

# Advanced Millimeter-wave Technologies

Antennas, Packaging and Circuits

Editors

Duixian Liu  
Brian Gaucher  
Ullrich Pfeiffer  
Janusz Grzyb

 WILEY

# Contents

<b>List of Contributors</b>	<b>xv</b>
<b>Preface</b>	<b>xix</b>
<b>Acknowledgements</b>	<b>xxi</b>
References . . . . .	xxi
<b>1 Introduction</b>	<b>1</b>
<i>Brian Gaucher</i>	
1.1 Challenges . . . . .	2
1.2 Discussion Framework . . . . .	4
1.3 Circuits . . . . .	4
1.4 Antenna . . . . .	5
1.5 RF Electronics . . . . .	6
1.5.1 Receiver . . . . .	6
1.5.2 Transmitter . . . . .	6
1.6 Packaging . . . . .	7
1.7 Organization and Flow of this Book . . . . .	9
References . . . . .	13
<b>2 Millimeter-wave Packaging</b>	<b>15</b>
<i>Ullrich Pfeiffer</i>	
2.1 Introduction . . . . .	18
2.1.1 Definition of Packaging . . . . .	21
2.1.2 Packaging Challenges and Future Directions . . . . .	23
2.2 Review of Microwave Packaging Technologies . . . . .	27
2.2.1 MMICs . . . . .	27
2.2.2 CNC Milled Metal Housings . . . . .	29
2.2.3 Multi-chip Packages . . . . .	30
2.3 Low-cost mmWave Packaging . . . . .	31
2.3.1 Low-cost Plastic Molding at mmWaves . . . . .	32
2.3.2 Chip-on-board at mmWaves . . . . .	33
2.4 Emerging Packaging Technologies . . . . .	34
2.4.1 Microcoaxial Wirebonds – Bridgewave . . . . .	34

2.4.2	Glass Microwave Integrated Circuit (GMIC, HMIC) – TYCO, M/A-COM . . . . .	34
2.4.3	Epsilon™ Packaging /MLMST™ Devices – Endwave . . . . .	35
2.4.4	Plastic Molded MMICs – UMS . . . . .	35
2.4.5	DCA with Integrated Antenna – IBM . . . . .	36
2.4.6	LGA with Integrated Antenna – IBM . . . . .	38
2.4.7	Wafer-level Packaging and Assembly of mmWave Devices . . . . .	41
2.5	Package Codesign at mmWaves . . . . .	42
2.5.1	Electromagnetic Modeling of mmWave Packages and Interconnects . . . . .	43
2.5.2	Integrated Antennas . . . . .	44
	References . . . . .	45
<b>3</b>	<b>Dielectric Properties at Millimeter-wave and THz Bands</b>	<b>49</b>
	<i>Khalid Z. Rajab, Joseph P. Dougherty and Michael T. Lanagan</i>	
3.1	Introduction . . . . .	49
3.2	Dielectric Characterization . . . . .	50
3.3	Outside the THz Gap – Material Characterization Techniques . . . . .	50
3.3.1	Parallel Plate (~DC–30 MHz) . . . . .	52
3.3.2	Resonant Cavity (~0.5–50 GHz) . . . . .	52
3.3.3	Transmission Line Methods (~0.01–300 GHz) . . . . .	55
3.3.4	Fourier Transform Infrared Spectroscopy (~1–100 THz) . . . . .	56
3.4	THz TDS (~0.1–10 THz) . . . . .	57
3.4.1	Transmission . . . . .	58
3.4.2	Error Analysis . . . . .	62
3.5	Dielectric Properties . . . . .	64
3.5.1	Semiconductors . . . . .	64
3.5.2	Ceramic Materials . . . . .	64
3.5.3	Thin Films . . . . .	65
3.5.4	Metamaterials . . . . .	65
3.5.5	Biomaterials . . . . .	65
3.5.6	Material Needs . . . . .	66
	References . . . . .	66
<b>4</b>	<b>Millimeter-wave Interconnects</b>	<b>71</b>
	<i>Janusz Grzyb</i>	
4.1	Introduction . . . . .	73
4.2	Interconnects at Millimeter-wave Frequencies . . . . .	74
4.2.1	Printed Planar Transmission Lines . . . . .	75
4.2.2	Metal Rectangular Waveguides . . . . .	90
4.3	Interconnect Technology Options for Millimeter-wave Applications . . . . .	91
4.3.1	Basic Technological Requirements . . . . .	91
4.3.2	MCM-L . . . . .	103
4.3.3	LTCC . . . . .	105
4.3.4	MCM-D . . . . .	107
4.3.5	Flexible Substrates . . . . .	111
4.3.6	Silicon Micromachining . . . . .	112

4.3.7	Plastic Injection Molding . . . . .	117
4.4	Performance-oriented Interconnect Technology Optimization . . . . .	118
4.4.1	Performance-oriented BCB Dielectric Thickness Optimization . . . . .	119
4.4.2	Transmission Line Discontinuities and Distributed Passives . . . . .	122
4.4.3	Bends . . . . .	125
4.5	Chip-to-package Interconnects at Millimeter-wave Frequencies . . . . .	134
4.5.1	Wirebonding . . . . .	136
4.5.2	Flip-chip Bonding . . . . .	140
4.5.3	Alternative Chip Interconnection Methods . . . . .	145
	References . . . . .	148
<b>5</b>	<b>Printed Millimeter Antennas – Multilayer Technologies</b>	<b>163</b>
	<i>O. Lafond and M. Himdi</i>	
5.1	Introduction and Considerations for Millimeter-wave Printed Antennas . . . . .	163
5.1.1	Introduction . . . . .	163
5.1.2	Results for Substrate Characterization Using Free Space and High- $Q$ Techniques . . . . .	166
5.1.3	Results of Substrate Characterization Using Printed Resonant Circuits	166
5.1.4	Substrate Choice: Impact on Antenna Efficiency . . . . .	170
5.1.5	Feeding Line Influence on Radiating Patterns . . . . .	173
5.2	Multilayer Interconnection Technology . . . . .	176
5.2.1	Introduction . . . . .	176
5.2.2	Multilayer Technologies on Soft Substrate with Thick Ground Plane .	180
5.3	Multilayer Antenna Array with Shaped Beam . . . . .	199
5.3.1	Directive Pattern with Passive Linear Array . . . . .	199
5.3.2	Sector Beam with Linear Array . . . . .	202
5.3.3	Cosecant Beam with Linear Array . . . . .	206
5.3.4	Highly Directive Antennas . . . . .	208
5.3.5	Multibeam Antenna . . . . .	215
5.4	Measurement Disturbances: Connector and Diffraction Problems for Printed Antennas . . . . .	219
5.4.1	Impact of Bonding Wire on Antenna Input Impedance . . . . .	222
5.4.2	Impact of Diffraction Effects on the Ground Plane and on the Connecting Circuitry . . . . .	224
5.5	Conclusion . . . . .	229
	References . . . . .	230
<b>6</b>	<b>Planar Waveguide-type Slot Arrays</b>	<b>233</b>
	<i>Jiro Hirokawa and Makoto Ando</i>	
6.1	Introduction . . . . .	233
6.2	Equivalent Length of a Round-ended Straight Slot . . . . .	234
6.2.1	Waveguide with a Round-ended Slot . . . . .	234
6.2.2	Comparison Between Calculation and Measurement . . . . .	235
6.2.3	Equal-area and Equal-perimeter Rectangular Slots for a Round-ended One . . . . .	237
6.2.4	New Definition of an Equivalent Rectangular Slot . . . . .	240

6.3	Alternating-phase Fed Single-layer Slotted Waveguide Array and its Sidelobe Suppression . . . . .	240
6.3.1	Alternating-phase Fed Arrays . . . . .	240
6.3.2	Array Design . . . . .	241
6.3.3	Measurements . . . . .	243
6.4	Center Feed Single Layer Slotted Waveguide Array . . . . .	247
6.4.1	Structure of a Center Feed Array . . . . .	247
6.4.2	Suppression of Sidelobes due to Aperture Blockage by Center Feed Waveguide . . . . .	248
6.4.3	Experimental Results . . . . .	249
6.4.4	Polarization Isolation between two Center-feed Single-layer Waveguide Arrays Arranged Side-by-Side . . . . .	253
6.5	Single-layer Hollow-waveguide Eight-way Butler Matrix . . . . .	256
6.5.1	Single-layer Eight-way Butler Matrix . . . . .	256
6.5.2	Design of the Couplers . . . . .	256
6.5.3	Design of Phase Shifters for the Eight-way Butler Matrix . . . . .	259
6.5.4	Characteristics of the Butler Matrix . . . . .	261
6.6	Radial Line Slot Antennas . . . . .	266
6.6.1	High Gain Radial Line Slot Antennas with a Boresight Beam . . . . .	266
6.6.2	Small Aperture Conical Beam Radial Line Slot Antennas . . . . .	269
6.7	Post-wall Waveguide-fed Parallel Plate Slot Arrays . . . . .	276
6.7.1	Transmission Loss in Post Waveguide . . . . .	276
6.7.2	Structure . . . . .	277
6.7.3	Antenna Efficiency as a Function of the Size . . . . .	278
6.7.4	Sidelobe Suppression and 45° Linear Polarization . . . . .	279
6.8	Coaxial-line to Post-wall Waveguide Transformers . . . . .	280
6.8.1	Transformer Using a Quasi-coaxial Structure and a Post-wall Waveguide . . . . .	280
6.8.2	Transformer between a Coaxial Line and a Post-wall Waveguide in PTFE Substrate . . . . .	284
	References . . . . .	291
<b>7</b>	<b>Antenna Design for 60 GHz Packaging Applications</b>	<b>295</b>
	<i>Duixian Liu</i>	
7.1	Introduction . . . . .	295
7.1.1	Material Selection . . . . .	296
7.1.2	Antenna Feed Line . . . . .	297
7.1.3	Flip-chip Mount . . . . .	298
7.1.4	Electromagnetic Interference Issues . . . . .	299
7.1.5	Packaging Effects . . . . .	300
7.1.6	Antenna Design . . . . .	302
7.2	Air-suspended Superstrate Antenna . . . . .	303
7.2.1	Air-suspended Superstrate Antenna Designs . . . . .	305
7.2.2	Air-suspended Superstrate Antenna Evaluation . . . . .	307
7.3	Packaged Antennas . . . . .	309
7.3.1	Cavity Size Effects on Antenna Performances . . . . .	315

7.3.2	Packaging Effects on Antenna Performance . . . . .	316
7.3.3	Antenna in System Performance . . . . .	323
7.4	A Patch Array . . . . .	325
7.5	Circularly Polarized Antenna . . . . .	328
7.6	Assembly Process . . . . .	334
7.7	Advanced Packaging Application . . . . .	335
7.7.1	LTCC-based Packages . . . . .	336
7.7.2	Silicon-based Packages . . . . .	342
	References . . . . .	348
<b>8</b>	<b>Monolithic Integrated Antennas</b> . . . . .	<b>353</b>
	<i>Erik Öjefors and Anders Rydberg</i>	
8.1	Introduction . . . . .	353
8.2	Monolithic Antenna Integration Challenges . . . . .	354
8.2.1	Antenna Size . . . . .	354
8.2.2	Substrate Modes . . . . .	356
8.2.3	Antenna Efficiency . . . . .	356
8.3	Manufacturing Techniques for Enhanced Antenna Performance . . . . .	357
8.4	Selection and Design of the On-chip Radiator . . . . .	358
8.4.1	Patch Antennas . . . . .	359
8.4.2	Dipole and Slot Antenna . . . . .	362
8.4.3	Inverted-F Antenna . . . . .	368
8.4.4	Loop Antennas . . . . .	370
8.5	Circuit Integration . . . . .	376
8.5.1	Cross-talk . . . . .	376
8.5.2	Monolithic Integrated Antenna Examples . . . . .	377
8.6	Packaging of Integrated Circuits with On-chip Antennas . . . . .	379
8.7	Monolithic Antenna Measurement Techniques . . . . .	380
8.8	Summary . . . . .	381
	References . . . . .	381
<b>9</b>	<b>Metamaterials for Antenna Applications</b> . . . . .	<b>385</b>
	<i>Anthony Lai, Cheng Jung Lee and Tatsuo Itoh</i>	
9.1	Introduction . . . . .	385
9.2	Left-handed Metamaterials: Transmission Line Approach . . . . .	386
9.2.1	Composite Right/Left-handed Resonator Theory . . . . .	387
9.2.2	Small Resonant CRLH TL Antennas . . . . .	389
9.2.3	Infinite Wavelength Resonant Antennas . . . . .	394
9.2.4	<i>N</i> -port Infinite Wavelength Series Feed Network . . . . .	400
9.3	Left-handed Metamaterials: Evanescent-mode Approach . . . . .	401
9.3.1	Leaky Wave Antennas Based on Evanescent-mode LH Metamaterials . . . . .	403
9.4	mmWave Metamaterial Antenna Applications . . . . .	405
9.4.1	94 GHz CRLH TL Feed Network . . . . .	406
9.4.2	W-band CRLH TL Leaky Wave Antenna . . . . .	407
9.5	Conclusions . . . . .	410
	References . . . . .	410

*Andrew R. Weily, Trevor S. Bird, Karu P. Esselle and Barry C. Sanders*

10.1	Introduction . . . . .	413
10.2	EBG Materials and Components . . . . .	414
10.2.1	One-dimensional, Two-dimensional and Three-dimensional EBG Materials . . . . .	414
10.2.2	EBG Waveguides and Components . . . . .	420
10.2.3	High Impedance Ground Planes . . . . .	424
10.3	Printed Antennas on EBG Substrates . . . . .	427
10.4	High Gain PRS, EBG and Metamaterial Antennas . . . . .	429
10.4.1	High Gain PRS and Fabry–Perot Antennas . . . . .	429
10.4.2	High-gain One-dimensional EBG Resonator Antennas . . . . .	430
10.4.3	High-gain Two-dimensional EBG Resonator Antennas . . . . .	433
10.4.4	High-gain Three-dimensional EBG Resonator Antennas . . . . .	434
10.4.5	High-gain Metamaterial Antennas . . . . .	437
10.5	Woodpile EBG Waveguides, Horn Antennas and Arrays . . . . .	438
10.5.1	Woodpile EBG Sectoral Horn Antennas . . . . .	438
10.5.2	Woodpile EBG Array Antennas . . . . .	440
10.6	Miscellaneous EBG Antennas and Components . . . . .	443
10.7	Summary . . . . .	443
	References . . . . .	444

## 11 Millimeter-wave Electronic Switches

*Jean-Olivier Plouchart*

11.1	Introduction . . . . .	451
11.2	Switch Applications in mmWave Wireless Communication Systems . . . . .	452
11.3	Switch Specifications . . . . .	454
11.4	Impact of Switch Performance on Communication System . . . . .	456
11.5	Small-signal mmWave Switch Design . . . . .	457
11.5.1	Series SPST Switch First-order Model . . . . .	457
11.5.2	Shunt SPST Switch First-order Model . . . . .	458
11.5.3	Series–shunt SPST Switch First-order Model . . . . .	458
11.5.4	Switch Figure-of-merit . . . . .	458
11.5.5	SPDT with Series Switches . . . . .	459
11.5.6	SPDT with Series and Shunt Switches . . . . .	459
11.5.7	SPDT with Series and Shunt Switches and Matching Inductor . . . . .	462
11.6	Solid-state Switch Implementation . . . . .	467
11.6.1	PIN Diode Switch . . . . .	467
11.6.2	NFET Switch . . . . .	469
11.6.3	Small-signal 65 nm CMOS mmWave Switch Design . . . . .	470
11.6.4	Large-signal 65 nm CMOS mmWave Switch Design . . . . .	471
11.7	Comparison of Electronic Switch Implementations . . . . .	474
11.7.1	Performance Comparison of PIN Diode Switches . . . . .	474
11.7.2	Performance Comparison of CMOS Switches . . . . .	474
11.7.3	Performance Comparison of III-V Switches . . . . .	476

11.7.4	Performance Comparison of mmWave Switches . . . . .	477
11.7.5	Power Handling for Different Semi-conductor Technologies . . . . .	479
11.7.6	Solid-state Switch Technology Challenges . . . . .	480
	References . . . . .	480
<b>12</b>	<b>MEMS Devices for Antenna Applications</b>	<b>483</b>
	<i>Nils Hoivik and Ramesh Ramadoss</i>	
12.1	Introduction . . . . .	483
12.2	Micromachining Techniques . . . . .	484
12.3	MEMS Switches – Principle of Operation . . . . .	486
12.3.1	Mechanical Spring Constant . . . . .	487
12.3.2	Electrostatic Force . . . . .	488
12.3.3	Pull-in and Release Voltage . . . . .	489
12.4	Contact and Capacitive MEMS Switches . . . . .	491
12.4.1	Ohmic Contact MEMS Switches – Series Configuration . . . . .	492
12.4.2	Broadband Capacitive MEMS Switches – Shunt Configuration . . . . .	497
12.4.3	Switch Performance and Design Considerations . . . . .	503
12.4.4	MEMS Varactors . . . . .	506
12.5	MEMS Reliability and Power Handling . . . . .	506
12.5.1	Reliability and Failure Modes . . . . .	507
12.5.2	Power Handling . . . . .	509
12.6	Integration of MEMS Switches with Antennas . . . . .	512
12.6.1	Hybrid Integration . . . . .	513
12.6.2	Monolithic Integration . . . . .	514
12.6.3	Integration Issues . . . . .	514
12.7	MEMS for Reconfigurable Antennas . . . . .	516
12.7.1	MEMS-based Frequency Reconfigurable Antenna . . . . .	517
12.7.2	Example Configurations . . . . .	519
12.7.3	Frequency Tuning by Changing the Effective Dielectric Constant . . . . .	522
12.8	MEMS-enabled Antenna Beam Scanning . . . . .	525
12.8.1	Mechanical Beam Steering . . . . .	525
12.8.2	Electronic Beam Scanning Using MEMS Phase Shifters . . . . .	526
12.8.3	MEMS-enabled Antenna Pattern Reconfiguration . . . . .	529
12.8.4	MEMS-enabled Reflect Array Antennas . . . . .	530
12.9	Future Applications/Outlook . . . . .	532
	References . . . . .	533
<b>13</b>	<b>Phased Array</b>	<b>537</b>
	<i>Hsueh-Yuan Pao and Jerry Aguirre</i>	
13.1	Phased Array Essentials . . . . .	537
13.1.1	Introduction . . . . .	537
13.1.2	Continuous Line Source Antenna . . . . .	538
13.1.3	From Continuous Line Source Antenna to Phased Array Antenna . . . . .	542
13.2	Antenna Element Design for Phased Arrays . . . . .	548
13.2.1	Mutual Coupling . . . . .	550
13.2.2	Large Array Design Methodology . . . . .	551



13.2.3	Finite Array Design Methodology . . . . .	560
13.3	Beam-forming Network . . . . .	569
13.3.1	Introduction . . . . .	569
13.3.2	Different Beam-forming Network of Complex Weightings . . . . .	570
13.4	Design and Manufacture Issues . . . . .	582
13.4.1	Design Considerations . . . . .	582
13.4.2	Fabrication . . . . .	588
13.4.3	Assembly . . . . .	591
	References . . . . .	595

**14 Integrated Phased Arrays** **597**

*Sanggeun Jeon, Aydin Babakhani and Ali Hajimiri*

14.1	Introduction . . . . .	597
14.2	Integrated Phased Arrays . . . . .	599
14.2.1	Principles of Phased Arrays . . . . .	600
14.2.2	Benefits of Phased Arrays . . . . .	601
14.2.3	Silicon Integration Challenges . . . . .	604
14.2.4	Integrated Antennas in Silicon . . . . .	605
14.2.5	Architectural Considerations . . . . .	608
14.3	Fully Integrated mmWave Phased-array Transceiver . . . . .	612
14.3.1	Architecture . . . . .	612
14.3.2	Circuit Blocks . . . . .	615
14.3.3	Experimental Results . . . . .	623
14.4	Direct Antenna Modulation (DAM) . . . . .	628
14.4.1	Concept . . . . .	629
14.4.2	Implementation . . . . .	632
14.4.3	Experimental Results . . . . .	635
14.5	Large-scale Integrated Phased Arrays . . . . .	636
14.5.1	Large-scale Phased-array Architecture . . . . .	638
14.5.2	CMOS Phased-array Element . . . . .	640
14.5.3	Experimental Results . . . . .	644
14.6	Conclusions . . . . .	647
	References . . . . .	648

**15 Millimeter-wave Imaging** **651**

*Zuowei Shen and Neville C. Luhmann, Jr*

15.1	Introduction to mmWave and THz Imaging . . . . .	651
15.2	Passive mmWave Imaging Systems . . . . .	655
15.3	Active mmWave Imaging . . . . .	659
15.4	Representative Examples of Passive and Active mmWave Imaging Systems . . . . .	660
15.4.1	Three-dimensional Active mmWave Video Camera . . . . .	661
15.4.2	PMMW Cameras . . . . .	663
15.4.3	ECEI/MIR . . . . .	667
15.4.4	mmWave Imaging System Applications in Astronomy . . . . .	677
15.4.5	mmWave and THz Radars . . . . .	679

15.5	THz Imaging Technology . . . . .	680
15.6	Technologies in mmWave/THz Imaging . . . . .	683
15.6.1	Mixers . . . . .	683
15.6.2	Direct Detection Receiver . . . . .	686
15.6.3	Microbolometer Focal Plane Arrays . . . . .	688
15.6.4	LO and Probe Sources . . . . .	689
15.6.5	Quasi-optical Power Combining . . . . .	691
15.6.6	Beam Formation and Shaping . . . . .	692
15.6.7	Imaging Optics . . . . .	697
15.7	Conclusion and Outlook . . . . .	699
	References . . . . .	699
<b>16</b>	<b>Millimeter-wave System Overview</b>	<b>709</b>
	<i>Scott K. Reynolds, Alberto Valdes-Garcia, Brian A. Floyd, Yasunao Katayama and Arun Natarajan</i>	
16.1	Outlook for Low-cost, High-volume mmWave Systems . . . . .	709
16.2	Example: 60 GHz SiGe Transceiver . . . . .	711
16.3	Demonstration Board for 60 GHz SiGe Transceiver . . . . .	716
16.4	Transceiver ICs as Part of Larger Digital System . . . . .	718
16.5	Future Evolution . . . . .	725
	References . . . . .	726
<b>17</b>	<b>Special Millimeter-wave Measurement Techniques</b>	<b>729</b>
	<i>Thomas Zwick and Ullrich Pfeiffer</i>	
17.1	Introduction . . . . .	729
17.2	Overview of Modern Vector Error Calibration Methods . . . . .	730
17.3	Lumped Element De-embedding . . . . .	731
17.4	Determination of Transmission Line Parameters from S-Parameter Measurements . . . . .	734
17.4.1	Propagation Constant Determination from Measurement of Two Transmission Lines of Different Length . . . . .	735
17.4.2	Accurate Impedance Determination of Transmission Lines . . . . .	737
17.5	Probe-based Antenna Measurement . . . . .	737
17.5.1	Calibration Method . . . . .	738
17.5.2	Derivation of Error Terms for SOL Calibration . . . . .	741
17.5.3	Example of Setup for the Frequency Range of 50 GHz to 65 GHz . . . . .	742
17.6	Non-destructive IC Package Characterization . . . . .	744
17.6.1	Formulation of the Algorithm . . . . .	746
17.6.2	Test Chips for Non-destructive Package Characterization . . . . .	749
17.6.3	Non-destructive COB and QFN Package Characterization . . . . .	754
17.6.4	Non-destructive FC-PBGA Package Characterization . . . . .	754
17.6.5	Non-destructive Flip-chip Ball Interconnect Characterization . . . . .	754
17.6.6	Discussion and Outlook . . . . .	763
17.6.7	Nomenclature . . . . .	764
	References . . . . .	765

<b>18 Silicon-based Packaging and Silicon Micromachining</b>	<b>771</b>
<i>Cornelia K. Tsang, Paul S. Andry and Michelle L. Steen</i>	
18.1 Introduction to mmWave Packaging . . . . .	771
18.1.1 Review Existing Packaging Technology . . . . .	771
18.1.2 Advantages and Limitations . . . . .	772
18.2 Introduction to Silicon-based Packaging . . . . .	773
18.2.1 Key Silicon-based Packaging Technology Elements and Application Examples . . . . .	773
18.3 Silicon-based Packaging: Process Options . . . . .	776
18.3.1 Introduction to Semiconductor Processing . . . . .	776
18.3.2 Lithography . . . . .	777
18.3.3 Silicon Micromachining . . . . .	783
18.3.4 Metallization . . . . .	788
18.3.5 Wafer Thinning . . . . .	797
18.4 Assembly Options for Silicon-based Packaging . . . . .	799
18.4.1 Wafer-level Processes . . . . .	799
18.4.2 Die-level Processing . . . . .	804
18.5 Example of mmWave System on Silicon Package . . . . .	805
References . . . . .	808