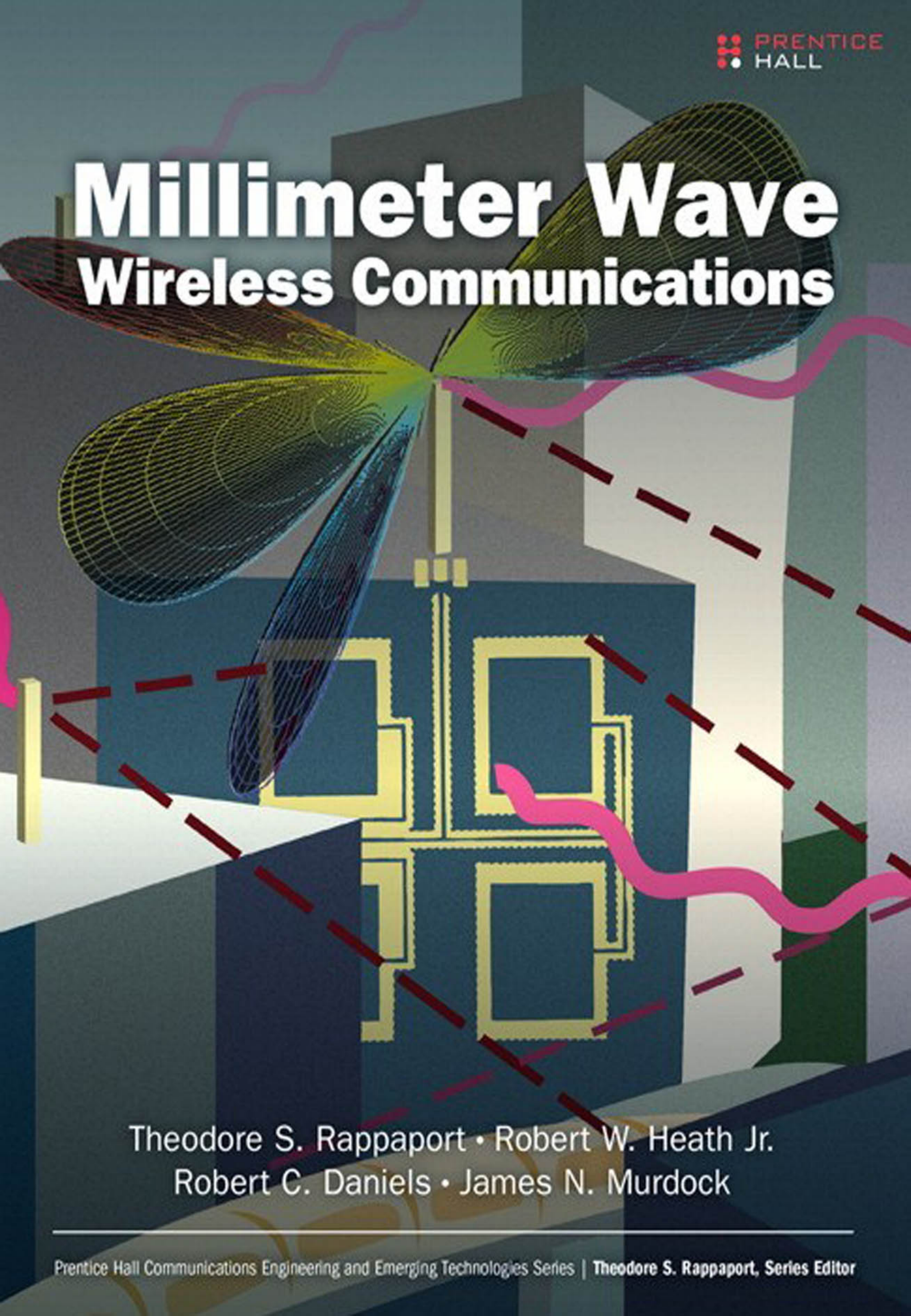

PRENTICE HALL

Millimeter Wave Wireless Communications

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Praise for *Millimeter Wave Wireless Communications*

"This is a great book on mmWave systems that covers many aspects of the technology targeted for beginners all the way to the advanced users. The authors are some of the most credible scholars I know of who are well respected by the industry. I highly recommend studying this book in detail."

—Ali Sadri, PhD, Sr. Director, Intel Corporation, MCG mmWave Standards and Advanced Technologies

"The most comprehensive book covering all aspects of 60 GHz/mm-Wave communication, from digital bits and signal processing all the way to devices, circuits, and electromagnetic waves. A great reference for engineers and students of mm-Wave communication."

—Ali Niknejad, Berkeley Wireless Research Center (BWRC)

"Due to the huge availability of spectrum in 30-100 GHz bands, millimeter wave communication will be the next frontier in wireless technology. This book is the first in-depth coverage addressing essential aspects of millimeter wave communication including channel characteristics and measurements at millimeter wave bands, antenna technology, circuits, and physical layer and medium access control design. It also has an interesting chapter on 60 GHz unlicensed band wireless standards. I found the book extremely useful and recommend it to researchers and practicing engineers who are keen on shaping the future of wireless communication. Thank you Rappaport, Heath, Daniels, and Murdock for giving us *Millimeter Wave Wireless Communications*."

—Amitabha (Amitava) Ghosh, Head, North America Radio Systems, Nokia

"I highly recommend *Millimeter Wave Wireless Communications* to anyone looking to broaden their knowledge in mmWave communication technology. The authors have introduced the key technologies relevant to the rapidly evolving world of wireless access communications while providing an excellent bibliography for anyone seeking to learn about specific topics in greater depth."

—Bob Cutler, Principal Solutions Architect, Agilent Technologies Inc.

Chapter 4

Antennas and Arrays for MmWave Applications

4.1 Introduction

The extremely short wavelengths of mmWave signals (e.g., 10.7 mm at 28 GHz, 5 mm at 60 GHz, and 789 μm at 380 GHz) offer enormous potential for mmWave antenna arrays that are adaptive, high gain, and inexpensive to fabricate and integrate in mass-produced consumer electronic products. There are both cost and performance advantages that result from extremely integrated and physically small antennas. From a cost perspective, mmWave antennas may be directly integrated with other portions of a transceiver and may be fabricated with either packaging or integrated circuit (IC) production technology. This is a stark departure from all existing wireless systems to date, which rely on coaxial cables, transmission lines, and printed circuit boards to connect antennas with the transmitter or receiver circuits in modern cellphones, laptops, and base stations.

The miniaturization caused by the smaller electrical wavelength now makes it possible to create entire wireless communication systems in one integrated circuit (IC) production process (also known as *circuit fabrication*, or *fab*), thereby eliminating costs associated with the interconnection cables and additional manufacturing steps that connect today's radio components together with many different processes. For example, rather than having to purchase a separate antenna for integration with a printed circuit board (PCB) that contains the rest of the transceiver, a mmWave on-chip antenna may be directly etched in on-chip metal during a complementary metal oxide semiconductor (CMOS) Back End of Line (BEOL) IC production process. Or, at slightly higher cost, the antenna may be fabricated in the packaging technology used to house the RF amplifier chip, or integrated in the printed circuit board used to house the transceiver. Both of these options will be less expensive than the use of a separate antenna with a separately packaged transceiver and will benefit further from lower ohmic losses due to the fact that less power is wasted when transferring mmWave signals between the antenna and the transceiver [HBLK14][LGPG09][RGAA09][RMGJ11][GJRM10][GAPR09].

In this text, we focus on emerging antennas that will likely be used in mobile and portable mmWave systems and devices of the future, as fixed antennas such as horn antennas or parabolic dishes are well known for conventional microwave and fixed mmWave wireless systems and are treated elsewhere in the literature. Our goal here is to introduce the reader to antenna topologies and fabrication methods appropriate for mmWave technologies. We also discuss various packaging technologies as they pertain to mmWave antennas that will be embedded in future cellular, personal/local area networking, and backhaul equipment. Proper characterization of mmWave antennas is challenging, due primarily to their unprecedented small size and implementation novelty. Before installing antennas in practical cellular or personal area networking systems or using integrated antennas for consumer or industrial connectivity equipment, antennas must be tested and understood in a laboratory setting. On-chip antennas, for example, may require the use of metal probing stations to excite the antenna in a laboratory. In-package antennas require precise coupling between the integrated circuit and the plastic package. Measurement gear, such as probing stations or custom test chips, is typically made of metal and introduce many obstacles that can interfere with pattern measurement by introducing multipath. Hence, accurate antenna patterns are difficult to ascertain in the laboratory, let alone for in-situ installations. An alternative to testing antennas with a probe station is to package the antenna with an active transmitter or receiver chip, or to place the antennas on an actual circuit board or enclosure, and to then use an anechoic chamber or outdoor antenna range for near-field or far-field patterns. This requires selection of a transmitter or receiver design, adding to testing cost. If the packaging process or enclosure is changed, all antenna measurements would have to be repeated due to the small wavelengths at mmWave frequencies.

Other challenges for mmWave antennas include design of the proper antenna pattern for the particular application and the proper design of passive feeding and/or active excitation elements such as baluns and hybrids. Even with adaptive arrays or multiple input multiple output (MIMO) systems, in which signal processing is used to alter the instantaneous antenna pattern, designers must know the efficiency and capabilities of antennas before installing them into actual systems and products. In this chapter, we discuss the challenges described above associated with mmWave antenna design and testing. We introduce the reader to both on-chip and in-package antennas, as well as their requirements and advantages. MmWave antennas are key to realizing the potential of mmWave systems such as 28 GHz, 60 GHz, and higher frequency transceivers, for either fixed (backhaul or fronthaul) or mobile/portable use. This chapter covers:

- review of certain mmWave antenna fundamentals, including array fundamentals;
- discussion of various antenna topologies that have been used for mmWave designs (including dipole, loop, Yagi-Uda, and traveling wave antennas such as Rhombic antennas);
- the on-chip antenna environment and associated challenges and solutions;
- in-package antenna environment;
- dielectric lens antennas;
- characterization methods for mmWave antennas.

In-package antennas, especially if fabricated using package technology and not simply placed inside the package, offer special challenges due to the relatively bulky size of antennas' elements and the limitations of integrated circuit packaging technology (e.g., the widths of metal vias and the height of metal layers above the ground plane). We describe various structures that have been used to improve the performance of mmWave antennas, including dielectric lenses and modern integrated lens antennas, and although recent advances in circuit board antennas have already been presented [HBLK14], we focus primarily on integrated on-chip and in-package antennas. We end the chapter with a discussion of characterization methods for mmWave antennas and describe the equipment that must be purchased to test mmWave antennas.

4.2 Fundamentals of On-Chip and In-Package MmWave Antennas

As discussed in Chapter 3, the short wavelengths at mmWave frequencies allow both the transmit and receive antennas or antenna arrays to be the size of many multiples of a wavelength and still easily fit within a package or on a chip. For example, at 60 GHz a quarter wave dipole is only 625 μm on a substrate with a relative permittivity of 4. A 100-element phased array, say a square 10×10 array of such dipoles, would have a maximum aperture length dimension of approximately $10 \times 625\,\mu\text{m} \times \sqrt{2} = 8.83$ mm $= \frac{3.53\lambda}{\sqrt{\epsilon_r}}$, where we have assumed a *relative permittivity* ϵ_r (where relative permittivity ϵ_r is also known as the *dielectric constant*) of the package substrate material equal to 4. At 2.4 GHz, 3.53 wavelengths would have required 0.22 m in the same material, or 24 times the length required at 60 GHz. The opportunity afforded by mmWave frequencies to integrate antenna arrays that are many multiples of a wavelength in a very small size is a key advantage. In fact, as should be clear from the preceding chapters, increased antenna gains that can be achieved in very small areas at mmWave frequencies are one of the keys to making a vast number of mmWave technologies feasible

Chapter 3 demonstrated how wireless systems in mmWave frequencies will most likely require beam steering in a very small form factor. Beam steering is possible due to the tight beamwidth that is achievable with *electrically large* (i.e., large compared to a wavelength in the particular material substrate) antenna arrays. This opens up the possibility of massive MIMO, improved link margin for cellular carriers, multi-Gbps personal area networks, and even hand-held radars (which may be useful, for example, to direct a user to a nearby object in indoor locations or other scenarios without the availability of GPS, for example, to find a car in an underground parking garage). From Chapter 3, Eqn. (3.3), the gain of an antenna or antenna array grows as the square of the electrical length D of the antenna or array—that is, gain grows by $\frac{D^2}{\lambda^2}$. Thus, if both the transmitter and receiver antenna sizes are grown, the path loss at mmWave frequencies may be easily compensated for since Eqn. (3.6) shows how antenna gain increases to the fourth power of antenna aperture length and free space path loss increases by the square of the transmitter-receiver separation distance in free space.

The beamwidth of an antenna or antenna array shrinks linearly with the increase in electrical size of the antenna or antenna array, with a good rule of thumb being [Bal05]

$$\text{Beamwidth} = \Theta \approx \frac{60^\circ}{\left[\frac{D}{\lambda}\right]}. \tag{4.1}$$

An implication of the different rates of growth and decay of antenna gain and beamwidth, respectively, is that for mmWave applications such as 60 GHz transceivers—and other low sub-terahertz devices—there will be two classes of devices: One class (for example, for personal area networking (PAN)) will be intended for short links and will use antennas that are only large enough to make short connections (by human standards), on the order of meters or tens of meters, and the other class of device (for example, for cellular/outdoor access) will be used in longer-range cellular, mobile, or backhaul systems. The antenna differences in these two classes are driven by application requirements. Personal area networking devices, for example, may not require small enough beam widths to require beam steering, and their design is likely to focus on very low cost, low power consumption, and extreme simplicity. The personal networking devices will likely operate with relatively simple baseband hardware and processing units, as the complexities of exotic beam steering will be avoided. Alternatively, mobile cellular, repeater/relay, or backhaul situations will be intended for longer-range connections at frequencies of 10 GHz and above, where these devices will enable network operation over distances up to 10-500 m, and also may be combined to use the spectrum simultaneously for outdoor backhaul and outdoor urban cellular mobile coverage. This second class of devices will require a substantial number of antennas or antenna elements, perhaps on the order of hundreds or even thousands, to meet link budget requirements. For example, early SiBEAM mmWave devices (now made by Silicon Image, which acquired SiBEAM in 2011) contain several dozen antenna elements for beam steering in a 60 GHz PAN (see Figs. 1.4 and 1.5). It is likely that future mmWave wireless long-distance devices, handsets, and infrastructure will employ 10 to 100 times as many antenna elements in the coming decade, and therefore these devices will have narrow and tunable antenna beamwidths that enable the transceiver to implement beam steering. Beam steering adds to the complexity of the physical layer protocols used to make over-the-air connections, as beam steering requires discovery and coordination between devices (see Chapters 7 and 8), as well as more sophisticated baseband processing hardware. Beam steering also forces the transceiver to implement additional RF or IF hardware including distribution circuits and possibly phase shifting circuits (assuming phase shifting is not performed at baseband)[Gho14]. At higher mmWave frequencies, sub-terahertz, and terahertz frequencies, all devices will eventually require the sophistication of spatial processing and a vast number of antenna elements, as those frequencies above 100 GHz will most likely require beam steering to meet link budget requirements and to exploit multipath and MIMO.

Despite their promise, mmWave antennas are associated with many challenges. High antenna efficiency (as high as possible) is critical and is not easy for on-chip or in-package antennas. The technical requirements of the two aforementioned classes of devices (i.e., long and short range) at mmWave frequencies has also added substantial confusion to the standards generating process—as technical standards such as IEEE 802.15.3c attempt to cover devices that individually and in networks operate according to very different principles and over varying distances. Fifth-generation (5G) cellular standards contemplated by 2020 will likely have to consider all aspects of indoor PAN, outdoor cellular, and backhaul for small cells [RRC14]. The rapidly emerging 60 GHz standards are discussed in Chapter 9.

Designing mmWave antennas and antenna arrays is also very challenging due to at least two factors: first, integrated mmWave antennas are in intimate contact with very complex environments (e.g., a stack of packaging material with other nearby metal objects or on the substrate of an integrated circuit), and they will generally not have the advantage of a separate radome to offer protection from the rest of the radio (although some packaging techniques provide some of the benefits of a radome). The complexity of the operating environment of mmWave antennas makes separating antenna design from transceiver design nearly impossible. An important implication of the requirement for an integrated design process is that a mmWave antenna, and especially a mmWave antenna array, may often decide the overall circuit IC, package, or circuit board layout (i.e., "floor plan") of a mmWave transceiver. This is especially true for applications that require isolation between antenna elements, for example, between receive and transmit elements. The importance of a floor plan to the design of any circuit board, integrated circuit, or packaged circuit should convince designers to begin antenna array design very early in the overall design process, as failure to lock down an integrated design can substantially delay development of other critical blocks, including active circuitry. A key to successful design of antenna array systems is to ensure that all transceiver circuitry fits on the substrate or in the package without being so far apart so as to cause *grating lobes* (undesired antenna pattern effects due to particular physical dimensions of the antenna).

The large electrical size of high gain, multi-element mmWave antennas also makes design and simulation of these antennas quite challenging. A popular electromagnetic simulation method, the *method of moments* (MoM), reveals that the amount of computer memory required to simulate a structure grows according to the level of discretization required to adequately represent the structure for acceptable simulation accuracy [Gib07, Chapter 3]. This is because the MoM works by breaking the structure into extremely small sections and finding a solution by enforcing boundary conditions over each small section. For example, a planar structure, such as an integrated antenna array, would require at least $\left[\frac{D}{\frac{\lambda}{10}}\right]^2$ sections, where D is the longest linear dimension of the array, to adequately simulate the radiation patterns of an antenna. This adds substantially to the circuit design and simulation time. Another popular method for solving computational electromagnetic problems, the *finite element method* (FEM), operates according to different principles but also requires the discretization of the antenna array or structure being simulated, and the number of elements also grows with the electrical size of the object [Dav10].

4.2.1 Antenna Fundamentals

Before proceeding further, we now review the desirable characteristics of an antenna, regardless of whether it is in an array or a single element. The most important consideration, especially in the context of mmWave antennas, is to attain high radiation efficiency. With traditional RF applications that use separate antennas, efficiency is often very high and thus may not be as important as gain, but efficiency for mmWave antennas may be challenging to attain. The efficiency of an antenna indicates the percentage of steady state power that is applied to the input of the antenna that radiates usefully. The rest of the input power is assumed to be lost in conduction currents in the antenna or the nearby environment (e.g., a chip or a package). Radiation efficiency is usually explained in terms of a radiation resistance and a loss resistance, as illustrated in Fig. 4.1. For an

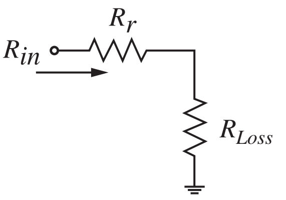

Figure 4.1 At resonance, an antenna may be modeled simply as a resistive circuit that includes both radiation and loss resistance.

input current I_o, the amount of power that is used to radiate is modeled by $I_0^2 R_r$, where R_r is the radiation resistance. The rest of the power is dissipated in R_{Loss}, resulting in an efficiency e_{ant} of:

$$e_{\text{ant}} = \frac{R_r}{R_r + R_{\text{Loss}}}. \tag{4.2}$$

As shown in Section 4.4, in-package mmWave antennas may achieve an efficiency of greater than 80% [SHNT05], whereas unsophisticated on-chip antennas typically have efficiencies closer to 10% [GAPR09]. Section 4.6 describes how on-chip antenna efficiencies can be increased to as high as 80% when fabricated out of more exotic materials than silicon, when lenses are used, or when antenna elements are elevated over a substrate with free-space carve outs.

The next most important characteristic of an antenna is its gain at the frequency of resonance. The gain of an antenna indicates how well it concentrates radiated power into a single beam. The antenna gain is related to the efficiency according to the antenna directivity, in addition to the fields radiated by the antenna:

$$G = \frac{|E \times H^*| (\theta, \phi)}{\frac{P_{\text{rad}}}{4\pi r^2}} = e_{\text{ant}} D \tag{4.3}$$

where G is the gain of the antenna, E and H are the radiated electric and magnetic fields in the far-field region, respectively, and θ and ϕ indicate that the gain of the antenna is in a certain direction (in spherical coordinates). P_{rad} is the power radiated by the antenna, r is the distance from the antenna to the observation point (in carrying out this calculation, r in the denominator will cancel with the distance dependence of E and H), E is antenna efficiency, and D is the directivity. As described in the introduction to this chapter, the easiest qualitative means for increasing gain is to use a larger array or antenna, but this is not always possible given other design constraints.

Computing fields in the far-field region of an antenna is fairly straightforward for an antenna in free space. In this case, the far-field is related to the spatial Fourier transform of the current on the antenna [Bal05][RWD94]:

$$E_{\text{ff}} \propto \int J_{\text{antenna}}(\vec{r}) e^{-j\vec{k}\cdot\vec{r}} dV_{\text{antenna}} \tag{4.4}$$

where J_{antenna} is the current on the antenna; $\vec{k}$ is the vector *wave number* that defines the radiation direction and relative wave propagation speed as described in Section 4.2.2,