MICROWAVE and RF PRODUCT APPLICATIONS

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Editor-in-Chief
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CRC PRESS

Boca Raton London New York Washington, D.C.

Library of Congress Cataloging-in-Publication Data

Catalog record is available from the Library of Congress.

Direct all inquiries to CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431.

The material included here first appeared in *The RF and Microwave Handbook* (CRC Press, 2001), Mike Golio, editor.

International Standard Book Number 0-8493-1732-0
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0
Printed on acid-free paper

Preface

Microwave and RF Product Applications is a single-volume, comprehensive reference for high-frequency commercial, military, and medical applications. The introduction of the book defines the RF and microwave electromagnetic energy spectrum and examines key characteristics of that energy that are exploited for modern RF communications, sensor, and heating product applications. Individual chapters then examine cellular and mobile communications, broadband wireless access, wireless LANs and PANs, satellite communications, electronic navigation, avionics, radar, and therapeutic medical applications. Additional chapters describe RF and microwave analysis and simulation techniques and provide descriptions of the fundamental physical phenomena that govern electromagnetic applications. Written by leading researchers in the field, *Microwave and RF Product Applications* provides important information for engineers working with wireless RF or microwave applications. It also serves as an excellent source for those requiring information outside their area of expertise, such as managers, marketers, and technical support workers who need a better understanding of the fields driving their decisions.

Acknowledgments

Developing a book like this one is a big job — much bigger than I originally anticipated. This would simply never have been completed if it were not for the efforts of the managing editor, Janet Golio. Her focus, persistence, software expertise, and organizational skills were essential to the project. Her efforts can be measured in the nearly 10,000 pieces of e-mail correspondence she handled, the 100+ telephone conversations she initiated, or the tracking of approximately 80 articles from initial contact to commitment to receipt to review through final modification and submission. Yet all of these metrics combined do not completely capture the full magnitude of her contribution to this text. I cannot offer enough gratitude to compensate for the many long evenings she spent on this project.

I am also significantly indebted to the Handbook Editorial Board. This Board contributed to every phase of the handbook development. Their efforts are reflected in the organization and outline of the material, selection and recruitment of authors, article contributions, and review of the articles. Their labors were essential to the project and I am happy to acknowledge their help.

Special thanks is extended to Nora Konopka, Acquisitions Editor at CRC Press, who has worked most closely with the project during chapter development and has been more patient and encouraging than I deserve. Finally, Helena Redshaw, Production Manager, has taken the stacks of manuscripts, disks, and CDs, identified and added the missing bits and pieces, and turned them into a book. Thanks also to all the CRC staff that I have not had the pleasure to work closely with, but who have contributed to this effort.

Editor-in-Chief

Mike Golio received his B.S.E.E. degree from the University of Illinois in 1976 and completed his M.S.E.E. and Ph.D. degrees at North Carolina State University in 1980 and 1983, respectively. His research has resulted in 15 patents and more than 200 publications. Dr. Golio is the editor of four books, including *RF and Microwave Handbook* (CRC Press, 2000). He has served as the Distinguished Microwave Lecturer for the IEEE MTT Society and as co-editor of the *IEEE Microwave Magazine*. He was elected Fellow of the IEEE in 1996.

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Introduction

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1.1 Overview of Microwave and Radio Frequency Engineering

Modern microwave and radio frequency (RF) engineering is an exciting and dynamic field, due in large part to the symbiosis between recent advances in modern electronic device technology and the current explosion in demand for voice, data, and video communication capacity. Prior to this revolution in communications, microwave technology was the nearly exclusive domain of the defense industry; the recent and dramatic increase in demand for communication systems with such applications as wireless paging, mobile telephony, broadcast video, and tethered as well as untethered computer networks is revolutionizing the industry. These systems are employed across a broad range of environments, including corporate offices, industrial and manufacturing facilities, infrastructure for municipalities, and private homes. The diversity of applications and operational environments has led, through the accompanying high production volumes, to tremendous advances in cost-efficient manufacturing capabilities of microwave and RF products. This, in turn, has lowered the implementation cost of a host of new and cost-effective wireless as well as wired RF and microwave services. Inexpensive handheld Global Positioning System (GPS) navigational aids, automotive collision-avoidance radar, and widely available broadband digital service access are among these. Microwave technology is naturally suited for these emerging applications in communications and sensing because the high operational frequencies permit both large numbers of independent channels for the wide variety of uses envisioned as well as significant available bandwidth per channel for high-speed communication. The interaction between microwave fields and biological tissues also enables exciting advances in medical diagnosis and treatment.

Loosely speaking, the fields of microwave and RF engineering together encompass the design and implementation of electronic systems utilizing frequencies in the electromagnetic spectrum from approximately 300 kHz to over 100 GHz. The term *RF engineering* is typically used to refer to circuits and systems having frequencies in the range from approximately 300 kHz at the low end to between 300 MHz and 1 GHz at the upper end. The term *microwave engineering*, meanwhile, is used rather loosely to refer to design and implementation of electronic systems with operating frequencies in the range from 300 MHz to 1 GHz on the low end to upward of 100 GHz. Figure 1.1 illustrates schematically the electromagnetic spectrum from audio frequencies through cosmic rays. The RF frequency spectrum covers the medium-frequency (MF), high-frequency (HF), and very high frequency (VHF) bands, while the microwave portion of the electromagnetic spectrum extends from the upper edge of the VHF frequency range to just below the THz radiation and far-infrared optical frequencies (approximately 0.3 THz and above). The wavelength of free-space radiation for frequencies in the RF frequency range is from approximately

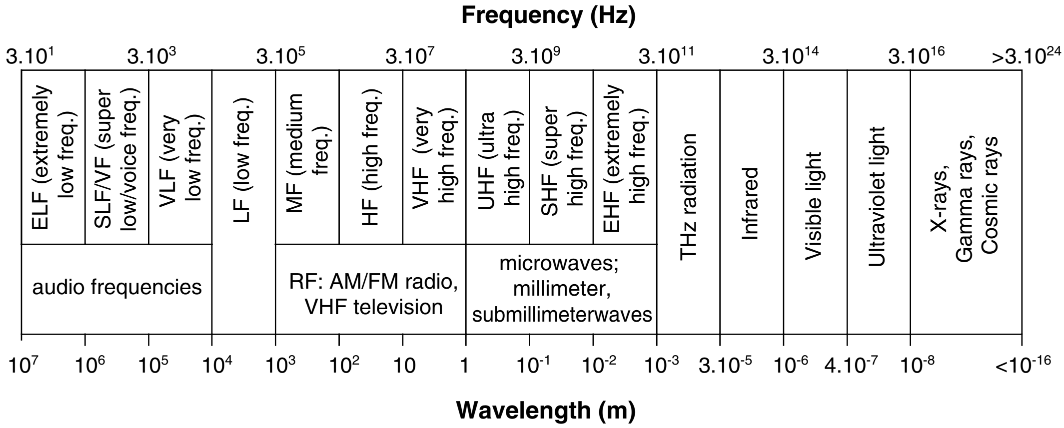


FIGURE 1.1 Electromagnetic frequency spectrum and associated wavelengths.

1 m (at 300 MHz) to 1 km (at 300 kHz), while those of the microwave range extend from 1 m to the vicinity of 1 mm (corresponding to 300 GHz) and below.

The boundary between RF and microwave design is both somewhat indistinct as well as one that is continually shifting as device technologies and design methodologies advance. This is due to implicit connotations that have come to be associated with the terms *RF* and *microwave* as the field has developed. In addition to the distinction based on the frequency ranges discussed previously, the fields of RF and microwave engineering are also often distinguished by other system features. For example, the particular active and passive devices used, the system applications pursued, and the design techniques and overall mindset employed all play a role in defining the fields of microwave and RF engineering. These connotations within the popular meaning of microwave and RF engineering arise fundamentally from the frequencies employed, but often not in a direct or absolute sense. For example, because advances in technology often considerably improve the high-frequency performance of electronic devices, the correlation between particular types of electronic devices and particular frequency ranges is a fluid one. Similarly, new system concepts and designs are reshaping the applications landscape, with mass-market designs utilizing ever higher frequencies rapidly breaking down conventional notions of microwave-frequency systems as serving “niche” markets.

The most fundamental characteristic that distinguishes RF engineering from microwave engineering is directly related to the frequency (and thus the wavelength) of the electronic signals processed. For low-frequency and RF circuits (with a few special exceptions such as antennas), the signal wavelength is much larger than the size of the electronic system and circuit components. In contrast, for a microwave system the sizes of typical electronic components are often comparable to (i.e., within approximately one order of magnitude) the signal wavelength. This gives rise to a reasonable working definition of the two areas based on the underlying approximations used in design. Because in conventional RF design the circuit components and interconnections are generally small compared to a wavelength, they can be modeled as lumped elements with parasitic inductances and capacitances incorporated to accurately model the frequency dependencies of devices and interconnects. For microwave frequencies, however, the finite propagation velocity of electromagnetic waves cannot be neglected because the time delay associated with signal propagation from one end of a component to the other is an appreciable fraction of the signal period. Consequently, lumped-element descriptions are no longer adequate to describe the electrical behavior; a distributed-element model is required to accurately capture the electrical behavior instead. The time delay associated with finite wave propagation velocity that gives rise to the distributed circuit effects is a distinguishing feature of the mindset of microwave engineering.

An alternative viewpoint is based on the observation that microwave engineering lies in a “middle ground” between traditional low-frequency electronics and optics, as shown in Fig. 1.1. As a consequence of RF, microwaves, and optics simply being different regimes within the same electromagnetic phenomena, there is a gradual transition between these regimes. The continuity of these regimes results in constant re-evaluation of the appropriate design strategies and trade-offs as device and circuit technology advances. For example, miniaturization of active and passive components often increases the frequencies at which lumped-element circuit models are sufficiently accurate because by reducing component dimensions, the time delay for propagation through a component is proportionally reduced. As a consequence, lumped-element components at traditionally microwave frequencies are becoming increasingly common in systems previously based on distributed elements due to significant advances in miniaturization, even though the operational frequencies remain unchanged. Component and circuit miniaturization also leads to tighter packing of interconnects and components, potentially introducing new parasitic coupling and distributed-element effects into circuits that could previously be treated using lumped-element RF models.

The comparable scales of components and signal wavelengths have other implications for the designer as well because neither the ray-tracing approach from optics nor the lumped-element approach from RF circuit design is valid in this middle ground. In this regard, microwave engineering can also be considered to be "applied electromagnetic engineering" because the design of guided-wave structures such as waveguides and transmission lines, transitions between different types of transmission lines, and antennas all require analysis and control of the underlying electromagnetic fields.

The distinction between RF and microwave engineering is further blurred by the trend of increasing commercialization and consumerization of systems using what have been traditionally considered to be microwave frequencies. Traditional microwave engineering, with its historical emphasis on military applications, has long been focused on delivering performance at any cost. As a consequence, special-purpose devices intended solely for use in high-performance microwave systems and often with somewhat narrow ranges of applicability were developed to achieve the required performance. With continuing advances in silicon microelectronics, including SiGe heterojunction bipolar transistors (HBTs) and conventional scaled CMOS, microwave frequency systems can now be reasonably implemented using the same devices as conventional low-frequency baseband electronics. In addition, the commercialization of low-cost III-V compound semiconductor electronics, including ion-implanted metal semiconductor field-effect transistors (MESFETs), pseudomorphic high electron mobility transistors (PHEMTs), and III-V HBTs, has dramatically decreased the cost of including these elements in high-volume consumer systems. This convergence, with silicon microelectronics moving ever higher in frequency into the microwave spectrum from the low-frequency side and compound semiconductors declining in price for the middle of the frequency range, blurs the distinction between microwave and RF engineering because microwave functions can now be realized with mainstream low-cost electronics. This is accompanied by a shift from physically large, low-integration-level hybrid implementations to highly integrated solutions based on monolithic microwave integrated circuits (MMICs). This shift has a dramatic effect not only on the design of systems and components but also on the manufacturing technology and economics of production and implementation.

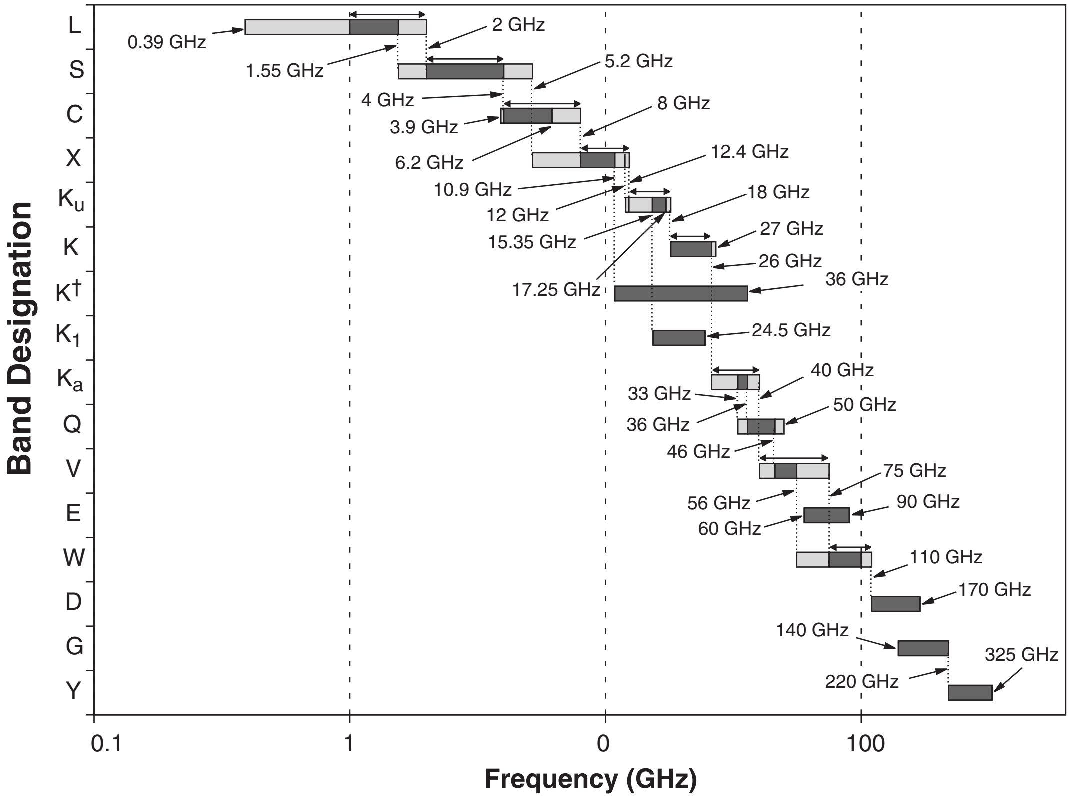
Aside from these defining characteristics of RF and microwave systems, a number of physical effects that are negligible at lower frequencies become increasingly important at high frequencies. Two of these effects are the skin effect and radiation losses. The skin effect is caused by the finite penetration depth of an electromagnetic field into conducting material. This effect is a function of frequency; the depth of penetration is given by $\delta_s = \frac{1}{\sqrt{\pi f \mu \sigma}}$, where μ is the permeability, f is the frequency, and σ is the conductivity of the material. As the expression indicates, δ_s decreases with increasing frequency, and so the electromagnetic fields are confined to regions increasingly near the surface as the frequency increases. This results in the microwave currents flowing exclusively along the surface of the conductor, significantly increasing the effective resistance (and thus the loss) of metallic interconnects. Radiation losses also become increasingly important as the signal wavelengths approach the component and interconnect dimensions. For conductors and other components of comparable size to the signal wavelengths, standing waves caused by reflection of the electromagnetic waves from the boundaries of the component can greatly enhance the radiation of electromagnetic energy. These standing waves can be easily established either intentionally (in the case of antennas and resonant structures) or unintentionally (in the case of abrupt transitions, poor circuit layout, or other imperfections). Careful attention to transmission line geometry, placement relative to other components, transmission lines, and ground planes, as well as circuit packaging is essential for avoiding excessive signal attenuation and unintended coupling due to radiative effects.

A further distinction in the practice of RF and microwave engineering from conventional electronics is the methodology of testing. Due to the high frequencies involved, the capacitance and standing-wave effects associated with test cables and the parasitic capacitance of conventional test probes make the use of conventional low-frequency circuit characterization techniques impractical. Although advanced measurement techniques such as electro-optical sampling can sometimes be employed to circumvent these difficulties, in general, the loading effect of measurement equipment poses significant measurement challenges for debugging and analyzing circuit performance, especially for nodes at the interior of the circuit under test. In addition, for circuits employing dielectric or hollow guided-wave structures, voltage and current often cannot be uniquely defined. Even for structures in which voltage and current are well-defined, practical difficulties associated with accurately measuring such high-frequency signals make this difficult. Furthermore because a dc-coupled time-domain measurement of a microwave signal would have an extremely wide noise bandwidth, the sensitivity of the measurement would be inadequate for many purposes. For these reasons, components and low-level subsystems are characterized using specialized techniques, including s-parameter analysis, microwave transition analysis, and many others. A recent review of these techniques may be found in References 6 and 7.

1.2 Frequency Band Definitions

The field of microwave and RF engineering is driven by applications, originally for military purposes such as radar and more recently increasingly for commercial, scientific, and consumer applications. As a consequence of this diverse applications base, microwave terminology and frequency band designations are not entirely standardized, with various standards bodies, corporations, and other interested parties all contributing to the collective terminology of microwave engineering. Figure 1.2 shows graphically some of the most common frequency band designations, with their approximate upper and lower bounds.

As can be seen, some care must be exercised in the use of the "standard" letter designations; substantial differences in the definitions of these bands exist in the literature and in practice. Light shading at the ends of the frequency bands in Fig. 1.2 indicates variations in the definitions by different groups and authors; dark regions in the bars indicate frequencies for which there appears to be widespread agreement in the literature. The double-ended arrows appearing above some of the bands indicate the Institute of Electrical and Electronics Engineers (IEEE) definitions for these bands. Two distinct definitions of K-band are in use; the first of these defines the band as the range from 18 GHz to approximately 26.5 GHz, whereas the other definition extends from 10.9 to 36 GHz. Both of these definitions are illustrated in Fig. 1.2. Similarly, L-band has two overlapping frequency range definitions; this gives rise to the large "variation" regions shown in Fig. 1.2. In addition, some care must be taken with these letter designations because the IEEE and U.S. military specifications both define bands designated D, E, G, and L, but with very different frequencies. For example, the IEEE-defined L-band resides at the low end of the microwave spectrum, whereas the military definition of L-band is from 40 to 60 GHz. The IEEE designations (L-Y) are currently used widely in practice and the technical literature, with the newer U.S. military designations (A-N) having not yet gained widespread popularity outside the military community.



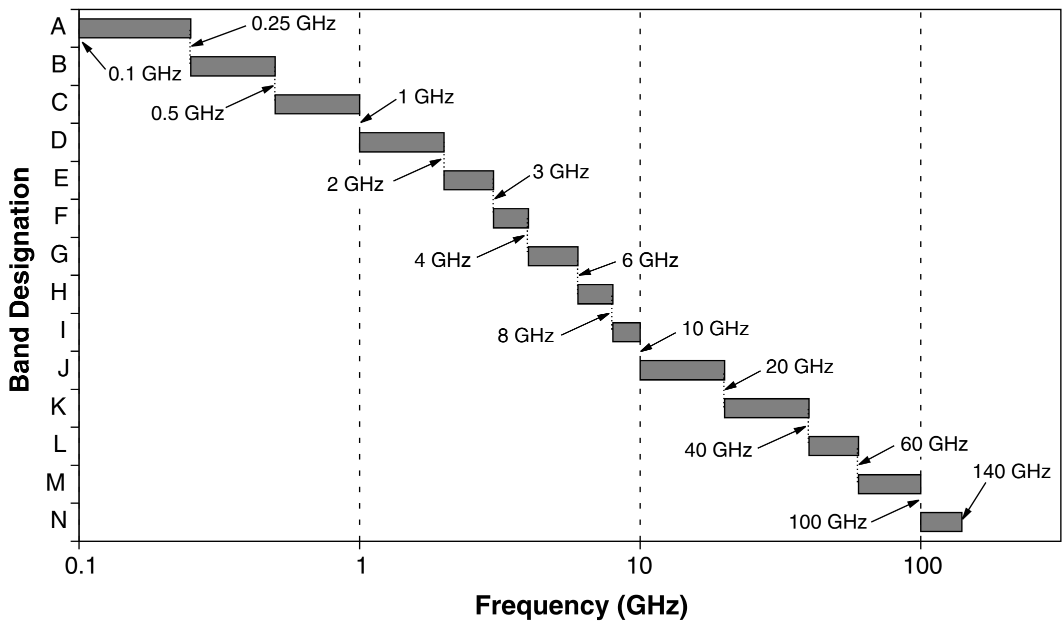


FIGURE 1.2 Microwave and RF frequency band designations.[1–5] (Top) Industrial and IEEE designations. Light shading indicates variation in the definitions found in literature; dark regions in the bars indicate frequencies for which there is widespread agreement. Double-ended arrows appearing above bands indicate the current IEEE definitions for these bands where they exist, and K† denotes an alternative definition for K-band found in Reference 5. (Bottom) U.S. military frequency band designations.[1–3]