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]

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