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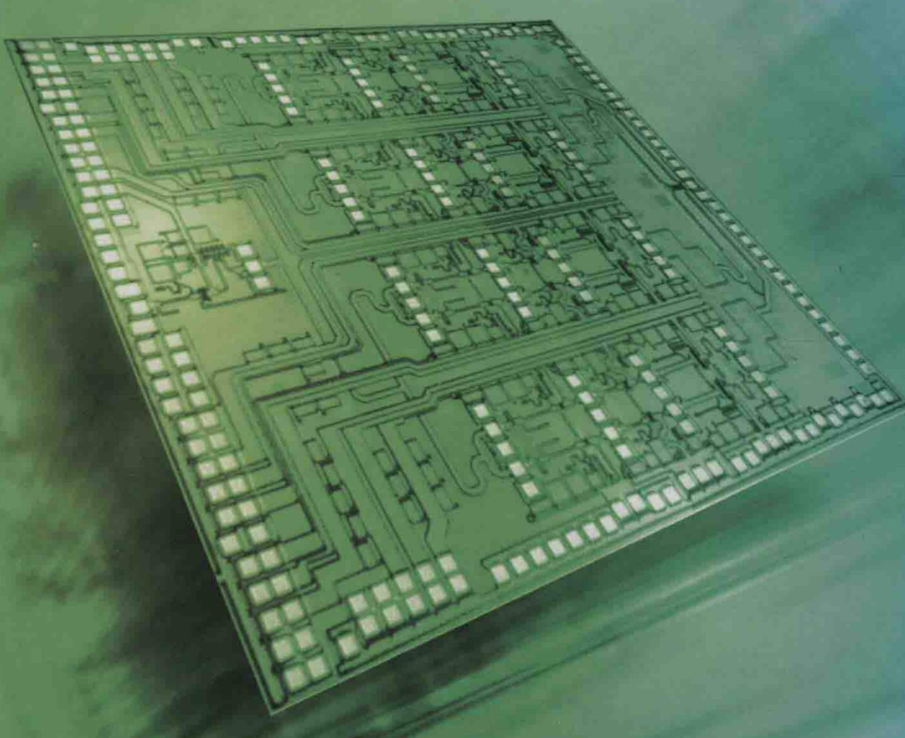

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mm-Wave Silicon Power Amplifiers and Transmitters

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mm-Wave Silicon Power Amplifiers and Transmitters

Build high-performance, spectrally clean, energy-efficient mm-wave power amplifiers and transmitters with this cutting-edge guide to designing, modeling, analyzing, implementing, and testing new mm-wave systems.

Suitable for students, researchers, and practicing engineers, this self-contained guide provides in-depth coverage of state-of-the-art semiconductor devices and technologies; linear and nonlinear power amplifier technologies; efficient power combining systems, circuit concepts, system architectures, packaging, and system-on-a-chip realizations.

The world's foremost experts from industry and academia cover all aspects of the design process, from device technologies to system architectures. Accompanied by numerous case studies highlighting practical design techniques, trade-offs, and pitfalls, this is a superb resource for those working with high-frequency systems.

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Preface

Silicon has become the uncontested technology of choice for commercial radio-frequency integrated systems such as those in smartphones, tablets, and televisions. Research over the past decade has demonstrated the feasibility of realizing complex silicon integrated systems at millimeter frequencies. There is little doubt that operation at millimeter waves not only offers advantages, but also is necessary in many commercial and noncommercial applications. Millimeter-wave integrated circuits for automotive radars and high-speed wireless connectivity are already in the market. The fifth-generation wireless standards will include millimeter-wave operation as an essential component to increase the overall capacity. The volume of millimeter-wave integrated systems may soon exceed billions of units per year.

Millimeter-wave operation has a long history. Sir Jagadish Chandra Bose demonstrated transmission and reception of 60 GHz electromagnetic waves over a distance of 23 m in 1895. The application of solid-state devices in the millimeter-wave range started in the second half of the twentieth century. In the 1970s, solid-state transceivers at 60 GHz were demonstrated primarily by using diodes for signal generation, frequency conversion, and amplification. Monolithic millimeter-wave receivers and transmitters were reported in the 1980s using III–V transistors capable of providing power gain well into the millimeter-wave region. Applicability of silicon technologies, including CMOS, for radio-frequency applications was established in the 1990s. Complex silicon integrated systems at millimeter waves were reported in the 2000s, and commercial products started entering the market shortly after.

Throughout history, technology has always been a limiting factor in the amount of radio-frequency signal power that can be generated. In the absence of devices that can provide power gain, generating electromagnetic signals will be power inefficient. Early demonstrations of electromagnetic signal generation at higher frequencies typically involve nonlinear processes such as harmonic signal generation. These approaches are gradually replaced with more linear amplification approaches once supporting technologies become available. In other words, efficient high-power electromagnetic signal generation and amplification oftentimes lags the demonstration and even deployment of wireless systems operating at those frequencies. It is hence natural to see that efficient high-power generation of millimeter-wave signals using silicon technologies is an ongoing research topic nearly a decade after the early demonstrations of complex silicon millimeter-wave integrated systems.

Not too long ago, silicon was considered to be incapable of serving as a proper technology for the realization of power amplifiers even at radio frequencies. In fact, the viability of CMOS in certain commercial RF wireless systems is still a debated topic. In 2009, the US Defense Advanced Research Projects Agency (DARPA) postulated that watt-level transmitter output power can be achieved in silicon technologies with efficiencies significantly beyond the state-of-the-art and these transmitters could be linearized on-chip to support high-order digitally modulated waveforms. This led to the launching of the Efficient Linearized All-Silicon Transmitters ICs (ELASTx) program, of which we were both key players (Sanjay as founding program manager, Hossein as leader of one of the key performer teams). In June 2012, we organized a workshop at the IEEE Radio Frequency Integrated Circuits (RFIC) Symposium with an ambitious title of "Towards Watt-Level mm-Wave Efficient Silicon Power Amplifiers." The workshop included talks by prominent individuals from academia and industry, including several ELASTx team members, covering challenges and research efforts around this topic. The enthusiasm from speakers and participants was accompanied by realistic skepticism about the viability of such an outrageous proposition in the near future. It is extremely gratifying to witness watt-level silicon power amplifiers and transmitters generating millimeter-wave signals efficiently from various research groups across the world a few short years after the workshop.

The seeds of this book were planted at the same IEEE RFIC Workshop. Cambridge University Press, led by Dr Julie Lancashire, concurred with our vision that a book on the topic of silicon millimeter-wave transmitters and power amplifiers is timely. We did not want the book to be a mere collection of research results that have appeared as papers over the past few years. The intent was to draft a book that includes technology, challenges, theory, and a systematic approach towards realization of silicon millimeter-wave power amplifiers and transmitters with research results offered as proof-of-concept case studies. Most chapters of the book are written in an advanced textbook style suitable for graduate students and practicing engineers. Many graphs and tables include comprehensive data about the relevant technologies, devices, and circuits, and serve as complete up-to-date references for researchers and developers. Maintaining consistency and flow across various chapters is a challenge in a multi-authored book. The authors have been very cooperative in drafting and revising their chapters in this spirit. It has been a pleasure to work with the world's top individuals in the area of silicon millimeter-wave integrated circuits for this project. We hope that all readers learn from reading this book as much as we did.

Editing a multi-authored book, especially when the authors are all prominent busy individuals, is not an easy task. It requires great patience and support. We have been lucky to work with the wonderful team at the Cambridge University Press on this project. Dr Julie Lancashire was nothing but graciously supportive and understanding over the past two years. Elizabeth Horne and Heather Brolly provided wonderful assistance. Thank you all!

Contents

List of Contributors *page* ix
Preface xi

1 **Introduction** 1
Hossein Hashemi and Sanjay Raman

1.1 Why mm-waves? 1
1.2 Why silicon? 3
1.3 Wireless communication basics 4
1.4 Wireless transmitter architectures 6
1.5 Power amplifier basics 7
1.6 Examples of commercial mm-wave applications 8
1.7 Examples of military mm-wave applications and initiatives 9
1.8 Conclusions 13
Acknowledgments 13
References 13

2 **Characteristics, performance, modeling, and reliability of SiGe HBT technologies for mm-wave power amplifiers** 17
David Harame, Vibhor Jain, and Renata Camillo Castillo

2.1 Introduction 17
2.2 Bipolar device physics 18
2.3 SiGe HBT processing and structures 27
2.4 Key circuit design metrics 37
2.5 BiCMOS passive devices and features 47
2.6 SiGe HBT modeling and characterization 52
2.7 Reliability 58
2.8 Performance limits of SiGe HBTs 64
2.9 Summary and conclusions 66
References 68

3 **Characteristics, performance, modeling, and reliability of CMOS technologies for mm-wave power amplifiers** 77
Antonino Scuderi and Egidio Ragonese

3.1 Introduction 77
3.2 Materials for high frequency: CMOS and its evolution 78

3.3 CMOS active devices 79
3.4 Nonlinearities 91
3.5 Noise 98
3.6 Thermal effect 102
3.7 Large-signal performance degradation and reliability 105
3.8 CMOS passive devices 114
3.9 Measurement and modeling issues 118
3.10 CMOS trends: SOI 121
3.11 Conclusions 132
Acknowledgment 133
References 133

4 Linear-mode mm-wave silicon power amplifiers 139
James Buckwalter

4.1 Why linear? 139
4.2 Linear amplifier design: large-signal device characterization 142
4.3 Gain of mm-wave amplifiers 148
4.4 Linear classes of operation 155
4.5 Optimization of mm-wave amplifiers: why linear? 162
4.6 Case study: Q-band SiGe power amplifier 166
4.7 Doherty amplifiers 170
4.8 Case study: a Q-band Doherty power amplifier 175
4.9 Summary 177
References 178

5 Switch-mode mm-wave silicon power amplifiers 180
Harish Krishnaswamy, Hossein Hashemi, Anandaroop Chakrabarti, and Kunal Datta

5.1 Introduction to switching power amplifiers 180
5.2 Design issues for CMOS mm-wave switching power amplifiers 181
5.3 Design issues for SiGe HBT mm-wave switching power amplifiers 187
5.4 Linearizing architectures for switch-mode power amplifiers 200
5.5 Conclusions 203
References 204

6 Stacked-transistor mm-wave power amplifiers 207
Peter Asbeck and Harish Krishnaswamy

6.1 Introduction 207
6.2 Motivation for stacking 207
6.3 Principles of transistor stacking 211
6.4 Transistor stacking for switch-mode operation 216
6.5 Application of stacking at microwave frequencies 218
6.6 Si device technology for stacked designs 223
6.7 Stacked FET mm-wave design 226

6.8	Design of mm-wave stacked-FET switching power amplifiers	232
6.9	Stacking versus passive power-enhancement techniques	238
6.10	Harmonic matching in stacked structures	240
6.11	Active drive for stacked structures	240
6.12	Case studies and experimental demonstrations	241
6.13	Summary and conclusions	253
6.14	Acknowledgments	254
	References	254

7 On-chip power-combining techniques for mm-wave silicon power amplifiers 257

Tian-Wei Huang, Jeng-Han Tsai, and Jin-Fu Yeh

7.1	On-chip power-combining techniques	257
7.2	Direct-shunt power combining	262
7.3	2D power combining	265
7.4	3D power-combining technique	282
7.5	Conclusion	297
	References	298

8 Outphasing mm-wave silicon transmitters 302

Patrick Reynaert and Dixian Zhao

8.1	Introduction	302
8.2	Outphasing basics	304
8.3	Outphasing signal generation	307
8.4	Outphasing signal combining	313
8.5	Outphasing non-idealities	317
8.6	Case study: 60-GHz outphasing transmitter	321
8.7	Conclusions	329
	References	331

9 Digital mm-wave silicon transmitters 334

Ali M. Niknejad and Sorin P. Voinigescu

9.1	Motivation	334
9.2	Architectures for high efficiency/linearity	337
9.3	Digital mm-wave transmitter architectures with on-chip power combining	344
9.4	Digital antenna modulation	356
9.5	Conclusion	371
	References	373

10 System-on-a-chip mm-wave silicon transmitters 376

Brian Floyd and Arun Natarajan

10.1	Introduction	376
10.2	Multi-Gb/s wireless links at mm-wave frequencies	376

10.3 On-chip mm-wave transmitter architectures 380
10.4 Single-element transmitters 386
10.5 Phased-array transmitters 387
10.6 Millimeter-wave transmitter examples 398
10.7 Conclusion 415
References 416

11 **Self-healing for silicon-based mm-wave power amplifiers** 419
Steven M. Bowers, Kaushik Sengupta, Kaushik Dasgupta, and Ali Hajimiri

11.1 Background 419
11.2 Introduction to self-healing 421
11.3 Sensing: detecting critical performance metrics 426
11.4 Actuation: countering performance degradation 433
11.5 Data converters: interfacing with the digital core 439
11.6 Algorithms: setting the actuators based on sensor data 442
11.7 System measurements of a fully integrated self-healing PA 445
11.8 Conclusions 453
Acknowledgment 453
References 453

Index 457

1 Introduction

Hossein Hashemi and Sanjay Raman

Advancements in semiconductor technology have led to a steady increase in the unity power gain frequency (f_{max}) of silicon transistors, both in CMOS and SiGe BiCMOS technologies. This, in turn, enables realization of complex monolithic silicon integrated circuits operating at the millimeter-wave (mm-wave) frequency range (typically defined as 30–300 GHz). Prime target applications of silicon mm-wave integrated systems include high-speed wireless access, satellite communications, high-resolution automotive radars, and imagers for security, industrial control, healthcare, and other applications. However, scaling of silicon transistors for high f_{max} comes at the expense of reduced breakdown voltages, and hence limitations on output voltage swing and power. The link range and energy consumption of wireless systems are direct functions of the transmitter output power and efficiency, respectively. Efficient generation and amplification of radio-frequency (RF) modulated waveforms using silicon transistors is an ongoing challenge due to the reduced breakdown voltage of scaled silicon transistors, loss of passive components, and the conventional linearity–efficiency trade-off. This book covers the fundamentals, technology options, circuit architectures, and practical demonstrations of mm-wave wireless transmitters realized in silicon technologies.

1.1 Why mm-waves?

The main motivation to operate the wireless systems at higher carrier frequencies is the larger available bandwidth which translates to higher data rate in communication systems and higher resolution in ranging and imaging systems. Furthermore, the size of the antenna and circuitry, typically proportional to the wavelength, reduces with increasing carrier frequency. On the other hand, operating at higher frequencies poses two fundamental challenges. First, the loss of most materials increases with the frequency; therefore, compared with radio and microwave frequencies (below 30 GHz) the electromagnetic wave at mm-wave frequencies is attenuated more as it propagates in an environment (Fig. 1.1). It should be noted that over the mm-wave spectrum there are "windows" of relatively lower attenuation around 35 GHz, 90 GHz, 140 GHz, etc., and, consequently, these bands are often selected for mm-wave applications; on the other hand, high atmospheric attenuation levels around frequencies such as 60 GHz enable more aggressive frequency reuse, and are therefore often selected for small cell or secure communications applications. Second, the performance of semiconductor

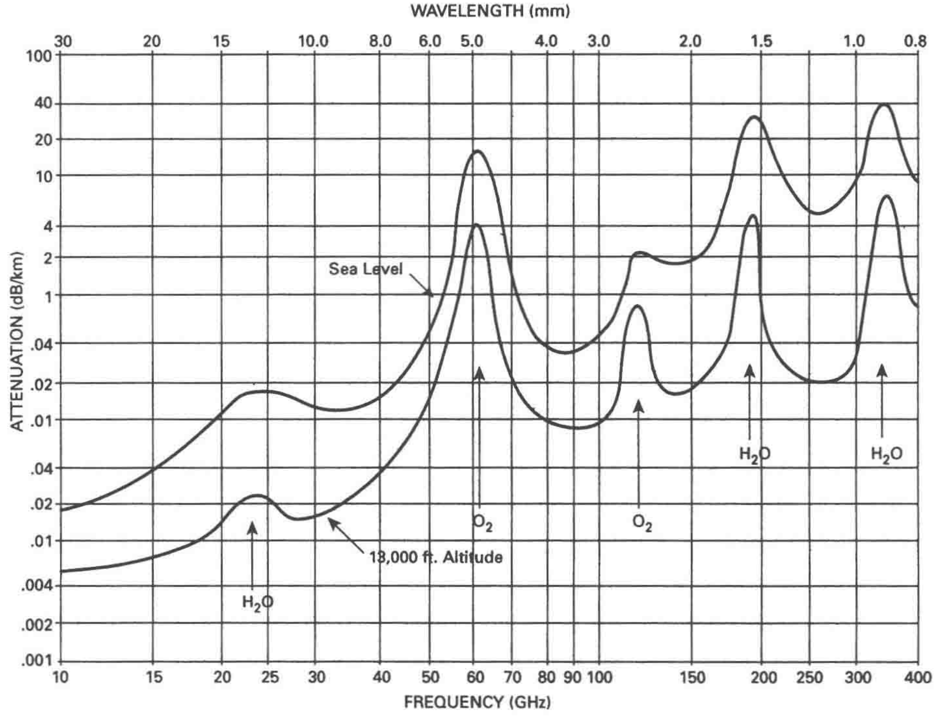

Fig. 1.1 Typical atmospheric attenuation in dB/km as a function of frequency.

devices worsens with frequency; this includes reduced gain, increased noise, and more nonlinearity at higher frequencies for a given technology.

Historically, mm-wave systems have been confined to defense, aerospace, and niche commercial applications due to the high cost of multi-chip-module (MCM) approaches and the need to use compound semiconductor processes to achieve required performance. However, over the past decade, there has been an explosion of research and development towards system-on-a-chip (SOC) realizations of complex wireless systems operating at mm-waves for high-volume commercial applications. Commercial complex mm-wave SOCs, such as 60 GHz phased array transceivers for high-speed wireless access, exist today [1–3]. Even certain defense applications, such as large-scale mm-wave phased arrays for helicopter operations, promise to be benefited by silicon implementations [4]. The main commercial applications being pursued at mm-waves include high-speed wireless connectivity with primary focus in the 60 GHz industrial, scientific, and medical (ISM) frequency band; high-resolution automotive radars with primary focus at the 77 GHz frequency band; mm-wave backhaul in the Ka and E bands; and active and passive RF imagers with primary focus at frequencies above 100 GHz. The fifth-generation commercial wireless standard (5G), targeting systems beyond 2020, is expected to include mm-wave operation for high-data-rate wireless access between small cells and mobile devices. High-resolution radar continues to be

IEEE Frequency Bands [GHz]	Frequency [GHz]	Applications	Applicable Standards
Ka (27-40)	28, 38	Mobile communications for 5G Cellular networks (emerging)	None yet available
	27.5-30	SATCOM uplinks (e.g., Inmarsat Global Xpress: 27.5-30) and downlinks (e.g., Iridium: 29.1-29.3)	MIL-STD-188-164, ITU-R S.524-9, FCC 25.138, ETSI EN 303 978
	24.25-30	L-3 ProVision imaging scanners at airports	IEEE C95.1
	35	Munitions and missiles seekers and sensors	Unknown
V (40-75)	43.5-45.5	U.S. AEHF military SATCOM system uplinks*	MIL-STD-3015
	57-66	"Last inch", short range wireless communications	IEEE 802.11ad, IEEE 802.11aj, IEEE 802.15c
	71-75	"Last mile", point-to-point backhaul wireless communications	ETSI TS 102 524
W (75-110)	75-76, 81-86, 92-95	"Last mile", point-to-point backhaul wireless communications	ETSI TS 102 524
	76-77	Autonomous cruise control (ACC) "long range" automotive radar	ETSI EN 301 091 parts 1 & 2
	77-81	Short range "stop & go" automotive radar	ETSI TR 102 263
	94	Missile seekers, collision avoidance radars	Unknown
	85-110	Imaging for medicine, biology, and security	IEEE C95.1
G (110-300)	110-120	Imaging for medicine, biology, and security	IEEE C95.1
	220-240	Long range wireless communications, atmospheric research radar	None yet available
	120, 183, 325	Short range wireless communications (emerging)	None yet available

* U.S. AEHF system downlink frequencies are located at 20.2 GHz – 21.2 GHz (IEEE K band).

Fig. 1.2 Summary of major mm-wave applications and applicable standards.

the primary application for mm-wave military systems. Figure 1.2 summarizes major mm-wave applications and their applicable standards.

1.2 Why silicon?

The advancement of silicon technologies, CMOS in particular, is motivated by performance gains of digital computation and signal-processing integrated circuits. Specifically, the computation speed and power consumption of digital circuits improve with technology scaling. The large investment required for advancing the silicon manufacturing technologies has been justified by the large demand due to the economy of scale. Thanks to groundbreaking research since the 1990s, today most of the RF functions of a wireless system are also realized in the same digital CMOS process leading to SOC realizations. Compared with the traditional multi-chip-module (MCM) approaches, SOCs reduce the cost, complexity, and power consumption, while enhancing robustness thanks to on-chip calibration, built-in self-test (BIST), and self-healing schemes. Furthermore, availability of "free" digital functions has enabled new system architectures with improved performance over conventional schemes.

The widespread usage of silicon technologies for complex mm-wave integrated systems is a result of large-scale research and development over the past two decades. Silicon technologies capable of operating at mm-waves were available in the 1990s [5, 6], followed by monolithic mm-wave circuit realizations shortly after [7]. Early efforts towards realization of complex mm-wave integrated circuits in standard silicon technologies were led by Caltech [8–11], IBM T. J. Watson Research Center [12, 13], UC Berkeley [14, 15], UCLA [16, 17], and the University of Toronto [18, 19] among others around the mid 2000s. Later, in addition to the aforementioned groups, several more research groups such as Georgia Tech [20], UCSD [21–24], National Taiwan University [25, 26], Intel [27], and Tokyo Institute of Technology [28] among others made significant contributions in the research and development of mm-wave silicon complex integrated systems.

While technology scaling provides transistors with higher transistor unity power-gain frequency, it also reduces the breakdown voltage and hence the maximum allowable voltage swing. In fact, there is an inverse relationship between maximum speed and breakdown voltage for a given semiconductor material. The lower allowable voltage swing degrades the signal-to-noise ratio (SNR) and linearity of many circuit building blocks, and also challenges efficient generation of high-power signals. Silicon technology does not lead to higher-performance circuit building blocks with a fixed topology when compared with a compound semiconductor realization. The main advantage of using a silicon technology for high-performance mm-wave systems, in addition to lower cost and footprint, is the higher performance of the entire system enabled by new integrated architectures that leverage combination of analog, mixed-signal, and digital designs.

Chapters 2 and 3 discuss the current state of the art in SiGe and CMOS technologies, respectively, for mm-wave transmitter applications.

Efficient, watt-level radio-frequency (typically <6 GHz) power amplifiers and transmitters now exist commercially. The choice of using silicon versus compound semiconductor technologies in an RF power amplifier depends on the specific application, market demand, and related economics. It is quite conceivable that the growth of wireless devices and connectivity at radio frequencies thanks to CMOS realizations will be repeated at mm-wave frequencies for a complementary set of applications.

1.3 Wireless communication basics

The general form of a modulated waveform, which can be the electric or magnetic field of a propagating electromagnetic wave, can be expressed in the so-called polar form as

$$x_{polar}(t) = a(t)\cos(\omega_c t + \phi(t)), \tag{1.1}$$

where ω_c is the carrier frequency, and $a(t)$ and $\phi(t)$ are the amplitude modulation (AM) and phase modulation (PM) portions of the waveform and contain the information. This expression can also be written in another form, commonly referred to as the Cartesian form, as

$$x_{Cartesian}(t) = I(t)\cos(\omega_c t) + Q(t)\sin(\omega t), \tag{1.2}$$

where $I(t)$ and $Q(t)$ contain the information and are referred to as the in-phase and quadrature-phase components, respectively. While the aforementioned two forms are