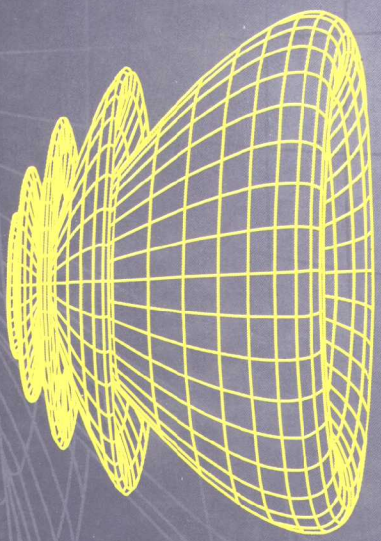
Antenna Theory and Design



Second Edition

Warren L. Stutzman
Gary A. Thiele

Antenna Theory and Design

SECOND EDITION

Warren L. Stutzman
Gary A. Thiele

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Antenna Theory and Design

This book is dedicated to our wives,
Claudia and Jo Ann
and to our children
Darren and Dana
Eric, Scott, and Brad

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Preface

Since the first edition of *Antenna Theory and Design* was published in 1981, there have been major expansions of application areas for antennas, mainly in wireless communications. In addition, in recent years new areas important to antennas have emerged into prominence. This second edition has been expanded to include new areas in antennas. Coverage of microstrip antennas (Sec. 5.8) as well as the use of antennas in systems and measurements (Chapter 9) have been added. In addition, the treatments of array antennas (Chapter 3), broadband antennas (Chapter 6), and aperture antennas (Chapter 7) have been expanded. Also, since the first edition was written there have been major advances in Computational Electromagnetics (CEM), due in part to the use of more sophisticated antennas and antenna systems. The second edition expands on the Method of Moments in Chapter 10, introduces a succinct treatment of the Finite Difference-Time Domain (FD-TD) technique for antennas in Chapter 11, and adds the topic of the Physical Theory of Diffraction (PTD) to high frequency methods in Chapter 12. The objective in the second edition has been to preserve the simplicity of the first edition, while adding modern topics.

This book is a textbook and finds its widest use in the college classroom. Thus, the primary purpose is to emphasize the understanding of principles and the development of techniques for examining and designing antenna systems. Handbooks are available to supplement the fundamentals and antennas discussed here. We have found that the first edition is in wide use by practicing engineers as well as students. This is because of the applied nature of the material and the treatment of basic topics that are directly useable for analyzing practical antennas. This is illustrated by the material in Chapters 1 to 6 and 9, which do not rely heavily on mathematics and use calculus sparingly.

Antenna Theory and Design covers antennas from three perspectives: antenna fundamentals, antenna techniques, and the design of popular antennas. The first four chapters stress antenna fundamentals. Since the student has probably had little exposure to antennas, many fundamentals are presented in Chapter 1. The emergence of antenna theory from Maxwell's equations is developed, along with a physical explanation of how antennas radiate. The four types of antenna elements (electrically small, resonant, broadband, and aperture) are introduced. The discipline of antennas has its own terminology that is quite different from other areas of engineering, so Chapter 1 includes definitions of many antenna terms. Chapter 2 examines simple radiating systems, such as dipoles, in order to solidify the principles of Chapter 1 and to equip the reader to move forward with analysis of antenna systems, such as arrays, that are treated in Chapter 3. Arrays are covered early in the book to introduce the relationship between the current distribution on an antenna and its spatial radiation characteristics using elementary mathematics. In addition, arrays are widely used in practice today. The discrete approach to antennas (arrays) is followed in Chapter 4 with line source antennas, which introduce the continuous form of antennas.

Chapters 5 to 7 give details on commonly used antenna elements. Chapter 5

surveys the resonant antenna elements encountered in practice, including dipoles, yagis, and microstrip patches. Chapter 6 covers broadband antennas such as helix, spiral, and log-periodic antennas. Chapter 7 treats aperture antennas. Emphasis in these chapters is on the operating principles using the fundamentals introduced in the Chapters 1 to 4 and on design guidelines. As appropriate, data are presented using numerical or experimental models, or computations based on theoretical formulations. In addition, empirical formulas are often presented for easy evaluation of performance parameters.

The synthesis of arrays and continuous antennas is presented in Chapter 8 for shaped main-beam or low side-lobe applications. The use of antennas as devices in systems is covered in Chapter 9, along with antenna measurements.

Chapters 10 to 12, as noted above, introduce CEM techniques for evaluating simple antenna elements as well as large complex antenna systems. Here, as in all the book, actual code statements are not listed. The wide variety of computing environments and the availability of high-level mathematics applications packages makes this inappropriate and unnecessary. Instead, some key computational and visualization antenna software packages are made available on the World Wide Web (see Appendix G).

It is important to be aware of the background that is assumed for this book. It is not necessary that the reader have complete mastery of the following subjects, but exposure to these topics is very helpful. A basic course in electromagnetics, such as is commonly required in engineering and physics, is assumed. Mathematics used often includes complex numbers, trigonometry, vector algebra, and the major coordinate systems (rectangular, cylindrical, and spherical). Vector calculus is used at various points and scalar integration is frequently used.

This book can be readily adapted to various academic programs at both introductory and advanced levels. For a first course, the text is usually used in a senior elective or entry level graduate course. A one-semester introductory course usually covers Chapter 1 to 6. For a master's degree-level course, parts of Chapters 7, 8, and 9 can be added. In a one-quarter senior course, material in the latter parts of Chapters 3, 4, or 5 can be eliminated. A second course can focus on advanced design, synthesis, and systems using Chapters 7, 8, and 9. Alternatively, a second course can specialize on computational methods using Chapters 10 to 12.

Several features have been included to aid in learning and in preparation for further self study. Defined terms follow the IEEE standard definitions. Literature references found at the end of each chapter provide sources for further reading. In addition, the bibliography in Appendix H lists literature sources by technical topic. The appendices also include information on the radio spectrum, data on materials, and important mathematical relations.

The authors are indebted to the many individuals who provided invaluable technical assistance to this second edition. The reviewers of the entire manuscript (two of whom also reviewed the first edition) gave essential input on the organization of the book and on several technical issues. Many students offered critical remarks during classroom testing of the manuscript. In addition, special thanks are owed to those who gave detailed evaluations, including Keith Carver (Secs. 5.8 and 6.2), David Jackson (Sec. 5.8), Ahmad Safaai-Jazi (Secs. 6.2 and 8.4), Dave Olver (Chapter 11), Buck Walter (Secs. 4.4 and 10.12), Gerald Ricciardi (Sec. 5.8), Marco Terada (Sec. 7.6) and Krish Pasala (Sec. 12.15). One author (Gary Thiele) extends special thanks to his son, Eric T. Thiele, for many long, valuable discussions on FD-TD,

for reviewing Chapter 11, and for generating the numerical data used in several illustrations in Chapter 11.

Finally, we recognize our wives, Claudia and Jo Ann, for enduring countless hours of neglect during the preparation for both editions. The same recognition goes to our children, Darren and Dana, and Eric, Scott, and Brad.

Warren L. Stutzman
Gary A. Thiele

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Chapter 1

Antenna Fundamentals and Definitions

1.1 INTRODUCTION

Communication between humans was first by sound through voice. With the desire for long distance communication came devices such as drums. Then, visual methods such as signal flags and smoke signals were used. These optical communication devices, of course, utilized the light portion of the electromagnetic spectrum. It has been only very recent in human history that the electromagnetic spectrum, outside the visible region, has been employed for communication, through the use of radio.

The radio antenna is an essential component in any radio system. An antenna is a device that provides a means for radiating or receiving radio waves. In other words, it provides a transition from a guided wave on a transmission line to a "free-space" wave (and vice versa in the receiving case). Thus, information can be transferred between different locations without any intervening structures. The possible frequencies of the electromagnetic waves carrying this information form the electromagnetic spectrum (the radio frequency bands are given in Appendix A). One of humankind's greatest natural resources is the electromagnetic spectrum and the antenna has been instrumental in harnessing this resource. A brief history of antenna technology [1–4] and a discussion of the uses of antennas follow.

Perhaps the first radiation experiment was performed in 1842 by Joseph Henry of Princeton University, the inventor of wire telegraphy. He "threw a spark" in a circuit in an upper room and observed that needles were magnetized by the current in a receiving circuit located in the cellar. This experiment was extended to a distance of over a kilometer. Henry also detected lightning flashes with a vertical wire on the roof of his house. These experiments marked the beginning of wire antennas.

Based on his observations in 1875 that telegraph key closures radiate, Thomas Edison patented a communication system in 1885 that employed top-loaded, vertical antennas.

The theoretical foundations for antennas rest on Maxwell's equations, which James Clerk Maxwell (1831–1879) presented before the Royal Society in 1864, that unify electric and magnetic forces into a single theory of electromagnetism. Maxwell also predicted that light is explained by electromagnetics and that light and electromagnetic disturbances both travel at the same speed.

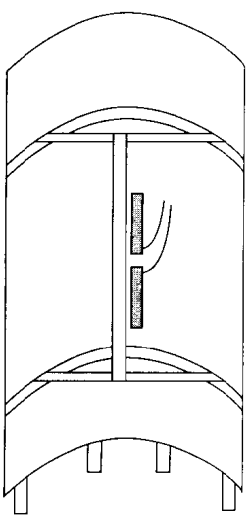
In 1887 the German physicist Heinrich Hertz (1857–1894) was able to verify

experimentally the claim of Maxwell that electromagnetic actions propagate through air. Hertz discovered that electrical disturbances could be detected with a single loop of the proper dimensions for resonance that contains an air gap for sparks to occur. The primary source of electrical disturbances studied by Hertz consisted of two metal plates in the same plane, each with a wire connected to an induction coil; this early antenna is similar to the capacitor-plate dipole antenna described in Section 2.1 and was called a "Hertzian dipole." Hertz also constructed loop antennas. Motivated by the need for more directive radiation, he also invented reflector antennas. In 1888 he constructed a parabolic cylinder reflector antenna from a sheet of zinc; see Fig. 1-1*a*. It was fed with a dipole along the focal line and operated at 455 MHz.

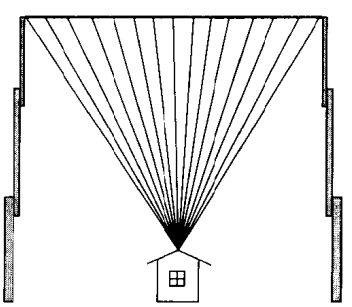
Guglielmo Marconi (1874–1937), an Italian inventor, also built a microwave parabolic cylinder reflector in 1895 for his original code transmission at 1.2 GHz. But his subsequent work was at lower frequencies for improved communication range. The transmitting antenna for the first transatlantic radio communication in 1901 consisted of a 70-kHz spark transmitter connected between the ground and a system of 50 wires, forming a 48-m tall fan monopole; see Fig. 1-1*b*. The antenna resembles a variation of the discone antenna described in Sec. 6.3. The receiving antenna was supported by kites.

Although Marconi is credited as the pioneer of radio, Mahlon Loomis (1826–1886), a dentist and inventor in Washington, DC, received a U.S. patent in 1872 for an "Improvement in Telegraphying" in which he described the use of an "aerial" to radiate and recieve "pulsations." In October 1866, Loomis demonstrated his wireless signaling system to U.S. senators in the Blue Ridge Mountains of Virginia using wire supported by kites at both the transmitting and receiving antennas about twenty miles apart.

The Russian physicist Alexander Popov (1859–1905) also recognized the importance of Hertz's discovery of radio waves and began working on ways of receiving



(*a*) The 455-MHz cylinder reflector antenna invented by Hertz in 1888



(*b*) The monopole transmitting antenna used by Marconi at 70 kHz for the first transatlantic radio communication

Figure 1-1 Examples of early antennas.

them a year before Marconi. He is sometimes credited with using the first antenna in the first radio system by sending a signal over a 3-mile ship-to-shore path in 1897. However, it was Marconi who developed radio commercially and also pioneered transoceanic radio communication. Marconi may be considered to be the father of what was then called wireless. Since then the term "radio" has been used, but "wireless" has also returned to popular use.

In 1912 the Institute of Radio Engineers was formed by the merger of the Wireless Institute and the Society of Radio Engineers. The importance of antennas is punctuated by the fact that the first article of the first issue of *Proceedings of the I.R.E.* was on antennas [5].

Antenna developments in the early years were limited by the availability of signal generators. Resonant length antennas (e.g., a half-wavelength dipole) of manageable physical size were possible about 1920 after the De Forest triode tube was used to produce continuous wave signals up to 1 MHz. Just before World War II, microwave (about 1 GHz) klystron and magnetron signal generators were developed along with hollow pipe waveguides. These led to the development of horn antennas, although Chunder Bose (1858–1937) in India produced the first electromagnetic horn antenna many years earlier. The first commercial microwave radiotelephone system in 1934 was operated between England and France at 1.8 GHz. The need for radar during the war spawned many "modern" antennas, such as large reflectors, lenses, and waveguide slot arrays [6].

Let us now direct our attention to the uses of antennas. Electromagnetic energy can be transported using a transmission line. Alternatively, no guiding structure is needed if antennas are used. For a transmitter-receiver spacing of R, the power loss of a transmission line is proportional to $(e^{-\alpha R})^2$, where α is the attenuation constant of the transmission line. If the antennas are used in a line of sight configuration, the power loss is proportional to $1/R^2$. Many factors enter into the decision of whether to use transmission lines or antennas. Generally speaking, at low frequencies and short distances transmission lines are practical. But high frequencies are attractive because of the available bandwidth. As distances become large and frequency increases, the signal losses and the costs of using transmission lines become large, and thus the use of antennas is favored. A notable exception to this is the fiber optic transmission line, which has very low loss. Transmission lines offer the advantages of not being subject to interference that is often encountered in radio systems and added bandwidth is achieved by laying new cable. However, there are significant costs and construction delays associated with cable.

In several applications, antennas *must* be used. For example, mobile communications involving aircraft, spacecraft, ships, or land vehicles require antennas. Antennas are also popular in broadcast situations where one transmit terminal can serve an unlimited number of receivers, which can be mobile (e.g., car radio). Nonbroadcast radio applications such as municipal radio (police, fire, rescue) and amateur radio also require antennas. Also, personal communication devices such as pagers and cellular telephones are commonplace.

There are also many noncommunication applications for antennas. These include remote sensing and industrial applications. Remote sensing systems are either active (e.g., radar) or passive (e.g., radiometry) and receive scattered energy or inherent emissions from objects, respectively. The received signals are processed to infer information about the objects or scenes. Industrial applications include cooking and drying with microwaves.

Other factors that influence the choice of the type of transmission system include

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