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Introduction

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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 iPhone™ or Google's GPhone™ [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

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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.

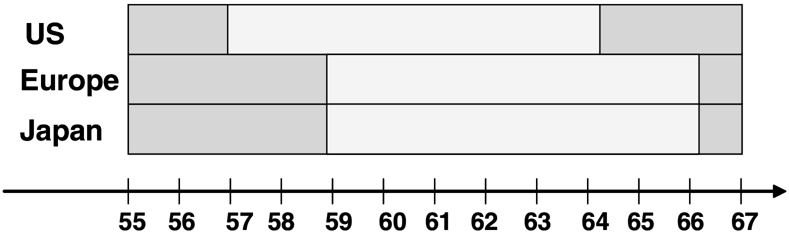

Figure 1.1: The 60 GHz spectrum chart.

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 consumer-level 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, 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

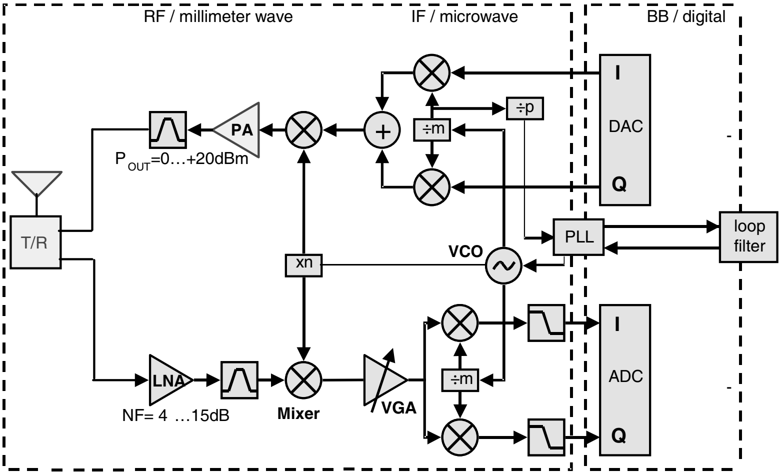

Figure 1.2: Generalized 60 GHz super-heterodyne block diagram.

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 (cost-sensitive) 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.

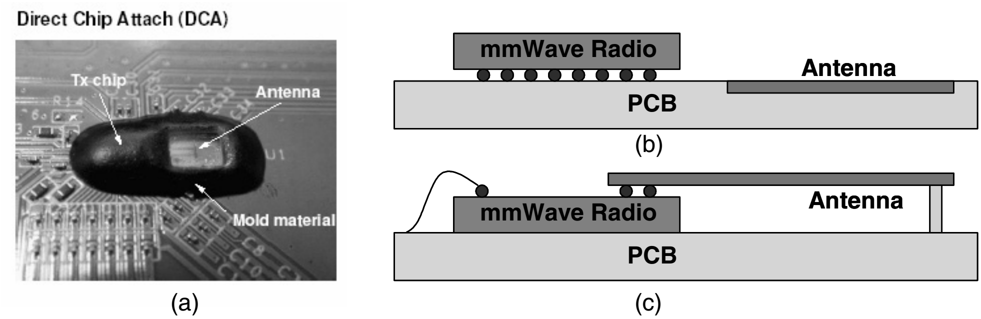

Figure 1.3: DCA with (a) integrated antenna using (b) flip chip or (c) wirebond techniques.

1.6 Packaging

mmWave packaging is an expansive and open set of topics which will be a significant focus for this book. To set the stage, two simple models that have been validated through tests will be shown, but there are a multitude of others such as multi-chip modules (MCM), low-temperature co-fired ceramic (LTCC), silicon microelectromechanical systems (MEMS), microwave chip on flex (MCOF), injection molding, wafer level silicon, etc. The latter ones will be discussed, but the first two will be used to highlight many of the common techniques and to frame the challenges.

Figure 1.3(a) shows a mmWave chip on printed circuit board (PCB) through direct chip attach (DCA). The DCA approach in Figure 1.3(b) highlights one of the most basic and simple approaches. The mmWave radio die is flipped chip attached to a reasonably similar thermal coefficient of expansion (TCE) material board with, e.g., C4 solder or gold stud bumps. In this configuration, an obvious approach for the antenna is to make it a part of the main PCB, as shown in Figure 1.3(b). Here the antenna is part of the main PCB. The main benefits are extremely low cost, ease of assembly and readiness for high-volume manufacturing. The challenges in this approach are matching TCE with acceptable materials, PCB losses in the C4 or stud bump and the Transmission line (T-line) losses to get to the antenna, PCB induced T-line resolution and tolerances, and net radiation efficiency of the antenna.

Figure 1.3(c) shows a slightly more complex approach where the die is simply bonded to a generic PCB and wirebonded in place. The antenna is connected via C4s or stud bumps. The benefits of such a configuration compared to Figure 1.3(b) are less TCE sensitivity, significantly lower losses between the antenna and the die, additional freedom of antenna materials to enhance performance, line resolution and tolerances and much better bandwidth and radiation efficiency through the use of a cavity structure. The challenges are slightly higher antenna and assembly costs.

There are significant technical challenges to make either of these approaches viable. As previously mentioned, basic material properties at mmWave frequencies are unknown, e.g. dielectric constant (Er) and loss tangent. In both approaches shown in Figures 1.3(b) and (c), mold and underfill materials are required to protect the die, bonds and the cavity

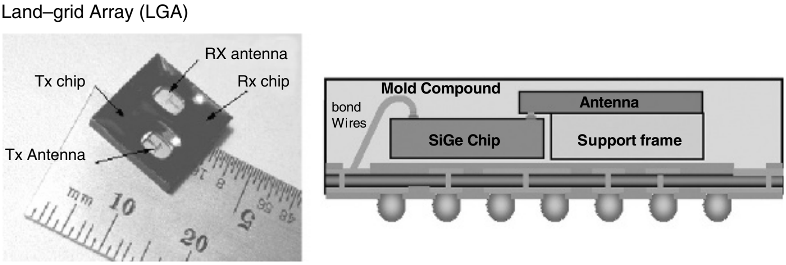

Figure 1.4: Plastic LGA suitable for injection molding, along with side-view schematic.

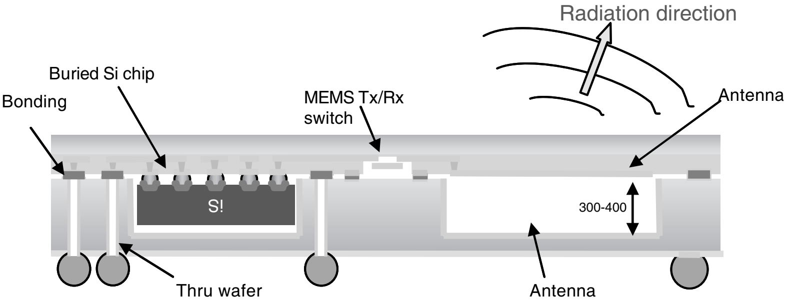

Figure 1.5: LTCC or silicon packaging approach (from reference [9], reproduced by permission of © 2007 IEEE).

in Figure 1.3(c), yet the effect of covering RF electronics at mmWave frequencies with such materials is largely unknown, e.g. isolation and coupling effects, antenna and match detuning. The interconnection losses, coupling and tolerances of mmWave die to PCB or antenna through C4s or gold stud bumps is just beginning to be understood through experiment and analysis.

A hybrid of Figure 1.3(c) and injection molding is illustrated in the land grid array (LGA) approach of Figure 1.4. On the left is an actual plastic LGA mmWave (60 GHz) transceiver shown with antennas exposed for clarity. On the right is a schematic representation of what is inside the LGA. This approach has the highly desirable benefit of standard plastic packaging, deconvolving the mmWave transceiver subsystem from the PCB. This allows a more general tape and reel manufacturing approach. The challenges of such a configuration are similar to that of Figure 1.3(c).

Other approaches that were built and tested, that make good candidates for archetypical packaging, are LTCC and silicon. Figure 1.5 shows a generalized schematic representing both of these options.

Here the RF electronics chip or die is mounted within a substrate material. These substrates offer reasonably low-loss short interconnects to efficient antenna structures. They can also include other passive devices such as decoupling capacitors (caps) resistors, MEMS devices such as transmit/receive (T/R) switches and hermetic packaging. The challenges beyond those previously mentioned include: increased cost, green sheet effects of shrinkage that need to be accounted for in LTCC, the dimensional requirements of antennas versus through wafer vias and wafer-bonding challenges of silicon.

In summary, the above discussion is the framework that will be used throughout the book, but it represents just a simple skeleton of topics that will be covered in much more detail. As the reader can imagine, this work extends far beyond simple packaging, circuits and antennas. As an example, if these packages with integral antennas can be made with outer dimensions less than half a wavelength, then integrated arrays of these could be built that form the basis of phased array systems. This could be taken to an extreme, where an entire wafer of silicon circuits could be wafer bonded to a passive silicon wafer with the antenna directly above the RF electronics and form the entire basis of a phased array system.

Such substrate approaches are also amenable to include other new devices such as EBG devices that could be used in a variety of ways at mmWave frequencies, e.g. filters. New metamaterials could also be incorporated for additional antenna flexibility. Lenses could be added. Each of these technologies is in its infancy at mmWave frequencies. Taken together these topics are a rich and open set of fields that are only now beginning to be explored. Throughout this book the reader will find samples of theory and measurement results for all of them. It is intended to show the beginnings of what is possible for consumer level electronics in the 'greenfield' mmWave bands and to stimulate further investigation.

1.7 Organization and Flow of this Book

The flow of this book follows a bottom-up approach, creating a foundation of building block elements and works up to the system level with examples. Each chapter is reasonably independent and a self-contained entity with its own references where the reader may delve deeper into any of the topics, and it is also an integral element of subsequent chapters.

Chapter 2 begins with an introduction to packaging that establishes the basic and necessary elements needed for mmWave packages. These include those found at lower frequencies, with special emphasis on the unique mmWave material properties and interconnects and how these packaging elements relate to both performance and cost. This leads into a discussion on the importance of system package co-design at mmWave frequencies.

Chapter 3 shifts the discussion to the electrical properties of these packaging elements and materials at mmWave frequencies, specifically dielectric constant and loss tangent. Although basic packaging materials are fairly well characterized into the microwave frequency region, there is a dearth of information above this range. Materials are proposed and their advantages and disadvantages are discussed. In addition to describing a number of common material types and suggesting new ones for various mmWave packaging applications, significant emphasis is also placed upon measurement techniques and material characterization in this extreme frequency range. These include extrapolating microwave techniques such as resonant cavity and transmission line approaches to mmWave frequencies and utilization of time domain spectroscopy.

Chapter 4 builds upon the materials discussion of Chapter 3 to describe a number of key mmWave interconnect types. These interconnects are used between basic devices, circuits, antennas and other structures. The results of this chapter will be built upon and used in subsequent chapters eventually evolving to system level examples. These interconnects described herein, utilize specific materials that complement each interconnect type, while detailing the critical nature of each, at mmWave frequencies. This interconnect discussion includes everything from mechanical issues and tolerances to electrical characteristics and performance. Printed transmission lines (T-lines) on various substrate materials, typical of low and microwave frequencies are presented for use on PCBs and integrated circuits (ICs) such as silicon (Si) or gallium arsenide (GaAs) and extrapolated to mmWave frequencies. Wave guide interconnects are also reviewed and their potential highlighted. With this as a foundation, various packaging approaches are described that make use of these. The design and use of each interconnect type is applied to various packaging approaches and applications and their advantages and disadvantages are highlighted throughout the chapter.

Chapter 5 discusses the use of multilayer technologies to print millimeter antennas. Building upon the packaging, materials and interconnect foundation of Chapters 2–4, we start to create useful circuit level building block elements beginning with the antenna. This discussion begins with critical issues that affect antennas, which are compounded at mmWave frequencies such as metallic and ohmic losses, spurious radiation and surface waves. The characterization of these effects in multilayer materials at mmWave frequencies is described and their impact on various antenna types and resulting performance is highlighted. This is used and applied to a number of antenna design examples from the most basic patch antenna to the more complex antenna arrays. This is then put in context by describing various packaging approaches and how one would create optimum feed networks for each.

Chapter 6 complements the printed antenna chapter with a presentation of planar waveguide-type slot arrays. It begins with single layer slotted waveguide array antennas and works into novel waveguide slot antennas and arrays. Along the way it describes reflection cancellation techniques, method of moment (MoM) analysis using Eigen-mode basis functions. The design and analysis of a number of other important antenna types and feed structures are also presented that are important to mmWave applications and packaging.

Chapter 7 introduces the basics of antenna design from materials selection to feed structures for specific 60 GHz applications and packaging. Flip-chip mounting is suggested as a potential interconnect technique amenable to the challenges of 60 GHz. An air-suspended superstrate antenna design is proposed as a packaging solution for a specific mmWave design that works well in a number of PCB and plastic packaging approaches. The design is detailed along with key characterization techniques and results. Then the design is analyzed for manufacturability and suitability for low-cost packaging through tolerancing analysis using High Frequency Structural Simulator (HFSS™). The HFSS results are then used to determine system performance. With this as a foundation, additional antenna types are investigated such as a 2 × 4 patch array for high gain, single and dual loop based antennas for circular polarization along with assembly details. Then, additional substrate packages are introduced that hold the potential for higher integration and lower cost such as LTCC and silicon carrier.

Chapter 8 takes the work of low-cost highly integrated antennas of Chapter 7 one step further by introducing the concept of monolithic integrated antennas, which are antennas directly integrated within the IC itself. The promises of these are further cost reductions and smaller size. One can then consider using these to address the needs and costs of commercial and consumer markets. The approach described uses the same substrate as the active radio circuits and adds the antenna, thereby saving the cost of interconnects and significantly altering the packaging goals. Electrically small antennas are defined along with their challenges of performance and issues of substrate modes and efficiency.

Manufacturing issues are discussed and radiator selection criteria are suggested. With this basis, a variety of antennas are investigated including patches, dipoles, loops and inverted-F structures. Their designs and performance are presented and the practical implementations of these into various packages are discussed and how they are measured.

Chapter 9 moves the discussion forward into the very new area of metamaterials for mmWave antenna applications. Simply defined, metamaterials are artificial materials with engineered properties not readily available in nature. In particular, metamaterials with simultaneous negative permittivity and negative permeability, known as left-handed (LH) metamaterials, will be shown to have good application to antenna designs, because of their unique characteristics of negative refractive index, fundamental backward wave, and infinite wave with non-zero group velocity. The chapter begins with three methods to realize LH metamaterials; the resonant method, based on pairing split ring resonators (SRRs) with metal wires, the second is the transmission line (TL) approach based on realizing LH TL unit-cells of series capacitance and shunt inductance. The third method is the evanescent-mode using dielectric resonators inside a cutoff background. Using these methods and different design approaches, several antenna types are investigated, including small resonant backward-wave antennas, fundamental-mode leaky-wave antennas, small circularly polarized antennas, planar and dual-band antennas.

Chapter 10 introduces EBG materials and antennas that leverage the small wavelength at mmWave frequencies. EBG materials will be shown to have properties that are suitable for controlling and manipulating the propagation of electromagnetic waves. EBG materials are created from dielectric and/or metallic structures that are periodic in one or more dimensions. One- and two-dimensional structures will be presented and analyzed and then a discussion ensues of how ‘defects’ can be added to create devices and waveguides that control the propagation of electromagnetic waves. High impedance ground planes are introduced that reduce surface waves and increase efficiency and are shown to be useful for corrugated horn antennas and other structures. It is then shown how EBG substrates can improve printed antenna efficiency. Low-profile high-gain antennas using EBGs are presented next, followed by high-gain one-, two- and three-dimensional resonator-type antennas and concludes with metamaterial and Woodpile EBG waveguide horn antennas and arrays.

Chapter 11 further builds on the mmWave integration theme through the introduction of RF switches. RF switches are used in many common wireless standards from cell phones to WiFi networks for duplexing and switching between frequency bands and modes. Metrics of reliability, power efficiency and cost are introduced along with key small and large signal specifications and these are used to compare various architectures and implementations and to determine the impact of switch performance on a communication system. Basic models are created that allow the simulation and optimization of key parameters such as on/off resistance and capacitance in relation to insertion loss, isolation and power handling. Inductor matching techniques are introduced to extend and improve performance at mmWave frequencies. Example implementations/devices in 65 nm CMOS (FET) are presented and are compared to other technologies such as GaAs (FETs and Diodes).

Chapter 12 describes the technology behind RF MEMS devices and their application to mmWave antenna systems. The basic principles behind micromachining techniques are introduced (and discussed further in Chapter 18). The concept of electrostatic actuation for switches is covered, followed by a description of two classes of RF MEMS switches, a comparison with solid-state devices, and performance and design considerations for RF

MEMS switches. MEMS switch reliability and power handling challenges are then discussed and various approaches for integration of RF MEMS switches with antennas. This leads to a discussion on the use of MEMS technology for implementation of tunable, steerable and reconfigurable antennas. The chapter is concluded with a look into the future of RF MEMS and NEMS for mmWave systems.

Chapter 13 takes the fundamentals of antenna designs presented thus far and begins a discussion of phased arrays. It begins with an applications discussion highlighting the importance of phased arrays and discusses the basics of beam forming networks and radiating elements. The phased array antenna concept is introduced and used to discuss a design approach that accounts for mutual coupling in the practical design of antenna arrays. The continuous line source antenna is used as a basis from which many antenna concepts are derived. The infinite array methodology is described and used to design a slot coupled patch antenna. Beam-forming networks are discussed in terms of their spatial filtering process through the appropriate use of complex weighting of the elements in the array. The chapter is concluded with a brief discussion of the fabrication of an antenna array designed for W-band operation in a LTCC material technology.

Chapter 14 takes the phased array concepts and importance highlighted in Chapter 13 another step forward as integrated phased arrays, essentially trying to address the cost of commercial and consumer products such as automotive radar, imaging, sensing and other systems through very high levels of integration. The discussion begins with basic principles of phased arrays, their benefits and the challenges of integration, specifically in silicon. Silicon-based antennas are discussed along with fundamental phased array architectures from RF, IF to LO. A candidate fully integrated mmWave silicon-based transceiver is presented with each block detailed and its performance summarized. Then a discussion of alternative methods ensues based upon direct antenna modulation for higher efficiency and security. It is presented in the context of a 60 GHz system with experimental results. The discussion moves into large-scale integrated phased array systems in CMOS technology at 6, 10.35 and 18 GHz along with experimental results.

Chapter 15 extends the application space of mmWave to imaging, which among many other applications, expands our vision by letting us ‘see’ things under poor visibility conditions. There exist significant military and commercial benefits for such systems from surveillance, precision targeting, navigation, search and rescue, to the commercial realm of aircraft landing aids, airport operations, and highway traffic monitoring in fog. It also suggests that mmWave frequencies are just the beginning and that THz frequencies will become important as well, if they can be achieved in low-cost technologies. Passive mmWave imaging is first presented, which essentially works off black body radiation; that is, passive emission and reflection of mmWave energy. Then active mmWave imaging is presented where a mmWave source is used to illuminate a scene, while the reflected energy is analyzed for content. This is useful for increasing the sensitivity of systems and potentially seeing through building materials. Advantages and disadvantages are presented for each approach. Several examples of commercial systems are presented. The chapter concludes with a survey of the state of the art in imaging technologies.

Chapter 16 provides a high-level overview of mmWave systems tying many of the preceding topics together. It begins with an outlook for low-cost, high-volume mmWave systems and moves into a discussion on the technology, integration and packaging aspects key to making it a commercial success. It suggests what the first high-volume applications might be in the consumer, automotive and military spaces and what the cost drivers are for each. One of the first 60 GHz fully integrated silicon based transceivers is presented and described in detail from design to performance. This chip-set, mounted on a simple PCB with integral antennas, is used to create a high definition streaming video demonstration similar to that envisioned by the IEEE 802.15.3c developing standard. The system design, modulation and demodulation are presented. This chip-set and antenna is then used to highlight how mmWave solutions might achieve low-cost commercial and consumer level packaged solutions through a Chip-on-Board (CoB) example.

Chapter 17 addresses some of the measurement challenges at mmWave frequencies. Up to this point, it was taken for granted that the reader understood the challenges of mmWave equipment, characterization and measurement techniques, but given that mmWave is only now beginning to be pervasive with strong pushes in multiple standards organizations such as the IEEE, ECMA and WirelessHD, the authors felt that this book would not be complete without some emphasis on the special mmWave measurement techniques required. This chapter highlights the fact that virtually any measurement at these frequencies requires great care. Even simple cables, connectors and probes used to contact the device under test (DUT) have non-negligible effects on the measurement result. Thus, special calibration techniques are essential and detailed throughout this section. A brief overview of modern vector error calibration methods are presented followed by special mmWave measurement techniques where the effect of the launching structures are de-embedded based on lumped element models of the launching structure. Two special measurement techniques for highly integrated mmWave systems are described. The first measurement technique allows measurement of the complex impedance and the antenna radiation pattern in an anechoic chamber. Finally, a novel non-destructive IC package characterization method is described that uses a recursive untermination method for non-destructive *in-situ* S-parameter measurements of multi-port packages.

Chapter 18 extends the MEMS work started in Chapter 12, with a more detailed discussion on micromachining and silicon processing. It begins with a review of mmWave packaging technologies and introduces silicon based packaging through examples and applications highlighting advantages and disadvantages along the way. Process options for lithography, machining, metallization, wafer thinning and assembly are presented. The chapter concludes with an example silicon-based mmWave package with integral antenna and its measurement results.

Through this brief introduction, it is hoped that the reader perceives the subject matter of this book as the beginning of a new and exciting wireless world and it is as wide a set of topics as it is rich and deep in novelty, complexity and challenge. Although the surface may only be scratched here, uncovering a few shiny gems, the authors' goal is that the reader is as captured by this field as they are and will become similar pioneers in this new area, contributing to and growing this body of work so that all may reap the benefits of this emerging set of technologies and may launch a new generation of wireless applications and devices.

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