Advanced Millimeter-wave Technologies

Antennas, Packaging and Circuits

Dr Duixian Liu IBM, USA

Mr Brian Gaucher IBM, USA

Dr Ulrich Pfeiffer *University of Wuppertal, Germany*

Dr Janusz Grzyb Huber & Suhner AG, Switzerland



Advanced Millimeter-wave Technologies

Advanced Millimeter-wave Technologies

Antennas, Packaging and Circuits

Dr Duixian Liu IBM, USA

Mr Brian Gaucher IBM, USA

Dr Ulrich Pfeiffer *University of Wuppertal, Germany*

Dr Janusz Grzyb Huber & Suhner AG, Switzerland



This edition first published 2009 © 2009 John Wiley & Sons Ltd.

Registered office John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Library of Congress Cataloging-in-Publication Data

Liu, Duixian.

Advanced millimeter-wave technologies : antennas, packaging and circuits / Duixian Liu ... [et al.]. p. cm.

Includes bibliographical reference and index. ISBN 978-0-470-99617-1 (cloth)

 Millimeter wave devices. 2. Millimeter waves. I. Liu, Duixian. TK7876.5.A38 2009 621.381–dc22

2008041821

A catalogue record for this book is available from the British Library.

ISBN 9780470996171 (H/B)

Set in 10/12pt Times by Sunrise Setting Ltd, Torquay, UK. Printed in Great Britain by CPI Antony Rowe, Chippenham.

Contents

Li	st of (Contributors	xv				
Pr	eface		xix				
Ac	Exhowledgements xxi References xxi						
1	Intr Bria	oduction n Gaucher	1				
	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				
	Refe	rences	13				
2	Millimeter-wave Packaging Ullrich Pfeiffer						
	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,	
			М/А-СОМ	. 34
		2.4.3	Epsilon TM Packaging /MLMS TM 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	Packag	ge Codesign at mmWaves	. 42
		2.5.1	Electromagnetic Modeling of mmWave Packages and Interconnects	. 43
		2.5.2	Integrated Antennas	. 44
	Refe	rences .		. 45
3	Diel	ectric P	roperties at Millimeter-wave and THz Bands	49
	Kha	lid Z. Ro	ijab, Joseph P. Dougherty and Michael T. Lanagan	
	3.1	Introdu	uction	. 49
	3.2	Dielec	tric Characterization	. 50
	3.3	Outsid	e 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 T	DS (~0.1–10 THz)	. 57
		3.4.1	Transmission	. 58
		3.4.2	Error Analysis	. 62
	3.5	Dielec	tric 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
	Refe	erences .		. 66
4	Mill	imeter-	wave Interconnects	71
-	Janı	ısz Grzy	b	
	4.1	Introd	uction	. 73
	4.2	Interco	onnects at Millimeter-wave Frequencies	. 74
		4.2.1	Printed Planar Transmission Lines	. 75
		4.2.2	Metal Rectangular Waveguides	. 90
	4.3	Interco	onnect 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	МСМ-Д	. 107
		4.3.5	Flexible Substrates	. 111
		4.3.6	Silicon Micromachining	. 112

		437	Plastic Injection Molding	117
	44	Perforr	nance-oriented Interconnect Technology Ontimization	118
		4 4 1	Performance-oriented BCB Dielectric Thickness Ontimization	110
		442	Transmission I ine Discontinuities and Distributed Passives	122
		443	Bends	122
	45	Chin_to	pends	120
	т.5	4 5 1	Wirebonding	134
		452	Flin-chin Bonding	140
		453	Alternative Chip Interconnection Methods	140
	Refe	rences .		148
5	Dmin	tod Mill	limeter Antonnes – Multilayer Technologies	162
5	O.L	afond an	nd M. Himdi	103
	5.1	Introdu	action 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	Multila	yer Interconnection Technology	176
		5.2.1	Introduction	176
		5.2.2	Multilayer Technologies on Soft Substrate with Thick Ground Plane .	180
	5.3	Multila	yer 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	Measu	rement Disturbances: Connector and Diffraction Problems for Printed	
		Antenn	as	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	Conclu	sion	229
	Refe	rences .		230
6	Plan	ar Wav	eguide-type Slot Arrays	233
	Jiro	Hirokaw	va and Makoto Ando	
	6.1	Introdu	ction	233
	6.2	Equiva	lent 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	200
			. 280
		6.8.2 Iransformer between a Coaxial Line and a Post-wall Waveguide in	20.4
	ъć	PIFE Substrate	. 284
	Refe	rences	. 291
7	Ante	enna Design for 60 GHz Packaging Applications	295
	Duix	sian Liu	
	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 Eff	ects on Antenna Performance	316
		7.3.3 Antenna in Sy	stem Performance	323
	7.4	A Patch Array		325
	7.5	Circularly Polarized A	Intenna	328
	7.6	Assembly Process		334
	7.7	Advanced Packaging	Application	335
		7.7.1 LTCC-based I	Packages	336
		7.7.2 Silicon-based	Packages	342
	Refe	ences		348
8	Mon	olithic Integrated Ant	ennas	353
	Erik	Öjefors and Anders Ry	dberg	
	8.1	Introduction		353
	8.2	Monolithic Antenna I	ntegration Challenges	354
		8.2.1 Antenna Size		354
		8.2.2 Substrate Mod	les	356
		8.2.3 Antenna Effic	iency	356
	8.3	Manufacturing Techni	ques for Enhanced Antenna Performance	357
	8.4	Selection and Design	of the On-chip Radiator	358
		8.4.1 Patch Antenna	as	359
		8.4.2 Dipole and Sl	ot Antenna	362
		8.4.3 Inverted-F An	tenna	368
		8.4.4 Loop Antenna	IS	370
	8.5	Circuit Integration		376
		8.5.1 Cross-talk		376
		8.5.2 Monolithic In	tegrated Antenna Examples	377
	8.6	Packaging of Integrate	ed Circuits with On-chip Antennas	379
	8.7	Monolithic Antenna N	Ieasurement Techniques	380
	8.8	Summary		381
	Refe	ences		381
9	Meta	materials for Antenn	a Applications	385
	Anth	ony Lai, Cheng Jung L	ee and Tatsuo Itoh	
	9.1	Introduction		385
	9.2	Left-handed Metamate	erials: Transmission Line Approach	386
		9.2.1 Composite Ri	ght/Left-handed Resonator Theory	387
		9.2.2 Small Resona	nt CRLH TL Antennas	389
		9.2.3 Infinite Wavel	ength Resonant Antennas	394
		9.2.4 N-port Infinite	Wavelength Series Feed Network	400
	9.3	Left-handed Metamate	erials: Evanescent-mode Approach	401
		9.3.1 Leaky Wave A	Antennas Based on Evanescent-mode LH Metamaterials	403
	9.4	mmWave Metamateria	al Antenna Applications	405
		9.4.1 94 GHz CRLI	I TL Feed Network	406
		9.4.2 W-band CRLI	H TL Leaky Wave Antenna	407
	9.5	Conclusions		410
	Refe	ences		410

10	EBG	Materials and Antennas	413
	Andr	ew 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
	Refe	rences	. 444
11	л л:н:	imatan waya Elaatnania Switchag	451
11	Iean	-Olivier Plouchart	431
	11 1		451
	11.1	Introduction	. 451
	11.2	Switch Applications in mm wave wireless Communication Systems	. 452
	11.5	Switch Specifications	. 434
	11.4	Small signal mmWaya Switch Dasign	. 430
	11.5	11.5.1 Series SDST Switch First order Model	. 437
		11.5.1 Series SFST Switch First-order Model	. 457
		11.5.2 Shuft SFST Switch First order Model	. 450
		11.5.5 Series-shuft of 51 Switch First-order Woder $\dots \dots \dots \dots \dots$. 458
		11.5.5 SPDT with Series Switches	. +50
		11.5.6 SPDT with Series and Shunt Switches	. 450
		11.5.0 SPDT with Series and Shunt Switches and Matching Inductor	57
	11.6	Solid-state Switch Implementation	467
	11.0	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
	Refe	rences.		. 480
12	MEN	MS Devi	ices for Antenna Applications	483
	Nils	Hoivik a	und Ramesh Ramadoss	
	12.1	Introdu	uction	. 483
	12.2	Micron	nachining 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	Contac	t 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	Integra	tion 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
	Refe	rences.		. 533
13	Phas	ed Arra	ay	537
	Hsue	eh-Yuan	Pao and Jerry Aguirre	
	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	Antenn	a Element Design for Phased Arrays	. 548
		13.2.1	Mutual Coupling	. 550
		13.2.2	Large Array Design Methodology	. 551

CON	FENTS
-----	--------------

	13.3	13.2.3 Finite Array Design Methodology	560 569 560
	13.4	13.3.2 Different Beam-forming Network of Complex Weightings Design and Manufacture Issues	570 582
		13.4.1 Design Considerations 13.4.2 Fabrication 13.4.2 Fabrication 13.4.3 Assembly	582 588 591
	Refe	rences	595
14	Integ Sang	g rated Phased Arrays geun Jeon, Aydin Babakhani and Ali Hajimiri	597
	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
	145	14.4.5 Experimental Results	626
	14.3	14.5.1. Large scale Dised erroy Arabitecture	620
		14.5.1 Large-scale rhased-array Floment	640
		14.5.2 CMOS Flidsed-allay Elefficitit	640
	14.6	Conclusions	647
	Refe	rences	648
15	Milli	meter-wave Imaging	651
	Zиоч	vei 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
		077
16	Millimeter-wave System Overview	709
	Scott K. Reynolds, Alberto Valdes-Garcia, Brian A. Floyd, Yasunao Katayama	
	and Arun Natarajan	
	16.1 Outlook for Low cost High volume mmWays Systems	700
	16.1 Outlook for Low-cost, High-volume finit wave Systems	709
	16.2 Example: 60 GHz SiGe Transceiver	/11
	10.5 Demonstration Board for 60 GHZ Side Transceiver	/10
	16.4 Transceiver ICs as Part of Larger Digital System	/18
	16.5 Future Evolution	725
	References	726
17	Special Millimeter wave Measurement Techniques	720
1/	Thomas Zwick and Illrich Dfaiffan	129
	Thomas Zwick and Ourich Fjeijjer	
	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 OFN Package Characterization	754
	17.6.4 Non-destructive FC-PBGA Package Characterization	754
	17.6.5 Non-destructive Flin-chip Ball Interconnect Characterization	754
	17.6.6 Discussion and Outlook	
	17.6.7 Nomenclature	703 764
	Pafarancas	704 765
		/ /

18	Silic Corn	o n-base elia K. 1	d Packaging and Silicon Micromachining Tsang, Paul S. Andry and Michelle L. Steen	771 771 771
	18.1	Introdu	ction to mmWave Packaging	771
		18.1.1	Review Existing Packaging Technology	771
		18.1.2	Advantages and Limitations	772
	18.2	Introdu	ction 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	Assem	bly Options for Silicon-based Packaging	799
		18.4.1	Wafer-level Processes	799
		18.4.2	Die-level Processing	804
	18.5	Examp	le of mmWave System on Silicon Package	805
	Refe	rences.		808
Inc	lex			813

xiv

813

LIST OF CONTRIBUTORS

Jerry Aguirre Kyocera America Inc., USA

Makoto Ando Tokyo Institute of Technology, Japan

Paul S. Andry Thomas J. Watson Research Center/IBM, USA

Aydin Babakhani California Institute of Technology, USA

Trevor S. Bird CSIRO ICT Centre, Sydney, NSW, Australia

Joseph P. Dougherty The Pennsylvania State University, USA

Karu P. Esselle Department of Electronics, Macquarie University, Sydney, NSW, Australia

Brian A. Floyd Thomas J. Watson Research Center/IBM, USA

Brian Gaucher Thomas J. Watson Research Center/IBM, USA

Janusz Grzyb Huber & Suhner AG, Switzerland, formerly IBM T. J. Watson Research Center, USA

Ali Hajimiri California Institute of Technology, USA

M. Himdi IETR, University of Rennes 1, France

Jiro Hirokawa Tokyo Institute of Technology, Japan

Nils Hoivik Vestfold University College, Norway

Tatsuo Itoh Department of Electrical Engineering, University of California, Los Angeles, USA

LIST OF CONTRIBUTORS

Sanggeun Jeon Korea University, Seoul, Korea

O. Lafond IETR, University of Rennes 1, France

Anthony Lai HRL Laboratories, LLC, Malibu, California, USA

Michael T. Lanagan The Pennsylvania State University, USA

Cheng Jung Lee Rayspan Corporation, San Diego, California, USA

Duixian Liu Thomas J. Watson Research Center/IBM, USA

Neville C. Luhmann, Jr University of California, Davis, USA

Yasunao Katayama Thomas J. Watson Research Center/IBM, USA

Arun Natarajan Thomas J. Watson Research Center/IBM, USA

Erik Öjefors University of Wuppertal, Germany

Hsueh-Yuan Pao Lawrence Livermore National Laboratory, USA

Jean-Olivier Plouchart Thomas J. Watson Research Center/IBM, USA

Ullrich Pfeiffer University of Wuppertal, Germany

Khalid Z. Rajab The Pennsylvania State University, USA

Ramesh Ramadoss Auburn University, Norway

Scott K. Reynolds Thomas J. Watson Research Center/IBM, USA

Anders Rydberg Uppsala University, Sweden

Barry C. Sanders Institute for Quantum Information Science, University of Calgary, Alberta, Canada

Zuowei Shen University of California, Davis, USA

xvi

LIST OF CONTRIBUTORS

Michelle L. Steen Thomas J. Watson Research Center/IBM, USA

Cornelia K. Tsang Thomas J. Watson Research Center/IBM, USA

Alberto Valdes-Garcia Thomas J. Watson Research Center/IBM, USA

Andrew R. Weily CSIRO ICT Centre, Sydney, NSW, Australia

Thomas Zwick Institut für Hochfrequenztechnik und Elektronik (IHE), Universität Karlsruhe (TH), Germany

Preface

This book is intended for a wide range of researchers, engineers, managers and the wireless industry at large who are interested to learn and influence the future direction of wireless. Its focus is on millimeter-wave (mmWave) antennas and packaging, but context and relevance is provided by including a systems perspective to give the reader an understanding of the importance of each element and the hidden depths beyond the seemingly simple topics. The goal of this book is not to showcase problems solved, but to educate everyone in this new and exciting area of research that holds the promise further to invigorate and fuel the wireless industry and pull together the brightest minds to solve some of the toughest technical challenges we have ever faced as a wireless industry. What the reader will find between these covers is the work of a small subset of people who have begun to scratch the surface enough for others to see the few brilliant gems hidden in the depths of granite-hard challenges.

At the time of writing, there were no books available on the subject of mmWave chip, antenna and packaging co-design. In order to fill this void, the authors decided to leverage some of the most recent efforts and pull them together into a coherent story that builds from a bottoms-up approach into useful and interesting systems.

Acknowledgements

The authors would like to acknowledge the many people and organizations that made this work possible, especially seed funding from programs including NASA, under contract NAS3-03070, and DARPA, contracts N66001-02-C-8014 and N66001-05-C-8013. As in every field, there are pioneers who began in this area years ago. There is no clear delineation of by whom and when work in the mmWave field began, but there was a defining demonstration of its potential as early as 1895 with J.C. Bose, and the field has been rich with many contributors since. Likewise, Japan stands out as the first country to promote strongly the use of mmWaves, beginning decades ago. Therefore, it only seems fitting to mention from a very long list a few key people who helped to inspire this work: J.C. Bose [1], Johann-Friedrich Luy [2], Keiichi Ohata [3,4], Peter F.M. Smulders [5], Herbert Zirath [6], Peter Russer [7], Hiroyo Ogowa [8,9], Ted Rappaport [10], Larry Larson [11], John Cressler [12]. Also, fundamental to the success of any new technical area is university involvement. A few of the key researchers and their universities who took up this challenge early on and helped to make great strides, as seen in recent ISSCC and other symposia, journals and conferences, are: Professor Ali Hajimiri of California Institute of Technology; Professors Robert Broderson and Ali Niknejad of UC Berkeley; Professors John Cressler and Joy Laskar of Georgia Institute of Technology; Professor Charles Sodini of the Massachusetts Institute of Technology (MIT); Professors Behzad Razavi, Frank Chang [8] and Tatsuo Itoh of UCLA; Professors Larry Larson, Gabriel Rabiz and Larry Milstein of UCSD; Professor John Long of Delft University; Professors Ken O of the University of Florida; Dr Efstratios Skafidas of Melbourne/NICT Australia; Professors Linda Katehi and Jennifer T. Bernhard of the University of Illinois; Professor John Volakis of Ohio State University; Professor Koichi Ito of Chiba University, Japan; Professor Yue Ping Zhang of Nanyang Technological University, Singapore; and Professor Jri Lee of Taiwan National University.

References

- T. Sarka and D. Sengupta, 'An appreciation of J. C. Bose's pioneering work in millimeter and microwaves', *History of Wireless* 9 (1977), pp. 291–310.
- [2] J.-F. Luy and B. Adelseck, 'Silicon MMICs for millimeter wave communication links', 1998 IEEE International Conference on Electronics, Circuits and Systems 1 (1998), pp. 51–4.
- [3] K. Ohata, K. Maruhashi, M. Ito, S. Kishimoto, K. Ikuina, T. Hashiguchi, N. Takahashi, and S. Iwanaga, 'Wireless 1.25 Gb/s transceiver module at 60 GHz-band', 2002 IEEE International Solid-State Circuits Conference ISSCC, 2002. Digest of Technical Papers, 1: pp. 298–468, 2002.

- [4] O. Keiichi, M. Kenichi, I. Masaharu, and N. Toshio, 'Millimeter-wave broadband transceivers', NEC Journal of Advanced Technology 2(3) (2005), pp. 211–16.
- [5] P. Smulders, 'Exploiting the 60 GHz band for local wireless multimedia access: prospects and future directions', *IEEE Communications Magazine* **40** (2002), pp. 140–7.
- [6] H. Zirath, C. Fager, M. Garcia, P. Sakalas, L. Landen, and A. Alping, 'Analog MMICs for millimeter-wave applications based on a commercial 0.14-μm pHEMT technology', *IEEE Transactions on Microwave Theory and Techniques* 49(11) (2001), pp. 2086–92.
- [7] P. Russer, 'Si and SiGe Millimeter-Wave Integrated Circuits', *IEEE Transactions on Microwave Theory and Techniques* 46(5) (1998) pp. 590–603.
- [8] H. Ogowa, 'A study on millimeterwave research in NICTi', Japan PROJECT REPORT, http://www.aptsec.org/Program/ICT/WebHRDICT/Batch-5/MillimiterWave.pdf.
- [9] Y. Shoji, Y. Hashimoto, and H. Ogawa, 'Fiber-optic broadband signal distribution link based on a millimeter-wave self-heterodyne transmission/optical remote heterodyne detection technique', *IEICE Transactions* 88-C(7) (2005), pp. 1465–74.
- [10] C. R. Anderson, and T. S. Rappaport, 'In-building wideband partition loss measurements at 2.5 and 60 GHz', *IEEE Transactions on Wireless Communications* **3**(3) (2004), pp. 922–8.
- [11] L. Larson, 'SiGe HBT BiCMOS technology as an enabler for next generation communications systems', *12th GAAS Symposium*, Amsterdam, 2004.
- J. D. Cressler, 'SiGe Research Activities'. http://users.ece.gatech.edu/~cressler/research/Cressler%20Georgia%20Tech%20SiGe%2012-05.pdf.

1 Introduction

Brian Gaucher

There is an unusual confluence of three major disruptive and threshold events taking place that are fundamentally reshaping the wireless industry. First, wireless has become a critical, accepted and necessary part of everyday life, e.g. the number of mobile phone users growing at approximately one billion per year and younger generations and countries skipping the PC in favor of handheld wireless devices [1]. The second threshold event is the now rapidly growing high-definition video, automotive radar and high-resolution imaging markets, which have created a sudden need for extremely broadband gigabits per second (Gbps), highly integrated, low-cost and low-power wireless devices in the millimeter-wave (mmWave) frequency bands, which previously only the military could afford. The third threshold event occurring is silicon technology and tools have been developed with suitable performance characteristics to enable radio design, integration and operation at mmWave frequencies; here we specifically discuss the range 60–194 GHz, although the literature is now showing silicon working at hundreds of gigahertz [2].

The enormous reliance of consumers and enterprises on wireless and the evolving mobile Internet is having a disruptive influence on the telco industry, e.g. wireless subscriptions now outnumber landline phone subscriptions and Apple's iPhoneTM or Google's GPhoneTM [3,4] are forcing mobile carriers into 'openness', effectively reinventing wireless networks and the way they operate and make money. This reliance and evolution speaks to the convenience factor as well as perceived new utility that this technology is providing consumers and enterprise users.

Likewise in the automotive industry, radar units are now options for high-end vehicles and may become mandatory under Intelligent Highway programs around the world, owing to the potential increased safety they can provide. This means a new market for tens of millions of mmWave systems per year.

The growing high-definition multimedia revolution will also require a significant portion of devices to be wireless. This is creating demand for high-speed bandwidth that goes well beyond what wireless systems of today can handle. If one looks at the lowest bandwidth requirement for uncompressed high definition television (HDTV), it is about 1.5 Gbps and with some minor coding to make it more robust to multi-path and fading, it easily tops 2 Gbps as discussed within the IEEE 802.15.3c [5]. Today's conventional WiFi delivers unprecedented performance for both office and home use, but tops out at 54 Mbps, with some proprietary systems going as high as 108 Mbps. There is hope that 802.11n and ultra wide band (UWB) systems will get as high as 480 Mbps. UWB systems that utilize limited spectrum between 3.1 and 10.6 GHz have met with marginal success so far, but also promise up to 960 Mbps over a meter or two. At the time of writing, such systems have met with only marginal success in both data rate and distance. Thus, wireless is exploding in use and rapidly evolving from convenience to need across multiple industries and will continue to grow in this direction. In order to satisfy these future WiFi, HDTV, radar and other system needs of speed, capacity, security and robust performance over distance, completely new mmWave (60–194 GHz) solutions will be required.

1.1 Challenges

There is a growing need to solve the huge technical hurdles to cost-effectively leverage the vast unlicensed bandwidth available at mmWave frequencies and satisfy these growing demands. Wireless HDTV is a good example of this and worthy of further exploration here. This application is demanding dramatically higher data rates on the order of 10-100 times current rates. Indeed, they are increasing much faster than current wireless systems can handle and an alternative solution is needed. Given the data rate, capacity and quality of service (QoS) requirements, this can only reasonably happen in a spectrum location where there is suitable worldwide bandwidth on the order of gigahertz with rules that allow one to close a reasonable link budget. These issues have been the fuel and motivation for looking upward in spectrum. As one climbs the spectrum ladder, the first frequency allocation where all of this has the possibility of working well across the varied application space is the 60 GHz band. At 60 GHz there is 3-7 GHz of worldwide bandwidth available depending upon the country; see Figure 1.1 for a sample of countries. In terms of available bandwidth and allowable rules such as transmit power, lack of incumbent users, simple flexible transmission rules, etc. 60 GHz is a boon but it also comes with significant challenges, e.g. ability to do this in a low-cost, physically suitable and robust manner; likewise, the 77 GHz band is the direction the automotive industry is taking, especially in Europe, for automotive radar systems, also called adaptive cruise control (ACC) and Collision Avoidance Systems. There is also increased development activity in the 94, 120 and 194 GHz bands which are being utilized for homeland security applications such as radar, imaging systems, remote sensing, active denial and many others.

Given this set of events, opportunities and constraints, wireless designers have begun developing mmWave system architectures, circuits, antennas and packages; but as expected, they face enormous challenges of simulation, design, integration, physical realization, packaging and test of complete systems that are literally orders of magnitude more difficult than 2.4 and 5 GHz WiFi systems of today; yet to be successful they have to be nearly the same cost.



Figure 1.1: The 60 GHz spectrum chart.

If designers can find ways around these challenges, then there are significant benefits that are well worth the effort. The bandwidth and flexible open rules are the most obvious, but there are other less obvious ones also, depending upon if the glass is viewed as half full or half empty. At 60 GHz the wavelength in free space is approximately 5 mm, so circuit designers have the option to use transmission line structures as matching elements and resonant structures, in ways impossible to think about at 2.4 or 5 GHz. Similarly, on-chip filtering becomes possible and on-chip or in-package antennas are now a choice. Traditional microwave board elements such as Lange couplers, 90° hybrids, rat-race structures and many others are now small enough for on-chip consideration. Antenna beam-forming, steering and spatial-power combining become viable system design considerations even in consumerlevel solutions, something previously only enjoyed by high-end military systems. Owing to this wavelength consideration, levels of integration go beyond what is achievable at 2.4 and 5 GHz, e.g. including filters and antennas on chip or in the chip package. Indeed, the whole area of packaging is flipped on its head when considering including antennas within the package itself. One's packaging mindset shifts from containing radiofrequency (RF) radiation to intentionally radiating specific frequencies, while attenuating others. This will be one of the themes for this book.

Then there is the glass half empty point of view. At mmWave frequencies, the world of consumer level systems, circuit, antenna and packaging design, is largely unknown. For example, at 2.4 and 5 GHz, a designer takes the dielectric constant of PC boards for granted, something that is known and can be relied upon; but this is not the case at e.g. 60 GHz and higher. At such frequency extremes, each material has to be characterized and relevant data extracted from samples. There are also new metamaterials and devices that might prove invaluable, e.g. electronic band gap (EBG), anisotropic approaches, new polarization techniques, etc., but as yet they remain largely untried and untested at mmWave frequencies. Simple interconnects that work well at 5 GHz may have untenable loss at 60 GHz, where each and every interface outside the chip has to be considered in the link budget. As designers pull the antenna design into the chip or chip package, there are many new and important considerations and design options that need to be taken into account and traded off, which affect the whole system. Then there are the circuit design challenges too. At 60 GHz basic transistors, as good as they have become recently, run out of gas in this frequency range, e.g. gain is considerably lower than 5 GHz, isolation decreases, power generation is much more challenging and losses are much higher [6]. On top of all of this, today's design tools have not been tested in any significant way at 60 GHz and even the smallest variation or error may have a significant impact on the end product's performance. Although time will help,

ADVANCED MILLIMETER-WAVE TECHNOLOGIES

today even relatively simple 60 GHz circuits require hours to simulate and it is not unusual to wait days for more complex circuits. Simulation times of digital systems that include analog front ends running at 60 GHz are currently un-simulateable due to both convergence and time required. And where do designers get valid active and passive models and macros they can trust for use in silicon level chip design that yield the correct designs at the first attempt? Even basic RF switches and switch elements need special consideration for device selection, design, use and simulation.

Thus, the challenges and benefits are many, making this an incredibly rich and deep area of research in the coming years, with streams of patents emerging around all of the above, virtually reinventing the wireless industry. As all of this takes shape, we will begin to benefit as consumers of this technology; we will find 60 GHz will enable 1–10 Gbps wireless solutions in a wide range of products such as next-generation WiFi, wireless HDTV, MP3 players and cell phones. These latter devices will be used as electronic wallets that can nearly instantly download, pay for and store a HD-movie for transport to the home and wirelessly upload it to home theater systems. There will be kiosks that act as displays for the hard drives and systems that reside in your cell phone and so much more.

As we master the design idiosyncrasies of 60 GHz, the wireless industry will move up to 77 GHz to develop cost-effective ACC for cars and Intelligent Highway Systems, where there exist a whole new set of packaging and antenna challenges on top of extreme environmental conditions. As next-generation silicon-based terahertz (THz) imagers evolve, inspectors will more easily be able to detect non-metallic weapons and explosives from a safe distance using THz imaging techniques and high-performance computing. This will make airports and critical entry points safer for everyone. However, to achieve all or any of the above in any cost-effective manner requires designers to solve a myriad of extremely challenging problems.

1.2 Discussion Framework

With a reasonable motivation of why the mmWave frequency is important and useful and the basics of what the challenges are, the next step is to establish a simple consistent framework that can be used throughout the book that addresses the system architecture, antennas, circuits and packaging in a holistic manner. Rather than highlight the multitude of architectural solutions for all wireless architectures and applications, e.g. direct conversion, low-intermediate frequency (IF), heterodyne, super-heterodyne, etc., and performance targets, we choose a single commonly applied approach of the super-heterodyne architecture [7,8]. We use this as our reference point for discussion purposes. It is not the simplest architecture, but is general purpose and contains all the elements of virtually any wireless system one can imagine. Based on that architectural approach, we call out circuits, antennas and packaging options that reference this and which then be addressed in the remainder of the book.

1.3 Circuits

The super-heterodyne architecture is one of the more complex and therefore more encompassing architectures, making it a good choice to frame the larger circuit, antenna and packaging challenges. Although not optimal for all, it could be used for any of the



Figure 1.2: Generalized 60 GHz super-heterodyne block diagram.

aforementioned applications; Gbps wireless, radar, imaging etc. A simplified block diagram of a 60 GHz radio architecture is shown in Figure 1.2. It is based on a single-voltage controlled oscillator (VCO) super-heterodyne (multiple mixing stages) time-division duplex (switches from transmit to receive (T/R) rather than simultaneous transmit and receive) design with variable-IF frequency (byproduct of a single local oscillator (LO)). The high-frequency 60 GHz signals connect directly from integrated antennas to the T/R switch and to the low noise amplifier (LNA) input or the power amplifier (PA) output to avoid the need for external packaging and waveguide structures with their associated size, weight and power losses.

1.4 Antenna

For reasons to be discussed in detail throughout the book, mmWave antennas will nearly always be integrated with the chip or chip package. The integrated antenna has two major functions: the first is an efficient radiator or collector and the second as a bandpass filtering function. The natural bandpass filtering provided by the antenna helps both to limit the noise bandwidth prior to the LNA and to provide some image rejection. It is critical to any wireless system, but at mmWave frequencies the antenna becomes even more so because of the potential detrimental effects of interconnection losses, distance to RF electronics, match and proximity effects of nearby materials, receiver noise figure and transmit power. At mmWave frequencies power generation is extremely difficult and 'expensive' DC power wise, making antenna efficiency paramount. Designers cannot afford to waste hard-fought-for RF power only to lose it to 'simple' but lossy interconnects. For consumer level (costsensitive) products, performance needs and ease of use, it is a virtual requirement that the antenna be an integral part of the chip package from start to finish. This places new constraints across the whole antenna/package simulation, design and test space.

1.5 **RF Electronics**

The RF electronics make up the body of any wireless device and consist of a receiver and transmitter where each place critical and sometimes conflicting requirements on both the antenna and the package. For example, loss between the antenna and the RF electronics decreases transmit output power and increases system noise figure directly; thus, each RF subsystem needs to be located close to the antenna. Since there are physical limitations and both cannot be minimized, tradeoffs must be made as to which should be the closest. To establish a common vocabulary for the rest of the book, it is worth reviewing both receive and transmit chains.

1.5.1 Receiver

As shown in Figure 1.2, the signal at the output of the receive antenna is amplified by an LNA with enough gain (>10–15 dB) to establish the system noise figure (<6 dB). The LNA drives an integrated bandpass image filter, which is designed to eliminate received noise power amplified by the LNA at the IF image frequency to minimize the noise. The output of the LNA drives a mixer that translates the mmWave signal to an IF frequency in the range of 9.2 GHz. This IF frequency is chosen to provide easy image rejection at the RF and to support very high data rates. The mixer then drives a variable-gain IF amplifier, which increases the dynamic range of the receiver.

A single VCO operating in the band around 17.6 GHz is multiplied by three to generate the LO for the up and down mixers. The VCO is also divided by two to generate the 8.8 GHz LO signals for the IF quadrature mixers, which translate the received signal to baseband frequency I and Q channels. The baseband I and Q channels are band limited by variable bandwidth low-pass filters. From here the signals are either A/D (Analog to Digital) converted or detected directly depending upon the chosen modulation. The only cost effective, power efficient and performance friendly design approach at mmWave frequencies is to implement fully integrated solutions in silicon; going off chip for any mmWave frequency element could prove disastrous.

1.5.2 Transmitter

The transmit path uses the same variable-IF technique as the receive path to minimize the complexity of the system design. The band limited IQ signals are combined to a real IF signal by the quadrature up mixer. The IF signal is amplified if necessary and translated to the 60 GHz carrier frequency by a second mixer. The 60 GHz signal is increased to the desired transmit power required to close the link budget by the power amplifier (PA). The output of the PA drives an integrated bandpass filter, which suppresses the out-of-band image and carrier feed-through products, as well as broadband noise from the PA. The image filter connects to a tuned antenna designed to pass the minimum amount of spectrum necessary for operation at the desired data rate. As mentioned above, full integration of receiver, transmitter and synthesizer/LO subsystem should be done and thought of as a system. The antenna also needs to be considered closely in the design since single-ended or differential approaches can dramatically impact realizability and performance.