

1

Introduction

1.1 Why This Book?

Wireless communication systems have evolved dramatically over the past few decades: from large, clunky mobile phones that only supported basic calls and texts to today's compact smartphones that stream high-definition video, support real-time global communication, and run powerful applications (Niu et al., 2015). At the heart of this evolution lies a constant push for higher speeds, larger data capacities, and more efficient spectrum utilization. Currently, the sub-6 GHz frequency spectrum is overcrowded, and is not enough to cover the current demands, and communication with large spectrum utilization is required (Rappaport et al., 2015). In fact, future-generation wireless communication systems need a larger bandwidth for high-speed wireless communication, which is impossible to use in sub-6 GHz frequency spectrum. In contrast, the millimeter-wave (mm-wave) frequency band has huge available spectrum which can be used without any restriction (Wang et al., 2018). Therefore, substantial work has been put forward to develop new wireless communication systems operating the mm-wave frequency band.

In this perspective, antennas act as the ears and eyes of modern communication systems, making it possible for devices and systems to exchange information wirelessly (Balanis, 2016). Therefore, this book focuses on mm-wave antennas and how they contribute to the advancement of fifth-generation (5G) and sixth-generation (6G) wireless communication. Although there are many books available on antennas and wireless systems, only a few cover mm-wave antennas in the context of emerging technologies. Some of these works deal mainly with theoretical concepts, while others concentrate on practical design. However, very few strike a balance between theory, practical applications, and system-level integration. This book aims to fill that gap by offering both a strong theoretical foundation and practical guidance. It also provides insights into how antennas perform

when integrated into real systems. In addition, it discusses the practical challenges engineers face when designing and implementing mm-wave antennas for next-generation technologies.

1.2 Why Focus on mm-Wave Antennas?

The mm-wave frequencies refer to the range above traditional microwave frequencies. Typically, they span from 30 to 300 GHz, corresponding to wavelengths between 10 and 1 mm. These frequencies offer several advantages over conventional microwave frequencies (Sun et al., 2014). Antennas at these frequencies can be significantly smaller, with a tiny footprint, allowing for high-density integration and compact arrays. Additionally, the wider bandwidths available at mm-wave enable ultra-high data rates, which are crucial for applications like real-time virtual reality, 8K streaming, autonomous vehicles, and massive internet-of-things (IoT) deployments.

However, the mm-wave band is not without its difficulties. Signals in this range suffer from increased free-space path loss, are more susceptible to obstruction from objects such as buildings, walls, or even human bodies, and experience greater attenuation due to rain and atmospheric absorption (Busari et al., 2018). To overcome these issues, mm-wave antenna systems must be highly efficient, directional, and, in many cases, reconfigurable to ensure robust and reliable communication links.

The aim of this book is to equip readers with both the theoretical background and the practical tools needed to overcome these challenges, and to view mm-wave antennas not as standalone components, but as integrated parts of a larger wireless system.

1.3 Intended Audience

This book is tailored for a broad audience, including:

- **Graduate students** pursuing studies in antennas, electromagnetics, wireless communications, or microwave engineering.
- **Researchers** working in academia or industry who need a comprehensive reference on mm-wave antenna design.
- **Professional engineers** involved in the development of next-generation communication systems, radar, automotive, biomedical, and satellite technologies.

For newcomers, the early chapters offer foundational knowledge that does not assume advanced expertise in electromagnetics or antenna design. For experienced practitioners, the book provides advanced design examples, real-world case studies, and discussions on simulation and measurement techniques that are directly applicable to ongoing projects.

1.4 What This Book Covers

This book provides a comprehensive and application-focused exploration of mm-wave antennas designed for modern wireless communication systems. It spans from foundational principles to advanced antenna architectures and cutting-edge innovations, offering readers both depth and breadth in the field of high-frequency antenna design.

At the core, the book begins by introducing the reader to the context and importance of mm-wave wireless systems. It explains how the growing demand for high-data rates, massive device connectivity, and low-latency services in technologies like 5G and beyond could boost mm-wave communication to the forefront. The book highlights the unique challenges posed by the mm-wave spectrum, including signal attenuation, material losses, and hardware limitations, while also offering strategies for mitigating these issues through careful antenna and system design.

Subsequent chapters cover a wide range of antenna structures tailored for mm-wave operation. Planar antennas, which include microstrip, aperture-coupled, slot, and substrate integrated waveguide (SIW) configurations, are thoroughly discussed. These low-profile and compact designs are especially relevant for integrated and wearable technologies.

The book then delves into dielectric resonator antennas (DRAs), presenting them as efficient and high-performing alternatives to conventional designs. Different coupling methods, such as coaxial probe, aperture coupling, and coplanar waveguide (CPW), feeding are explained with practical examples and applications.

Building on the concept of SIWs, the book explores SIW-based antennas in detail. Readers learn how SIW technology offers a low-loss, cost-effective solution for both narrowband and broadband mm-wave systems, and how it enables scalable antenna arrays suitable for beamforming and multiple-input multiple-output systems.

Recognizing the growing need for bandwidth, a dedicated chapter addresses wideband mm-wave antenna technologies. It presents various bandwidth enhancement techniques including stacked patches, parasitic elements, and hybrid configurations, making the designs more resilient to frequency-selective fading and useful in multistandard wireless platforms.

The book also emphasizes the importance of antenna arrays at mm-wave frequencies, focusing on array configurations, feeding networks, and critical design trade-offs. This is followed by an exploration of reconfigurable antennas using frequency selective surfaces (FSS), which are increasingly being used to enable dynamic control over antenna parameters such as frequency, polarization, and radiation pattern.

The final technical chapter introduces the concept of orbital angular momentum (OAM) in mm-wave antenna systems. OAM-based antennas represent a frontier in wireless communications, offering new ways to increase spectral efficiency and secure data transmission through the use of twisted EM waves.

Each chapter not only discusses theoretical aspects but also covers design practices, material selection, fabrication techniques, and real-world applications, providing engineers, researchers, and students with the tools and insights needed to implement high-performance mm-wave antennas for next-generation wireless systems.

This book serves as both a solid academic resource and a practical design guide, bridging the gap between microwave theory and modern wireless engineering.

1.5 Scope and Limitations

While this book is comprehensive in its treatment of mm-wave antennas, it does not attempt to cover the entire wireless communication stack. Topics such as signal processing algorithms, modulation schemes, or network protocols are only briefly discussed when they directly relate to antenna system performance.

Additionally, the focus is primarily on the frequency range of 24–100 GHz, which encompasses most current commercial and experimental mm-wave systems. Frequencies beyond 100 GHz, including the emerging terahertz (THz) domain, are discussed primarily from a future outlook perspective.

1.6 Concluding Remarks

Millimeter-wave technology is more than just an academic curiosity; it's a cornerstone of next-generation communication systems. Designing efficient, compact, and reliable mm-wave antennas opens the door to innovations across countless industries: from real-time 6G networks to remote healthcare and intelligent transportation systems.

This book is your guide through that journey. Whether you're taking your first steps into mm-wave antenna design or aiming to push the boundaries of what is possible in the field, the pages ahead are designed to help you think critically, design effectively, and innovate confidently.

1.7 Organization and Flow of the Book

This book is structured to offer a clear and gradual pathway into the world of mm-wave antenna design for wireless communication systems. The chapters in this book are organized in a way that makes it easy to follow: from the basics to more advanced topics and recent developments. Each chapter can be read on its own, but together they build a complete and connected understanding of the subject.

Chapter 2 lays the groundwork by introducing readers to mm-wave wireless communication systems. This chapter walks you through the basics, like what the radio-frequency spectrum is, where mm-wave technology is used, and the kinds of signal issues you might run into at these high frequencies. It also looks at how these systems are designed, along with the tools and techniques used to build and test them. The goal is to give you a clear picture of why mm-wave antennas need special attention and what makes designing them particularly challenging.

Chapter 3 takes a more hands-on approach, focusing on planar antennas: an important type of antenna that is especially useful in compact, integrated systems. This chapter explores various types of planar antennas, including microstrip, aperture-coupled, slot, and SIW antennas. It provides detailed design considerations, typical performance characteristics, and insight into their relevance for mm-wave applications.

Chapter 4 delves into DRAs, a powerful alternative to conventional planar antennas. The chapter covers the theoretical basis, material choices, and feeding mechanisms used in DRA designs. Special attention is given to various coupling techniques such as coaxial probe, EM, aperture, and CPW-fed configurations. Readers also gain insight into DRA performance, losses, and practical implementation in real-world systems.

Chapter 5 builds on the SIW concept introduced earlier by focusing exclusively on SIW-based mm-wave antennas. This chapter examines a range of SIW antenna designs, from single-band and multiband antennas to wideband and array configurations. It addresses their advantages in terms of low-loss performance, ease of integration, and suitability for mass production, making them ideal candidates for modern communication systems.

Chapter 6 is dedicated to wideband mm-wave antennas: an increasingly important area given the bandwidth demands of 5G and 6G networks. The chapter starts by discussing bandwidth limitations at mm-wave frequencies and then introduces several techniques for bandwidth enhancement. These include stacked microstrip structures, parasitic elements, and hybrid approaches that combine multiple bandwidth-widening strategies.

Chapter 7 shifts focus to antenna arrays, which are essential for high-gain, beam-steerable communication systems. This chapter breaks down different feeding architectures, including series-fed, parallel-fed, and hybrid-fed arrays. It also

highlights key design considerations and trade-offs, making it a critical reference for engineers designing high-performance array systems for mm-wave bands.

Chapter 8 introduces FSS and their role in enabling reconfigurable antennas. The chapter discusses different FSS geometries, their electromagnetic behavior, and how they can be integrated into antenna systems for dynamic performance tuning. The use cases and their practical uses are explained in the last section of this chapter.

Chapter 9 concludes the technical content by exploring one of the most cutting-edge topics in antenna research: orbital angular momentum. This chapter examines various antenna structures capable of generating OAM modes, discusses feeding techniques, and outlines the design considerations for implementing OAM in mm-wave systems. OAM has real potential to boost both channel capacity and communication security, which makes it an especially exciting area to explore.

This book is meant to be both thorough and useful. Whether you are a graduate student just getting started, a researcher diving deeper into specific topics, or an engineer working on real-world mm-wave antenna systems, you will find the content flexible and easy to navigate. You can read it from start to finish or simply skip to the chapters that are most relevant to your work.

Each chapter ends with a concise conclusion and curated references to guide further exploration. Throughout the book, theory is balanced with design insights and real-world applications, reflecting the evolving landscape of mm-wave wireless communication and antenna technologies.

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