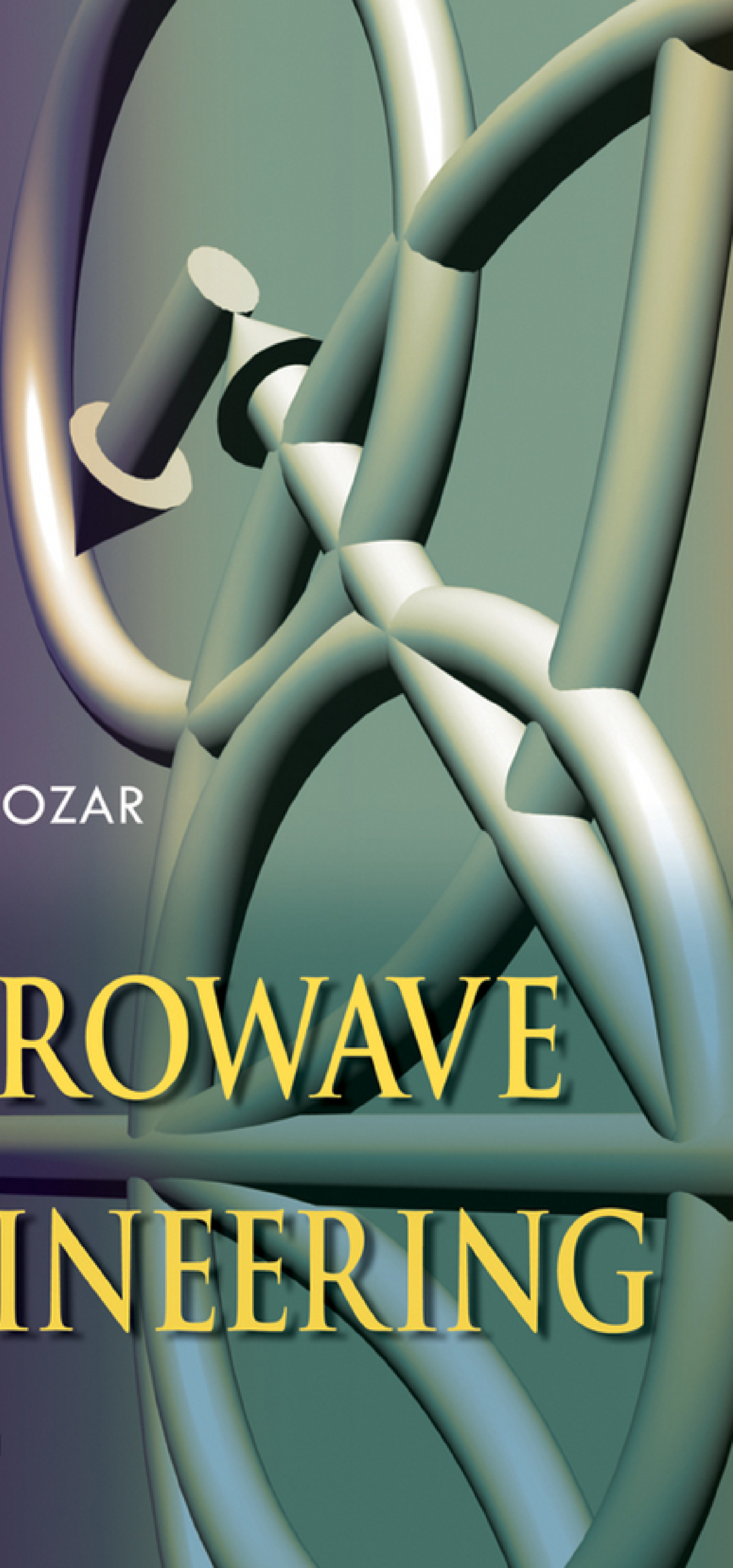

DAVID M. POZAR

MICROWAVE ENGINEERING

FOURTH EDITION

Microwave Engineering

Microwave Engineering

Fourth Edition

David M. Pozar
University of Massachusetts at Amherst

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Preface

The continuing popularity of *Microwave Engineering* is gratifying. I have received many letters and emails from students and teachers from around the world with positive comments and suggestions. I think one reason for its success is the emphasis on the fundamentals of electromagnetics, wave propagation, network analysis, and design principles as applied to modern RF and microwave engineering. As I have stated in earlier editions, I have tried to avoid the handbook approach in which a large amount of information is presented with little or no explanation or context, but a considerable amount of material in this book is related to the design of specific microwave circuits and components, for both practical and motivational value. I have tried to base the analysis and logic behind these designs on first principles, so the reader can see and understand the process of applying fundamental concepts to arrive at useful results. The engineer who has a firm grasp of the basic concepts and principles of microwave engineering and knows how these can be applied toward practical problems is the engineer who is the most likely to be rewarded with a creative and productive career.

For this new edition I again solicited detailed feedback from teachers and readers for their thoughts about how the book should be revised. The most common requests were for more material on active circuits, noise, nonlinear effects, and wireless systems. This edition, therefore, now has separate chapters on noise and nonlinear distortion, and active devices. In Chapter 10, the coverage of noise has been expanded, along with more material on intermodulation distortion and related nonlinear effects. For Chapter 11, on active devices, I have added updated material on bipolar junction and field effect transistors, including data for a number of commercial devices (Schottky and PIN diodes, and Si, GaAs, GaN, and SiGe transistors), and these sections have been reorganized and rewritten. Chapters 12 and 13 treat active circuit design, and discussions of differential amplifiers, inductive degeneration for nMOS amplifiers, and differential FET and Gilbert cell mixers have been added. In Chapter 14, on RF and microwave systems, I have updated and added new material on wireless communications systems, including link budget, link margin, digital modulation methods, and bit error rates. The section on radiation hazards has been updated and rewritten. Other new material includes a section on transients on transmission lines (material that was originally in the first edition, cut from later editions, and now brought back by popular demand), the theory of power waves, a discussion of higher order modes and frequency effects for microstrip line, and a discussion of how to determine unloaded Q from resonator measurements. This edition also has numerous new or revised problems and examples, including several questions of the “open-ended” variety. Material that has been cut from this edition includes the quasi-static numerical analysis of microstrip line and some material related to microwave tubes. Finally, working from the original source files, I have made hundreds of corrections and rewrites of the original text.

Today, microwave and RF technology is more pervasive than ever. This is especially true in the commercial sector, where modern applications include cellular telephones, smartphones, 3G and WiFi wireless networking, millimeter wave collision sensors for vehicles, direct broadcast satellites for radio, television, and networking, global positioning systems, radio frequency identification tagging, ultra wideband radio and radar systems, and microwave remote sensing systems for the environment. Defense systems continue to rely heavily on microwave technology for passive and active sensing, communications, and weapons control systems. There should be no shortage of challenging problems in RF and microwave engineering in the foreseeable future, and there will be a clear need for engineers having both an understanding of the fundamentals of microwave engineering and the creativity to apply this knowledge to problems of practical interest.

Modern RF and microwave engineering predominantly involves distributed circuit analysis and design, in contrast to the waveguide and field theory orientation of earlier generations. The majority of microwave engineers today design planar components and integrated circuits without direct recourse to electromagnetic analysis. Microwave computer-aided design (CAD) software and network analyzers are the essential tools of today's microwave engineer, and microwave engineering education must respond to this shift in emphasis to network analysis, planar circuits and components, and active circuit design. Microwave engineering will always involve electromagnetics (many of the more sophisticated microwave CAD packages implement rigorous field theory solutions), and students will still benefit from an exposure to subjects such as waveguide modes and coupling through apertures, but the change in emphasis to microwave circuit analysis and design is clear.

This text is written for a two-semester course in RF and microwave engineering for seniors or first-year graduate students. It is possible to use *Microwave Engineering* with or without an electromagnetics emphasis. Many instructors today prefer to focus on circuit analysis and design, and there is more than enough material in Chapters 2, 4–8, and 10–14 for such a program with minimal or no field theory requirement. Some instructors may wish to begin their course with Chapter 14 on systems in order to provide some motivational context for the study of microwave circuit theory and components. This can be done, but some basic material on noise from Chapter 10 may be required.

Two important items that should be included in a successful course on microwave engineering are the use of CAD simulation software and a microwave laboratory experience. Providing students with access to CAD software allows them to verify results of the design-oriented problems in the text, giving immediate feedback that builds confidence and makes the effort more rewarding. Because the drudgery of repetitive calculation is eliminated, students can easily try alternative approaches and explore problems in more detail. The effect of line losses, for example, is explored in several examples and problems; this would be effectively impossible without the use of modern CAD tools. In addition, classroom exposure to CAD tools provides useful experience upon graduation. Most of the commercially available microwave CAD tools are very expensive, but several manufacturers provide academic discounts or free "student versions" of their products. Feedback from reviewers was almost unanimous, however, that the text should not emphasize a particular software product in the text or in supplementary materials.

A hands-on microwave instructional laboratory is expensive to equip but provides the best way for students to develop an intuition and physical feeling for microwave phenomena. A laboratory with the first semester of the course might cover the measurement of microwave power, frequency, standing wave ratio, impedance, and scattering parameters, as well as the characterization of basic microwave components such as tuners, couplers, resonators, loads, circulators, and filters. Important practical knowledge about connectors, waveguides, and microwave test equipment will be acquired in this way. A more advanced laboratory session can consider topics such as noise figure, intermodulation distortion, and mixing. Naturally, the type of experiments that can be offered is heavily dependent on the test equipment that is available.

Additional resources for students and instructors are available on the Wiley website. These include PowerPoint slides, a suggested laboratory manual, and an online solution manual for all problems in the text (available to qualified instructors, who may apply for access at the website http://he-cda.wiley.com/wileycda/).

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It is a pleasure to acknowledge the many students, readers, and teachers who have used the first three editions of *Microwave Engineering*, and have written with comments, praise, and suggestions. I would also like to thank my colleagues in the microwave engineering group at the University of Massachusetts at Amherst for their support and collegiality over many years. In addition I would like to thank Bob Jackson (University of Massachusetts) for suggestions on MOSFET amplifiers and related material; Juraj Bartolic (University of Zagreb) for the simplified derivation of the μ-parameter stability criteria; and Jussi Rahola (Nokia Research Center) for his discussions of power waves. I am also grateful to the following people for providing new photographs for this edition: Kent Whitney and Chris Koh of Millitech Inc., Tom Linnenbrink and Chris Hay of Hittite Microwave Corp., Phil Beucler and Lamberto Raffaelli of LNX Corp., Michael Adlerstein of Raytheon Company, Bill Wallace of Agilent Technologies Inc., Jim Mead of ProSensing Inc., Bob Jackson and B. Hou of the University of Massachusetts, J. Wendler of M/A-COM Inc., Mohamed Abouzahra of Lincoln Laboratory, and Dev Gupta, Abbie Mathew, and Salvador Rivera of Newlans Inc. I would also like to thank Sherrill Redd, Philip Koplin, and the staff at Aptara, Inc. for their professional efforts during production of this book. Also, thanks to Ben for help with PhotoShop.

David M. Pozar
Amherst

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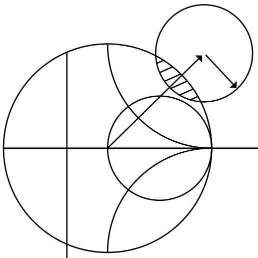


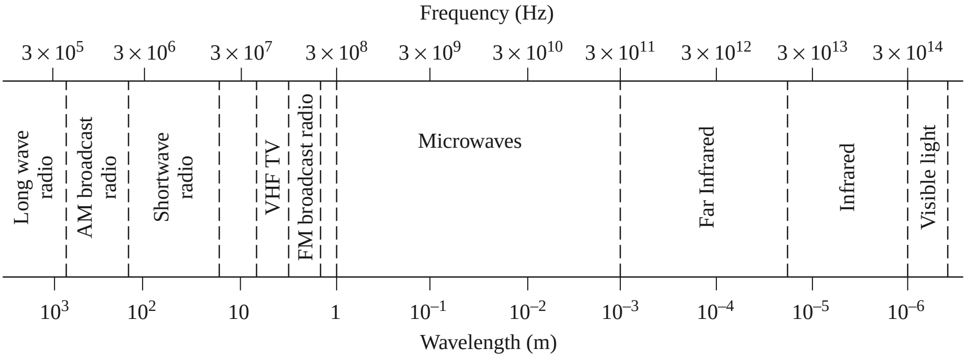
Chapter One

Electromagnetic Theory

We begin our study of microwave engineering with a brief overview of the history and major applications of microwave technology, followed by a review of some of the fundamental topics in electromagnetic theory that we will need throughout the book. Further discussion of these topics may be found in references [1–8].

1.1 INTRODUCTION TO MICROWAVE ENGINEERING

The field of radio frequency (RF) and microwave engineering generally covers the behavior of alternating current signals with frequencies in the range of 100 MHz (1 MHz = 10^6 Hz) to 1000 GHz (1 GHz = 10^9 Hz). RF frequencies range from very high frequency (VHF) (30–300 MHz) to ultra high frequency (UHF) (300–3000 MHz), while the term *microwave* is typically used for frequencies between 3 and 300 GHz, with a corresponding electrical wavelength between $\lambda = c/f = 10$ cm and $\lambda = 1$ mm, respectively. Signals with wavelengths on the order of millimeters are often referred to as *millimeter waves*. Figure 1.1 shows the location of the RF and microwave frequency bands in the electromagnetic spectrum. Because of the high frequencies (and short wavelengths), standard circuit theory often cannot be used directly to solve microwave network problems. In a sense, standard circuit theory is an approximation, or special case, of the broader theory of electromagnetics as described by Maxwell's equations. This is due to the fact that, in general, the lumped circuit element approximations of circuit theory may not be valid at high RF and microwave frequencies. Microwave components often act as *distributed elements*, where the phase of the voltage or current changes significantly over the physical extent of the device because the device dimensions are on the order of the electrical wavelength. At much lower frequencies the wavelength is large enough that there is insignificant phase variation across the dimensions of a component. The other extreme of frequency can be identified as optical engineering, in which the wavelength is much shorter than the dimensions of the component. In this case Maxwell's equations can be simplified to the geometrical optics regime, and optical systems can be designed with the theory of geometrical optics. Such



Typical Frequencies	
AM broadcast band	535–1605 kHz
Short wave radio band	3–30 MHz
FM broadcast band	88–108 MHz
VHF TV (2–4)	54–72 MHz
VHF TV (5–6)	76–88 MHz
UHF TV (7–13)	174–216 MHz
UHF TV (14–83)	470–890 MHz
US cellular telephone	824–849 MHz 869–894 MHz
European GSM cellular	880–915 MHz 925–960 MHz
GPS	1575.42 MHz 1227.60 MHz
Microwave ovens	2.45 GHz
US DBS	11.7–12.5 GHz
US ISM bands	902–928 MHz 2.400–2.484 GHz 5.725–5.850 GHz
US UWB radio	3.1–10.6 GHz

Approximate Band Designations	
Medium frequency	300 kHz–3 MHz
High frequency (HF)	3 MHz–30 MHz
Very high frequency (VHF)	30 MHz–300 MHz
Ultra high frequency (UHF)	300 MHz–3 GHz
L band	1–2 GHz
S band	2–4 GHz
C band	4–8 GHz
X band	8–12 GHz
Ku band	12–18 GHz
K band	18–26 GHz
Ka band	26–40 GHz
U band	40–60 GHz
V band	50–75 GHz
E band	60–90 GHz
W band	75–110 GHz
F band	90–140 GHz

FIGURE 1.1 The electromagnetic spectrum.

techniques are sometimes applicable to millimeter wave systems, where they are referred to as *quasi-optical*.

In RF and microwave engineering, then, one must often work with Maxwell's equations and their solutions. It is in the nature of these equations that mathematical complexity arises since Maxwell's equations involve vector differential or integral operations on vector field quantities, and these fields are functions of spatial coordinates. One of the goals of this book is to try to reduce the complexity of a field theory solution to a result that can be expressed in terms of simpler circuit theory, perhaps extended to include distributed elements (such as transmission lines) and concepts (such as reflection coefficients and scattering parameters). A field theory solution generally provides a complete description of the electromagnetic field at every point in space, which is usually much more information than we need for most practical purposes. We are typically more interested in terminal quantities such as power, impedance, voltage, and current, which can often be expressed in terms of these extended circuit theory concepts. It is this complexity that adds to the challenge, as well as the rewards, of microwave engineering.

Applications of Microwave Engineering

Just as the high frequencies and short wavelengths of microwave energy make for difficulties in the analysis and design of microwave devices and systems, these same aspects provide unique opportunities for the application of microwave systems. The following considerations can be useful in practice:

- Antenna gain is proportional to the electrical size of the antenna. At higher frequencies, more antenna gain can be obtained for a given physical antenna size, and this has important consequences when implementing microwave systems.
- More bandwidth (directly related to data rate) can be realized at higher frequencies. A 1% bandwidth at 600 MHz is 6 MHz, which (with binary phase shift keying modulation) can provide a data rate of about 6 Mbps (megabits per second), while at 60 GHz a 1% bandwidth is 600 MHz, allowing a 600 Mbps data rate.
- Microwave signals travel by line of sight and are not bent by the ionosphere as are lower frequency signals. Satellite and terrestrial communication links with very high capacities are therefore possible, with frequency reuse at minimally distant locations.
- The effective reflection area (radar cross section) of a radar target is usually proportional to the target's electrical size. This fact, coupled with the frequency characteristics of antenna gain, generally makes microwave frequencies preferred for radar systems.
- Various molecular, atomic, and nuclear resonances occur at microwave frequencies, creating a variety of unique applications in the areas of basic science, remote sensing, medical diagnostics and treatment, and heating methods.

The majority of today's applications of RF and microwave technology are to wireless networking and communications systems, wireless security systems, radar systems, environmental remote sensing, and medical systems. As the frequency allocations listed in Figure 1.1 show, RF and microwave communications systems are pervasive, especially today when wireless connectivity promises to provide voice and data access to "anyone, anywhere, at any time."

Modern wireless telephony is based on the concept of *cellular frequency reuse*, a technique first proposed by Bell Labs in 1947 but not practically implemented until the 1970s. By this time advances in miniaturization, as well as increasing demand for wireless communications, drove the introduction of several early cellular telephone systems in Europe, the United States, and Japan. The *Nordic Mobile Telephone* (NMT) system was deployed in 1981 in the Nordic countries, the *Advanced Mobile Phone System* (AMPS) was introduced in the United States in 1983 by AT&T, and NTT in Japan introduced its first mobile phone service in 1988. All of these early systems used analog FM modulation, with their allocated frequency bands divided into several hundred narrow band voice channels. These early systems are usually referred to now as *first-generation* cellular systems, or 1G.

Second-generation (2G) cellular systems achieved improved performance by using various digital modulation schemes, with systems such as GSM, CDMA, DAMPS, PCS, and PHS being some of the major standards introduced in the 1990s in the United States, Europe, and Japan. These systems can handle digitized voice, as well as some limited data, with data rates typically in the 8 to 14 kbps range. In recent years there has been a wide variety of new and modified standards to transition to handheld services that include voice, texting, data networking, positioning, and Internet access. These standards are variously known as 2.5G, 3G, 3.5G, 3.75G, and 4G, with current plans to provide data rates up to at least 100 Mbps. The number of subscribers to wireless services seems to be keeping pace with the growing power and access provided by modern handheld wireless devices; as of 2010 there were more than five billion cell phone users worldwide.

Satellite systems also depend on RF and microwave technology, and satellites have been developed to provide cellular (voice), video, and data connections worldwide. Two large satellite constellations, Iridium and Globalstar, were deployed in the late 1990s to provide worldwide telephony service. Unfortunately, these systems suffered from both technical drawbacks and weak business models and have led to multibillion dollar financial failures. However, smaller satellite systems, such as the Global Positioning Satellite (GPS) system and the Direct Broadcast Satellite (DBS) system, have been extremely successful.

Wireless local area networks (WLANs) provide high-speed networking between computers over short distances, and the demand for this capability is expected to remain strong. One of the newer examples of wireless communications technology is *ultra wide band* (UWB) radio, where the broadcast signal occupies a very wide frequency band but with a very low power level (typically below the ambient radio noise level) to avoid interference with other systems.

Radar systems find application in military, commercial, and scientific fields. Radar is used for detecting and locating air, ground, and seagoing targets, as well as for missile guidance and fire control. In the commercial sector, radar technology is used for air traffic control, motion detectors (door openers and security alarms), vehicle collision avoidance, and distance measurement. Scientific applications of radar include weather prediction, remote sensing of the atmosphere, the oceans, and the ground, as well as medical diagnostics and therapy. Microwave radiometry, which is the passive sensing of microwave energy emitted by an object, is used for remote sensing of the atmosphere and the earth, as well as in medical diagnostics and imaging for security applications.

A Short History of Microwave Engineering

Microwave engineering is often considered a fairly mature discipline because the fundamental concepts were developed more than 50 years ago, and probably because radar, the first major application of microwave technology, was intensively developed as far back as World War II. However, recent years have brought substantial and continuing developments in high-frequency solid-state devices, microwave integrated circuits, and computer-aided design techniques, and the ever-widening applications of RF and microwave technology to wireless communications, networking, sensing, and security have kept the field active and vibrant.

The foundations of modern electromagnetic theory were formulated in 1873 by James Clerk Maxwell, who hypothesized, solely from mathematical considerations, electromagnetic wave propagation and the idea that light was a form of electromagnetic energy. Maxwell’s formulation was cast in its modern form by Oliver Heaviside during the period from 1885 to 1887. Heaviside was a reclusive genius whose efforts removed many of the mathematical complexities of Maxwell’s theory, introduced vector notation, and provided a foundation for practical applications of guided waves and transmission lines. Heinrich Hertz, a German professor of physics and a gifted experimentalist who understood the theory published by Maxwell, carried out a set of experiments during the period 1887–1891 that validated Maxwell’s theory of electromagnetic waves. Figure 1.2 is a photograph of the original equipment used by Hertz in his experiments. It is interesting to observe that this is an instance of a discovery occurring after a prediction has been made on theoretical grounds—a characteristic of many of the major discoveries throughout the history of science. All of the practical applications of electromagnetic theory—radio, television, radar, cellular telephones, and wireless networking—owe their existence to the theoretical work of Maxwell.

Because of the lack of reliable microwave sources and other components, the rapid growth of radio technology in the early 1900s occurred primarily in the HF to VHF range. It was not until the 1940s and the advent of radar development during World War II that microwave theory and technology received substantial interest. In the United States, the Radiation Laboratory was established at the Massachusetts Institute of Technology to develop radar theory and practice. A number of talented scientists, including N. Marcuvitz,

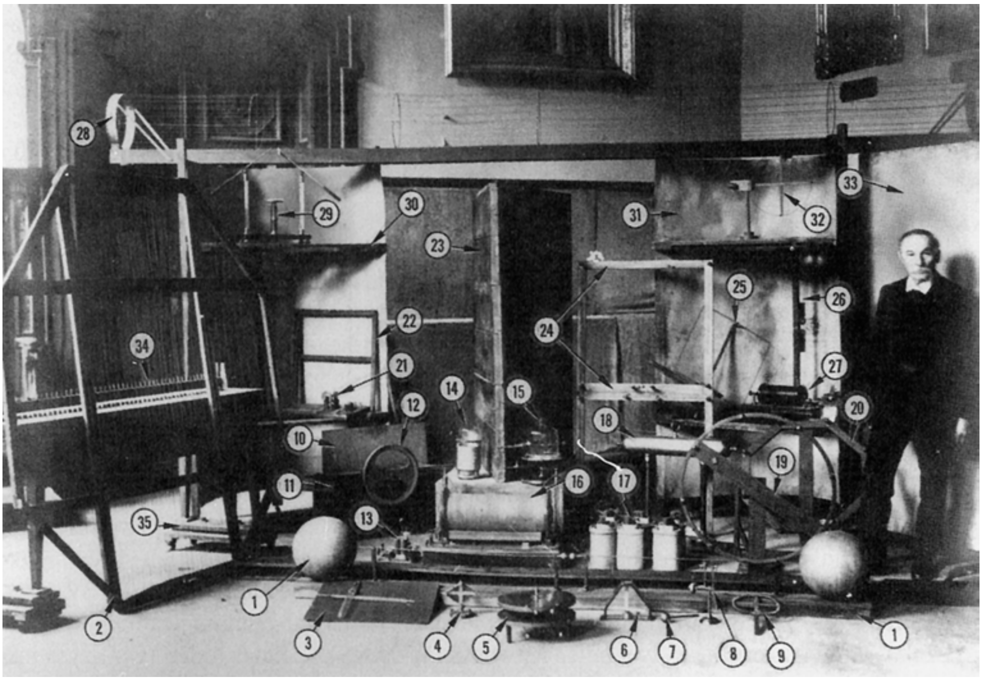


FIGURE 1.2 Original apparatus used by Hertz for his electromagnetics experiments. (1) 50 MHz transmitter spark gap and loaded dipole antenna. (2) Wire grid for polarization experiments. (3) Vacuum apparatus for cathode ray experiments. (4) Hot-wire galvanometer. (5) Reiss or Knochenhauer spirals. (6) Rolled-paper galvanometer. (7) Metal sphere probe. (8) Reiss spark micrometer. (9) Coaxial line. (10–12) Equipment to demonstrate dielectric polarization effects. (13) Mercury induction coil interrupter. (14) Meidinger cell. (15) Bell jar. (16) Induction coil. (17) Bunsen cells. (18) Large-area conductor for charge storage. (19) Circular loop receiving antenna. (20) Eight-sided receiver detector. (21) Rotating mirror and mercury interrupter. (22) Square loop receiving antenna. (23) Equipment for refraction and dielectric constant measurement. (24) Two square loop receiving antennas. (25) Square loop receiving antenna. (26) Transmitter dipole. (27) Induction coil. (28) Coaxial line. (29) High-voltage discharger. (30) Cylindrical parabolic reflector/receiver. (31) Cylindrical parabolic reflector/transmitter. (32) Circular loop receiving antenna. (33) Planar reflector. (34, 35) Battery of accumulators. Photographed on October 1, 1913, at the Bavarian Academy of Science, Munich, Germany, with Hertz's assistant, Julius Amman.

Photograph and identification courtesy of J. H. Bryant.

I. I. Rabi, J. S. Schwinger, H. A. Bethe, E. M. Purcell, C. G. Montgomery, and R. H. Dicke, among others, gathered for a very intensive period of development in the microwave field. Their work included the theoretical and experimental treatment of waveguide components, microwave antennas, small-aperture coupling theory, and the beginnings of microwave network theory. Many of these researchers were physicists who returned to physics research after the war, but their microwave work is summarized in the classic 28-volume Radiation Laboratory Series of books that still finds application today.

Communications systems using microwave technology began to be developed soon after the birth of radar, benefiting from much of the work that was originally done for radar systems. The advantages offered by microwave systems, including wide bandwidths and line-of-sight propagation, have proved to be critical for both terrestrial and satellite