Active switches are commonly applied on antennas to allow pattern, polarization and frequency reconfigurations. The switch selection is determined from three major considerations; high isolation, low insertion loss and high linearity. Each new generation of cellular networks
required progressively higher linearity and was required to support the increasing number of frequency bands for wireless applications. Thus, RF front ends have become extremely complex from the stringent requirements to reduce intermodulation and cross modulation from one or more receiver and transmitter paths. In this environment, linearity performance of RF components with RF switches in particular, is becoming a crucial specification. Thus, there is a continuous research dedicated into improving the RF switch linearity in reconfigurable devices.

The research work in this thesis will be devoted to switchable reconfigurable antennas. Solid state RF switches will be introduced to reconfigure the frequency of the antennas. From a linearity point of view, these active switches will behave in a nonlinear manner at high frequencies which can be measured from several nonlinearity parameters. Third-order intermodulation distortion (IMD3) products are crucial in nonlinearity measurements. From the output spectrum of a nonlinear circuit with two-tone input signals at $f_1$ and $f_2$, it can be observed that the IMD3 products are located very close to the fundamental signals. The worst case will happen when the IMD3 products appear within the operating bandwidth of any particular antenna as this will cause distortion to the output signals of communication systems.

However, there seems to be a reasonable gap in the open literature when it comes to addressing the issue of nonlinearity in reconfigurable antennas. Most of the available research papers are focussing on the linear characteristics of the reconfigurable antennas while neglecting the nonlinear characteristics. Therefore, based on the knowledge gap found from the literature, this research project will highlight the nonlinearity issues faced in reconfigurable antennas with active switches. In order to investigate the nonlinearity of the antennas, three experimental setups have been proposed.
1.4 **Objectives**

The objectives of this research work are listed below:

i. To design and fabricate frequency reconfigurable antennas for wireless communication applications by incorporating PIN diode and E-PHEMT switches within the frequency range from 1 to 6 GHz.

ii. To design and fabricate a reference antenna using a copper bridge to replace the active switch for comparison purpose and to provide a highly linear reference design.

iii. To conduct nonlinearity measurements on the reconfigurable and reference antennas in transmit mode and to provide a comprehensive study on the nonlinear behaviour of the antennas.

1.5 **Scope**

The research work focussed on reconfigurable antennas with active switches for wireless communication applications. Two types of active switches were used and they are listed as below:

i. BAR50-02V PIN diode

ii. ATF 54143 E-PHEMT switch

At the same time, two PIFAs with copper bridges were fabricated to replace the switches. The copper bridge serves as a linear interconnection to provide a highly linear reference.
In order to achieve the objectives, a number of activities were planned and identified as outlined below:

i. Investigate the characteristics of frequency reconfigurable antennas and various methods to implement them.

ii. Select the type of frequency reconfigurable antenna for wireless applications.

iii. Select the type of active switches to reconfigure the antenna.

iv. Design and simulate the reconfigurable antennas with similar geometry and dimensions.

v. Design and simulate the reference antennas with copper bridges.

vi. Fabricate and measure the antennas to ensure small signal properties agree well.

vii. Perform nonlinearity measurements on the antennas which are listed below:

   a. Investigate the experimental setups to measure the IMD3 products when the antenna is transmitting signals.

   b. Measure the ratio of the IMD3 products to carrier.

   c. Measure the input third-order intercept point (IIP3).

   d. Measure the 1-dB gain compression point (P_{1\,dB}).
1.6 Contribution to Knowledge

The most significant contributions of this research work to the existing knowledge are outlined as follows:

i. The nonlinearity measurements of reconfigurable PIFAs with active switches

Two types of RF switches are used to reconfigure the frequencies of the reconfigurable PIFAs namely the BAR50-02V PIN diode and ATF 54143 E-PHEMT switch. Each type of switch is implemented on a PIFA with similar geometry and dimensions. The nonlinearity measurements are performed on these antennas in transmit mode to investigate their nonlinear characteristics. For linear comparisons, two antennas with copper bridges are fabricated to provide a highly linear interconnection to replace the active switches. Moreover, the nonlinearity performance of the reconfigurable antennas with PIN diode and E-PHEMT switches is compared for further investigation.

ii. The 10 dB power-series-based approximation

In this work, it has been shown that the difference between 1-dB gain compression point and IIP3 is close to 10 dB as predicted by the power-series-based approximation.

iii. The proposed reconfigurable PIFA with ATF 54143 E-PHEMT switch

The use of E-PHEMT switch to reconfigure the frequencies of a PIFA in this work can be considered as the first work reported in the literature. Prior to the design and fabrication of reconfigurable PIFA with E-PHEMT switch, the Modelithic™ model of the transistor has been obtained from the manufacturer and was simulated in AWR Microwave Office (MWO) software
with a dedicated biasing circuit for the transistor to behave as a switch within the operating frequency from 1 to 6 GHz.

iv. The IMD radiation patterns measurement

There are no measurements of radiation patterns at IMD frequencies reported in the literature. The nonlinearity measurements performed in this work indicate that the ratio of IMD3 products to carrier does not vary significantly with radiation angles.

1.7 Thesis Outline

In Chapter 1, a brief introduction on active switches for antenna reconfiguration is presented. Depending on the technology used to manufacture the switch, these switches behave nonlinearly at high frequencies. Thus, a continuous research is required to improve linearity. The effort is in line with the evolution of cellular networks which require a huge number of frequency bands to support wireless applications. The underlying problems concerning the issue of nonlinearity in active reconfigurable antennas are also addressed.

Chapter 2 describes cognitive radio (CR) and software defined radio (SDR) architectures with further justifications on the need of a reconfigurable antenna to be a part of the system. However, the inclusion of active switches to reconfigure the antenna has generated an interesting topic on the study of nonlinearity. Thus, nonlinearity measurements to evaluate the nonlinearity of reconfigurable antennas are identified and discussed. Previous works are also reviewed and summarized to establish the knowledge gap on the nonlinearity issue faced in reconfigurable antennas.
The next two chapters discuss the reconfigurable PIFA with PIN diode and E-PHEMT switches. The design, simulation and fabrication of the antennas are examined. For each type of active switch, a dedicated biasing circuit is proposed but the geometry and dimensions of the reconfigurable PIFA are similar.

In Chapter 3, a preliminary study is conducted on the reconfigurable PIFA to study its switching capability. The work on reconfigurable PIFA with PIN diode is also presented. The first resonant frequency remains similar in both states of the PIN diode. Depending on the switching state of the PIN diode, the second resonant frequency can be switched to the upper and lower resonant frequency.

In Chapter 4, the work on reconfigurable PIFA with E-PHEMT switch is discussed. Before the transistor can be used as a switch, two simulations are carried out to observe the performance of $S_{11}$ and $S_{21}$ of the transistor with its biasing circuit. In this case, a low insertion loss in the ON state and a high isolation in the OFF state are required before the transistor can be used as a switch.

For comparison purposes, two reference antennas with copper bridges are fabricated. Copper bridge is selected to replace the active switch as it provides a highly linear interconnection. The discussion can be read in Chapter 5.

In Chapter 6, the methodology to perform the nonlinearity measurements on the reconfigurable PIFAs is discussed. The nonlinearity measurement results are also presented and analyzed. The comparisons are made between the reconfigurable PIFAs and reference antennas.

Finally, Chapter 7 concludes the findings of this work and suggestions for future works.
CHAPTER 2

2. BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

Software defined radio (SDR) and cognitive radio (CR) are two new concepts in wireless platforms which have greatly influenced the future antenna designs with varying degrees of reconfiguration and band tuning [6]. To begin with, CR is a wireless transponder which has the ability to sense the spectrum and changing system parameters such as frequency, transmitted power or standard, if required. SDR, on the other hand, is a technology that is necessary for a full implementation of CR [7].

CR communication is predicted to be the new unconventional paradigm to enhance the performance of radio communication systems which is realized via efficient utilization of the radio spectrum. A cognitive communication system is an intelligent communication system which is capable of learning from its radio environment and adapting its operational parameters to sense the spectrum for reliable communication and efficient utilization of radio spectrum.

Severe difficulties are expected in the implementation of CR from a system or network point of view and in the technology required to operate it. These can be attributed to the fact that the initial systems will have to operate in an environment populated by two groups of systems; those that are regulated and those that are allowed to operate as cognitive radios. Reconfigurable
antennas provide degree of freedom in system adaptation that can potentially help towards overcoming these difficulties.

Future cognitive communication systems require reconfigurable antennas as the underlying hardware to have the capability to operate over a wide range of frequencies and over a multiple wireless standards [8]. The design of reconfigurable antennas should allow the operations in multiple and wideband frequency bands to cover multiple standards simultaneously. This requirement can be made possible by the implementation of switchable antennas which use active switches to sustain their operations.

2.2 Software Defined Radio (SDR) Architecture

Enormous possibilities offered by modern signal processing have enlightened the software radio concept. From hardware point of view, SDR can be described as a system in which the majority of the functionality is defined by software algorithms. In the system, wideband antennas are connected directly to analogue-to-digital converters (ADC) and the digitized radio signal will then be processed [9]. Thus, the processor should contain all the processing which is done previously by analogue radio frequency (RF) and baseband circuits. The processor has a significant advantage of reconfiguration to the standard that the radio is using. This kind of flexibility seems to be necessary as more and more radios are being integrated to allow maximum connectivity in a single wireless platform.

In another approach, an amplifier followed by ADC has been used at very low frequency (VLF) applications but this concept has not been realized at microwave frequencies due to a very large power required to drive the ADC. However, the enhancement has been made with an additional
low noise amplifier (LNA) and power amplifier (PA) which has resulted in a possible SDR architecture [10]. Figure 2.1 shows the possible architecture of SDR.

![Possible software defined radio (SDR) architecture][10]

CR further enhances the concept of SDR using a model-based reasoning in handset to provide a local control which greatly increases capacity with the advantage of *spectrum pooling*. The increasing number of wireless communication applications with a particular emphasis placed on a frequency range from 0.8 to 3 GHz has caused a significant spectrum congestion [11]. CR, on the other hand, should be able to access the frequency band from 30 MHz to 5.9 GHz. A typical block diagram of a CR can be seen in Figure 2.2.
Wideband antennas in the transmitter and receiver have been implemented in the cognitive radio architecture in Figure 2.2. Wideband antennas can only produce coarse spectrum sensing while narrowband antennas can sense the spectrum accurately. Another disadvantage of wideband antennas is that they tend to be bigger than narrowband antennas which will be an issue in terms of portability in mobile handsets. This generates the need for substitution of wideband antennas with multiband or reconfigurable antennas which has greatly influenced the choice of antenna in this research work.

2.3 Fixed Multiband Antenna

Multiband antennas are those antennas which are able to operate at more than one band or service at the same time. It has been one of the most practical and affordable wireless module solutions. The term fixed can be referred to the operating frequency, radiation patterns and polarization that
are fixed depending on the applications and once the antenna has been fabricated and located in the system, the performance of the antenna remains unchangeable.

Fixed multiband antennas normally require complicated filters with flexible requirements to improve their out-of-band noise rejection. These filters are bulky and obviously will add complexity to the communication systems. This is the drawback of fixed multiband antennas as the next generation devices requires smaller built-in antennas to follow the downsizing trend of the terminal unit but at the same time, are able to support the growing number of wireless frequency bands [12].

These problems can be solved with deployments of reconfigurable antennas.

2.4 Reconfigurable Antenna

Fixed multiband antennas can be realized in various communication systems and devices. However, they are still lacking in terms of flexibility to accommodate new services. Those requirements have motivated the evolution of fixed multiband antennas to reconfigurable antennas. Reconfigurable antennas have the capability to change their radiation topology within the same physical dimension which is attributed to their selectivity of frequency, radiation or polarization, and compact size [5]. In other words, reconfigurable antennas can alter their resonant frequencies, radiation patterns, or polarization states depending on applications and their surrounding environment [13]. Antenna reconfiguration capabilities are usually achieved by incorporating switches or tunable devices such as PIN diodes, FET switches, RF MEMS switches, variable capacitors or varactor diodes in the design stage of the antenna [14]. These will
enable the frequency response, radiation patterns, gain or the combination of various antenna parameters to be controlled.

The main advantage of reconfigurable antennas is the ability to operate in multiple bands in which the total antenna volume can be reused [15]. This would greatly reduce the complexity but at the same time, increases the capability of the antenna system. As a result, a particular device that use a single compact antenna will allow reduction in its dimensions and this will provide more space to integrate other electronic components [16].

A number of papers on the design of switchable reconfigurable antennas have been reviewed and they are summarized and compared in Table 2.1.

Table 2.1: A review of switchable reconfigurable antennas

<table>
<thead>
<tr>
<th>Reference</th>
<th>Antenna Type</th>
<th>Number of Bands</th>
<th>Number of Switch</th>
<th>Frequency Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>[17]</td>
<td>PIFA</td>
<td>5</td>
<td>1 RF MEMS</td>
<td>UTRA Bands of:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Band I: 1901 – 2185 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Band II: 1849 – 2156 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Band III: 1840 – 2151 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Band V: 748 – 912 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Band VIII: 765 – 950 MHz</td>
</tr>
<tr>
<td>[18]</td>
<td>Slot-patch</td>
<td>3</td>
<td>3 PIN diodes</td>
<td>2.5 GHz (Bluetooth);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.5 GHz (WiMAX);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.8 GHz (WLAN)</td>
</tr>
<tr>
<td>[19]</td>
<td>Patch</td>
<td>1</td>
<td>2 PIN diodes</td>
<td>5.27 – 5.74 GHz</td>
</tr>
<tr>
<td>[20]</td>
<td>Slot-patch</td>
<td>4</td>
<td>2 PIN diodes</td>
<td>5.6 and 6.2 GHz (Dual-band);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 and 5.7 GHz (Dual-band);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5 to 7 GHz (Wideband)</td>
</tr>
<tr>
<td>[21]</td>
<td>Slot-patch</td>
<td>1</td>
<td>2 PIN diodes</td>
<td>2.4 – 2.5 GHz (WLAN IEEE 802/11 b/g)</td>
</tr>
<tr>
<td>[22]</td>
<td>Printed dipole</td>
<td>1</td>
<td>2 PIN diodes</td>
<td>2.5 – 2.7 GHz (WiMAX)</td>
</tr>
</tbody>
</table>
From the table, there are two common traits of the reconfigurable antennas that may cause some problems and need to be addressed.

Firstly, the multiple numbers of switches will enhance the features of the antennas. However, this will add complexity to the communication systems as the biasing circuits will be more complicated and interference between the electronic components might disrupt the output signals. Thus, the number of switches should be reduced.

Secondly, the number of bands increases with the increase in the size of the antennas. However, the sizes of the devices are getting smaller these days while at the same time, must be able to support multiple wireless services. Thus, there is an urgency to reduce the size of the antennas. Table 2.2 further highlights the advantages of reconfigurable antennas [23].

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Multiple Antennas</th>
<th>Multiband/Wideband Antennas</th>
<th>Reconfigurable Antennas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usage Model</td>
<td>Single-band antenna supports one frequency of wireless service</td>
<td>One antenna supports all frequency bands of wireless service/module</td>
<td>One antenna supports many wireless standards</td>
</tr>
<tr>
<td>Space Requirement</td>
<td>Multiple antennas require more spaces</td>
<td>Reduced space but wide bandwidth deters miniaturization efforts</td>
<td>Minimal space requirement</td>
</tr>
<tr>
<td>Front-end Complexity</td>
<td>Loose filter specification, simple front-end</td>
<td>Many stringent filters required, introduce high insertion loss and cost</td>
<td>Relaxed filter specifications but complex reconfigurable front end required</td>
</tr>
<tr>
<td>Individual Radio</td>
<td>Excellent</td>
<td>Good; lower receiver sensitivity due to insertion loss at front end</td>
<td>Acceptable performance, additional loss introduced by switches</td>
</tr>
<tr>
<td>Performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio Coexistence</td>
<td>Little spacing between antennas, strong coupling between radios</td>
<td>Poor out-of-band rejection, transmitted signal of other radio may cause noise jamming</td>
<td>Degraded through simultaneous operation as antenna supports one service at a time</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Cost</td>
<td>Increased number of cables contributes most of the cost</td>
<td>High-cost stringent filters required at front end</td>
<td>Cost of low loss, low power consumption RF MEMS switch is high. However, other options of cheaper switching devices are also available.</td>
</tr>
</tbody>
</table>

## 2.5 Reconfigurable Performance Metrics

Reconfigurable performance metrics can be classified into three overarching categories which are listed as below:

i. Frequency reconfigurable

ii. Radiation pattern reconfigurable

iii. Polarization reconfigurable

### 2.5.1 Frequency Reconfigurable

Frequency reconfigurable antennas allow a single radio device to operate at multiple frequencies which is the advantage. Frequency reconfigurable antennas of this type are commonly applied to RF communication systems such as multiband mobile devices [24]. The frequency agility will include shifting or switching a resonant frequency, impedance bandwidth or facilitating multiband characteristics. The shape of the radiation patterns will remain unchanged as the
frequencies are tuned or switched from one frequency to another. For instance, a switching method can be used to switch into multiple bands for mobile applications as can be seen in [20]. The concept of frequency reconfiguration in that work can be further illustrated from the reflection coefficient graphs in Figure 2.3. From the figure, it can be seen that the reconfigurable antenna has the capability to shift from one frequency band to another depending on the states of the two PIN diodes.

![Reflection Coefficient Graphs](attachment:image.png)

(a) Simulated in OFF-ON state, Measured in OFF-ON state
(b) Simulated in ON-OFF state, Measured in ON-OFF state
(c) Simulated in ON-ON state, Measured in ON-ON state

Figure 2.3: Multiple frequency bands achieved in frequency reconfigurable antenna in [20] when two PIN diodes are switched; (a) OFF - ON (b) ON - OFF (c) ON - ON
2.5.2 Radiation Pattern Reconfigurable

Radiation pattern reconfigurable antennas will enable changes in radiation pattern while maintaining the frequency bands based on the system requirements. As a result, the antennas can steer their radiation beams to different directions to enhance signal reception as can be seen in [25]. In this work, the radiation pattern will change depending on the current states of the two PIN diodes. This concept is explained further in Figure 2.4.

![Radiation Pattern Reconfigurable](image)

(a) Mode 1 (PIN diodes ON - OFF)  (b) Mode 2 (PIN diodes OFF - ON)

Figure 2.4: The radiation pattern in different states of PIN diodes in [25]; (a) Mode 1 (PIN diodes ON - OFF)  (b) Mode 2 (PIN diodes OFF - ON)

2.5.3 Polarization Reconfigurable

Polarization reconfigurable antennas have significant advantages at improving signals reception performance in severe multipath fading environments in Wireless Local Area Networks (WLAN), as a modulation scheme in Radio Frequency Identification (RFID) systems and at...
increasing security complexity in military wireless systems [26]. In general, microstrip antennas are designed to operate in a single polarization mode such as linear or circular polarization (CP). In wireless communications, CP is more favorable since the antennas of the transmitter and receiver do not have to be aligned to be parallel with each other. CP antennas exhibit both right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP). In terms of implementation, a polarization reconfigurable antenna can be designed from a simple patch antenna. This can be performed by a proper design of the feed network and by adjusting the dimensions of the patch in such a way to excite two orthogonal modes with a phase difference of 90°. Figure 2.5 shows a CP reconfigurable antenna as proposed in [27]. The antenna employs two diagonal rectangular slots along two diagonals which are controlled by two pairs of PIN diodes. The antenna will radiate in RHCP mode when switches L are off and switches R are on. On the other hand, when switches L are on and switches R are off, the antenna will radiate in LHCP mode.

Figure 2.5: Polarization reconfigurable antenna [27]
2.6 Reconfiguration Mechanisms

There are three reconfiguration mechanisms which can be applied to reconfigurable antenna systems depending on their specific applications [28] which are:

i. Electronically controlled mechanism which is attached to the primary radiator. This includes any terminal-connected devices such as PIN diodes, RF MEMS, varactors and other terminal-connected components that require an applied electrical stimulus to facilitate reconfiguration.

ii. Pressure-driven or optically controlled mechanism which is connected to the parasitic radiator. This encompasses any terminal-free devices such as photodiodes, microfluidic mechanisms and other devices that do not require direct electrical stimulus or contact to facilitate reconfiguration.

iii. Dynamic material-based perturbation which includes similar technologies as in (i) and (ii) but it is embedded into the bulk or composite substrate and controlled both with and without a direct connection to the radiating and parasitic elements.

2.7 Reconfiguration Technologies

Reconfiguration mechanisms or control devices in the design of reconfigurable antenna systems can be further divided into four reconfiguration technologies. They are named as electromechanical, ferroic materials, solid state devices and fluidic reconfiguration [5].
2.7.1 Electromechanical Devices

Electromechanical devices can be very robust and can facilitate the operation of reconfigurable antennas. RF MEMS and RF NEMS have been used specifically in high frequency applications where loss mechanisms, electrical dimension, wave impedance and linearity are critical [29]. The small size of the electromechanical system is an attractive merit to incorporate switching and loading mechanisms in packaged configuration or as a mechanism that can be fabricated in situ or onto the antennas [30]. In addition, the small size will help to avoid unwanted transmission line effects or loading within the device and at the same time, can be used to create structurally reconfigurable electromechanical antenna systems where the moving parts act as the structural elements of the design [31].

MEMS, NEMS and other electromechanical mechanisms are often interfaced with through wire bonds and terminals for biasing and control [32]. These terminals must be sufficiently isolated by means of packaged and electromechanical design in order for the topology to be ideally suited for switching, routing and other tasks in the RF front-end chain [28]. The RF front-end chain requires electrically conductive bias and control lines to effectively navigate to and around the terminals in a multilayer environment. However, there is a design challenge when the electromechanical switches are to be integrated into reconfigurable antennas in terms of isolation. In this case, the isolation from bias and control structure must be sufficient to avoid interference with the intended operation of that particular antenna through spurious radiation or reactive loading.
There are a few fabrication methods to integrate RF MEMS and NEMS devices into the antenna structures which are discussed as follows:

2.7.1.1 Packaged RF MEMS and NEMS

Packaged RF MEMS and NEMS can be utilized in reconfigurable antenna designs as switching mechanisms or tunable discrete elements such as variable inductors and capacitors (varactors) [33]. RF MEMS and related micro or nano–scale components are sealed or packaged in these structures to protect the movable part from exposure to environmental parameters such as moisture and dust while at the same time, to provide physical protection from damage during handling or normal operation [34]. In addition, using a packaged unit makes it attractive for integration into platforms using rapid pick-and-place methods for mass fabrication. Two examples that demonstrate the implementation of packaged RF MEMS switches in reconfigurable antenna structures can be found in [35] and [36].

2.7.1.2 In Situ Fabricated RF MEMS and NEMS

This method is implemented by fabricating RF MEMS and NEMS onto or within the antenna structure which is a direct method for the integration of reconfiguration mechanisms into the antenna design. However, fabrication of these devices directly onto the antenna will give rise to undesired interaction with the packaging or hermetic sealing and loading from wire bonding. Thus, the challenge lies in providing bias signal and control to the antennas. The ability to provide biasing directly through these structures in a non-terminal configuration will create many opportunities. Previous works are exemplified in [37], [38] and [39].
2.7.1.3 *Structurally Reconfigurable Electromechanical Systems*

This method consists of a wide range of technologies which includes micro-machined Vee antenna [40]. However, material-based techniques using electroactive and shape-memory materials is the emerging technology which provides unique solutions and alternatives to electromechanical reconfiguration technology driven by electrostatic actuation of metallic elements. The material-based techniques will have the ability to transduce an electrical stimulus into a physical movement or displacement through their structure-property relations which serve as an advantage in providing continuous reconfigurability instead of a discrete set of reconfigurable states. Pattern reconfigurable antennas using electroactive polymer (EAP) actuators have been reported in [41, 42]. Two different types of EAP actuators have been applied in each of those works which are ionic and dielectric EAPs. Helical shape memory alloy (SMA) has been implemented in the design of an axial-mode pattern reconfigurable helix antenna [43].

2.7.2 Ferroic Materials

The *ferroic* term comes from the combination of ferroelectric and ferromagnetic. Ferroic materials have the special feature to alter the dielectric, magnetic and conductive material properties both locally and across an entire antenna structure or aperture. These materials have also shown the same capability to provide continuous tunability similar to the electroactive materials but do not make structural changes beyond changes to their crystallographic morphology when biased [44]. Barium Strontium Titanate (BST) is one example of ferroelectric material which has seen the application in tunable antennas due to high tunability, high dielectric constant, relatively low loss and fast switching speed as observed in [16, 45, 46].
REFERENCES


[99] Digi-Key. (2010, RF Switches Add Flexibility. Article Library.


