MICROWAVE CIRCUIT DESIGN USING LINEAR AND NONLINEAR TECHNIQUES

Second Edition

GEORGE D. VENDELIN
Vendelin Engineering

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WILEY-INTERSCIENCE

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FOREWORD

Fifteen years have passed since I was asked to write the Foreword to the first edition of this book. Much has happened since that time in the fields of application addressed by this edition. For example, the design and technology of integrated microwave circuits (MMICs) have matured for both military applications and commercial applications such as found in communication systems. Wireless technology is now in full bloom. Silicon technology for active devices is complemented by gallium arsenide, SiGe, and MOS technologies for the microwave bands. Solid-state active devices are routinely being manufactured for higher power and frequency applications and for lower noise performance.

This second edition, a vastly expanded and revised version of the first edition, provides the engineer with the necessary additional data and design tools to best enable him or her to address the new requirements introduced by these technological developments. Five new chapters have added for this purpose.

The book begins with an introductory review chapter entitled “RF and Microwave Systems.” It covers a variety of topics ranging from Maxwell’s equations to RF wireless/microwave/millimeter-wave applications, analog and digital requirements, basic RF transmitters and receivers, and CAD for nonlinear circuit analysis, among others.

The next chapter, “Lumped and Distributed Elements” pertains to the frequency range from the RF band up through the millimeter bands. Over this huge frequency expanse, circuit elements exhibit a continuous transition in circuit behavior from that of lumped elements to that of distributed components. Understanding this behavior is of particular importance in broadband designs.

The third chapter, “Active Devices,” is by far the largest chapter in the book. It covers in considerable detail all essential active microwave devices including diodes, bipolar transistors, field-effect transistors (FETs) and their variants such as MOSFETS and HEMTs. The small- and large-signal properties, modeling, and applications of these devices are addressed. More than 200 device-related equations are presented, presumably enough to meet the needs of any designer. Also a subchapter on foundry requirements has been added.

It is safe to say that most applications of active devices consist of networks of two or more ports and their interconnections. Chapter 4, "Two-Port Networks," presents the tools needed for RF/microwave design based on two-port networks and, in addition, three- and four-port networks. Four-port parameters, for example, are necessary for the design and characterization of differential circuits that are common to communication circuits. Design considerations for power and current/voltage gain amplifiers, and their stability and noise performance also are addressed. Numerous examples are presented to demonstrate the utility of multiport parameters.

The next chapter entitled "Impedance Matching" complements Chapter 4 and follows, more or less, the traditional approach to impedance matching involving both lumped and distributed elements. Both analytic and graphical (Smith Chart) methods are illustrated. Many examples are chosen to illustrate the matching techniques.

Chapter 6, "Microwave Filters," is a welcome addition to the this text. Filters are crucial components of nearly every microwave system, whether it is a radar system or a cell phone transmitter. Much has been written about filter design in the literature harking back over nearly a century. Filters now are designed by a variety of methods ranging from the purely classical analytic approach, such as the Butterworth method, to techniques based on element optimization by computers. This chapter exploits the former approach. Low-pass, band-pass, and high-pass filter designs based on the Butterworth and Chebyshev response are described as are the Richards and Kuroda Transformations for transmission line filters. Numerous examples are used to illustrate these analytic approaches.

The next chapter addresses noise in linear two-ports and is a vastly enhanced version of the corresponding chapter in the first edition. One of the new features is a detailed treatment of the noise correlation matrix approach to noise analysis. This technique is particularly suited to computerization since noise matrices can be treated like two-port signal matrices, and can be intermixed with the latter. The noise matrix approach is a general scheme applicable to both linear passive and active devices. Examples of application to bipolar and field-effect transistors are included. An exhaustive set of equations is presented which should fulfill the needs of most designers.

Chapters 8 and 9, entitled "Small and Large-Signal Amplifier Design," and "Power Amplifier Design," respectively reflect the important advancements made in the wireless industry, both in circuit design and in circuit integration based on planar solid-state technology.

The next chapter on oscillators is a complete rewrite and expansion of the corresponding chapter in the previous edition. The most recent frequency and time domain analytic techniques have been applied. Strong emphasis is given to power optimization and noise analysis. To complement this chapter, an extensive bibliography of more than 180 references has been included.

Chapter 11, "Microwave Mixer Design" also has been broadened and now has a new subchapter that deals with the mathematics of mixer noise for two types of FETs. Also the use of CAD in mixer design is illustrated. The bibliography has been extended to reflect these additions.

Chapter 12 is a new chapter covering pin diodes and switches and attenuators based on them. FET switches also are covered. The final chapter on microwave CAD is essentially identical to the last chapter of the previous edition.

My objective has been to describe the salient features of this second edition. However, only a personal examination of the book will convey to the reader the broad scope of its coverage and how well it succeeds in addressing the changing needs of the microwave field and the communications industry.

The authors are to be commended for their efforts in this endeavor. This volume will be an asset to the designer's bookshelf.

ROBERT A. PUCEL, SC. D.
RCP Consultants

April, 2005

PREFACE

Approximately 15 years have passed since the first edition of this book, which was well received by both graduate schools and industry. While the basic principles of physics and mathematics have not changed, today's technology has provided us with huge opportunities to improve the circuit design for linear and nonlinear techniques. In addition, we felt it would be useful to streamline the book by following the concepts of systems and their requirements at microwave frequencies, showing the transition between lumped and distributed elements, and the new exciting devices, particularly the silicon-germanium transistors and the low-cost BiCMOS technology, which is competing heavily with gallium arsenide and seems to be winning in many wireless applications. The cutoff frequencies for modern transistors are in excess of 200 GHz, with low noise figures and low-voltage operation. Practical oscillators can now be made up to 70 GHz. For higher power applications gallium arsenide FETs are over 100 W, and LDMOS devices are also available for frequencies up to 3 GHz. The future looks very bright for lower noise, higher power, and higher frequencies as the technology continues to improve at a very rapid pace.

In streamlining the book, we now offer a separate chapter on two-port networks and all of their characteristics followed by two new chapters, one on matching networks and an extensive one on RF microwave filters, including silicon-based filters for cellular telephone applications.

The noise in the linear two-ports chapter has been extended by showing temperature-dependent noise and detailed derivations of noise figure for both bipolar and FETs. The small-signal amplifier and power amplifier chapters have incorporated the latest designs and circuit choices, including linearization.

The oscillator chapter has been extended to include BiCMOS and SiGe HBT oscillators suitable for high integration, and modern noise reduction circuits have been added. Also, time-domain analysis for startup conditions have been incorporated. The microwave mixer section has been extended with a wealth of new designs.

Consistent with the industry's needs, there is also a new chapter on RF switches and attenuators. As in the first edition, we close the book looking at and using modern design software, realizing this field constantly changes by offering better and faster software tools, although the basic capabilities remain the same.

Most of the software tools in this book came from Ansoft. There are three student versions downloadable from their website. Other companies may also provide demonstration versions free of charge.

Of course, there have been numerous contributions by many people to this work, which took much longer than expected. Engineers from Synergy Microwave and Motorola have contributed generously. Professors from all over the world have given input, including Tim Healy, Robert Owens (who also wrote Chapter 6 on filters), Allen Sweet, and Martin Grace of Santa Clara University; G. R. Branner of UC Davis; Tom H. Lee of Stanford University; Ali Niknejad and Robert Broderson of UC Berkeley; Jose Carlos Pedro of University of Aveiro (Portugal); and Steve Long of University of California Santa Barbara (UCSB). Important inputs from industry were provided by Klaus Aufinger of Siemens (Germany); Steve Kovacic of SiGe (Canada); Rene Douville of CRC (Canada); Dipak Patel of Philips; Kirk Laursen of Oepic; Mike Zybura of RFMD; Jim Cochrane of Infineon; Jon Martens of Anritsu; Karl Niclas of Watkins Johnson; Paul Khanna of Agilent/Celeritek; Li-Wu Yang and Tanhua Wu of RFIC; Greg Zhou of MWT; Edison Fong of Motorola; Harpreet Randhawa and Pat Tesera of Ansoft; Peter Sturzu (consultant); Mike Bailey of Filtronics; Larry Dunleavy and Tom Weller of Modelithics; Al Ward, Biniam Ayele, and Rich Ruby of Agilent; and finally Ken Kawakami of Avnet (who wrote Appendix E). Several students assisted in putting the book and solution manual in final form, including Chi-Chung (Calvin) Chien, Hu-Sun (Luke) Huang, and Francisco Madriz.

The 13 chapters were written as follows: Vendelin—Chapters 1, 2, 4, 5, 6 (Owens), 8, and Appendices D and E (Kawakami); Pavio—Chapters 9, 11, and 12; Rohde—Chapters 3, 7, 10, Section 11.10, 13, and Appendices A, B, C, and F.

As always, Wiley has been a joy to work with through the leadership, patience, and understanding of George Telecki. Coordinating the efforts of three IEEE Fellows is a monumental task, fitting to the scope of this second edition.

Finally, we would like to thank Dr. Robert A. Pucel, one of the greatest pioneers in microwave circuit design and a good friend to have. He thoroughly reviewed both the first edition of this book and now 15 years later the second edition.

George D. Vendelin
Anthony M. Pavio
Ulrich L. Rohde

Saratoga, California
Phoenix, Arizona
Paterson, New Jersey
April, 2005

CHAPTER 1

RF/MICROWAVE SYSTEMS

1.1 INTRODUCTION

This book is similar to many well-known texts in the field [1.1–1.12]; they all have a different slant on the same engineering topics, that is, radio-frequency (RF) and microwave circuit design, from an intuitive and engineering point of view. This book was first written in 1982 [1.13] using only linear techniques, which is out of print, and was later augmented in 1990 [1.14] including both linear and nonlinear techniques. This second edition is an attempt to update the technology to include all of the very latest engineering tools, particularly the best of modern microwave computer-aided design (CAD), which is always in a state of rapid advancement.

The audience is both graduate students of RF/microwave courses and practicing engineers in this industry. We expect you have already mastered the fundamentals (component definitions for amplifiers, oscillators, and mixers; two-port network theory; power gains; Smith chart matching; direct current (dc) biasing; etc.), but these are also included in the text for careful review. Prior to using the CAD tools, the practicing engineer should be able to do general RF/microwave problems with a calculator and Smith chart. The CAD software is only a check on the engineer's design and in some cases an enhancement to the basic design. This entire process is only as good as the nonlinear models provided by the device manufacturers, which is a work in progress that improves every year.

This textbook is used in a four-quarter graduate sequence taught at Santa Clara University by one of the authors:

Fall: Fundamental Design—no CAD, Active Microwave Devices I (ELEN 711)

Microwave Circuit Design Using Linear and Nonlinear Techniques, Second Edition
by Vendelin, Pavio and Rohde
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Winter: Linear Design (*S* Parameters with CAD), Active Microwave Devices II (ELEN 712)

Spring: Nonlinear Design (ELEN 714)

Summer: Advanced Nonlinear Design (ELEN 719)

This is often followed by thesis units, publications, papers, Ph.D. programs, and so on. The emphasis is always on understanding why CAD is working so well when the engineer understands the basic principles of circuit design with accurate nonlinear models. An excellent example of this will be shown in Chapter 8, where lossless feedback amplifiers are discussed, which was an extra credit problem in the spring quarter of 2002.

A book of this magnitude must begin with a brief history of the nineteenth- and twentieth-century communications achievements, which are tabulated in Table 1.1 [1.15]. While key scientific events occurred over a century ago, the present digital wireless era was demonstrated in 1962 and introduced commercially in 1988.

From a solid-state device perspective, the key events were the inventions of the bipolar junction transistor (BJT) and GaAs MESFET, which are even today the heart of electronics. The Ge BJT was quickly replaced by the Si BJT due to temperature considerations and the discovery of SiO_2 (the planar process). Bell Labs accidentally discovered the Ge BJT while attempting to build a variable resistor, or field-effect transistor (FET).

The first solid-state X-band radar was developed by Texas Instruments during the period 1966 to 1970 under contract to Wright Patterson Air Force Base [1.16]. This

TABLE 1.1 Historical Events in Communications

Event	Names	Year
Maxwell's equations	James Clerk Maxwell	1873
Invention of telephone	Alexander Graham Bell	1876
Validation of Maxwell's theory	Heinrich Hertz	1891
Transatlantic communications	Guglielmo Marconi	1901
Galena (lead sulfide) detector	J. C. Bose	1901 (Patent filed)
Superheterodyne receiver	Edwin H. Armstrong	1917
X-band radar	MIT Radiation Labs	1942
Invention of transistor	John Bardeen, William Brittain, and William Shockley, Bell Labs	1947
Digital voice transmission	ATT	1962
Invention of GaAs metal–semiconductor field-effect transistor (MESFET)	C.A. Mead Cal Tech	1965
First solid-state X-band radar	Texas Instruments	1970
First GaAs MESFETs in satellites	SPAR/CRC	1975
Analog cellular radio	ATT/Motorola	1983
Digital cellular radio	ATT	1988
Digital personal communication service (PCS) radio code division multiple access (GSM/CDMA)	Europe/Qualcomm	1993
WCDMA (wide-band CDMA) 4G CDMA Networks	Mobile Internet	2000

contract, which was called the MERA program (Microwave Electronics Radar Applications), revolutionized microwave engineering, providing new insights into the use of hybrid microwave integrated circuit (MIC) construction using microstrip transmission lines on alumina, after determining silicon would never succeed in this role. This is a phased array antenna which is pointed by the phase shifters preceding the 1-W transmitters, 640 of them. This was replaced in the 1990s by GaAs MESFET modules by Raytheon and Texas Instruments for the BMDO [Ballistic Missile Defense Operation for ground-based radar (GBR)] when 60,000 units were shipped about 1996 [1.17].

The first introduction of GaAs MESFETs into space deserves some comments. At this point in time (1973), two major companies were producing devices with about 2 μm gate lengths, Fairchild and Plessey, at a price of about $500 each. A satellite was about to be launched in 1975 by SPAR, which hired Communications Research Center CRC (Canada), which selected the new MESFETs from both suppliers, to design the low-noise amplifier (LNA). The first purchase of space-qualified GaAs MESFETs was 23 devices for $40,000 from Fairchild. These were all burned out in 2 months due largely to electro static discharge (ESD) problems, so they purchased an entire wafer next. To shorten the story, which is documented in Refs. 1.18 and 1.19, both suppliers provided transistors for five- or six-stage amplifiers (see Fig. 1.1) with 26 dB gain and 10 dB noise figure at 12 GHz [300 MHz bandwidth (BW)], and two satellites were launched in 1975; the project was a complete success, with a lifetime of about 3 years [1.20] for the Plessey amplifier; the Fairchild amplifier never turned on due to switching problems in the satellite. The circuits were made on 25-mil polished alumina with TiW/Au metal 6 μm thick. The resistance of the TiW was 50 Ω/square. Some photographs of these amplifiers, which were used in the world's first direct broadcast TV satellite, which was launched in Australia in late 1975, are shown in Figure 1.1.

Turning to cellular telephone, analog cellular systems introduced in 1984 are commonly referred to as first-generation systems. The digital systems currently in use, such as GSM, personal digital cellular (PDC), CDMAOne (IS-95), and US_TDMA (IS-136), are second-generation systems. These systems serve both voice communications and other services such as text messaging and access to data networks. Third-generation systems are designed for multimedia communication: With these person-to-person communication can be enhanced with high-quality images and video, and access to information and services on public and private networks will be enhanced by the higher data rates and new flexible communication capabilities of third-generation systems. WCDMA technology has emerged as the most widely adopted third-generation air interface. Its specification has been created in 3GPP (the Third Generation Partnership Project). Within 3GPP, WCDMA is called UTRA (Universal Terrestrial Radio Access), FDD (Frequency Division Duplex), and TDD (Time Division Duplex). The differences between WCDMA FDD and WCDMA TDD are explained in 1.21.

Consumer surveys have shown that extra features added to cell phones are secondary while voice performance and cost are primary. Secondary features include video, digital pictures, Internet browsing, and so on, which obviously add to the cost. Customers want "Zero-G," which could be defined as voice only, with minimum cost. Forget the bells and whistles; it is voice only, nothing else is of any interest to the average consumer at the time of this writing. New revolutions in cellular telephone are needed to bring the cost down, and these are in progress.

Another way of expressing the present state of complementary metal–oxide–semiconductor (CMOS) technology is the cost of a 40 × 40-mm silicon chip in

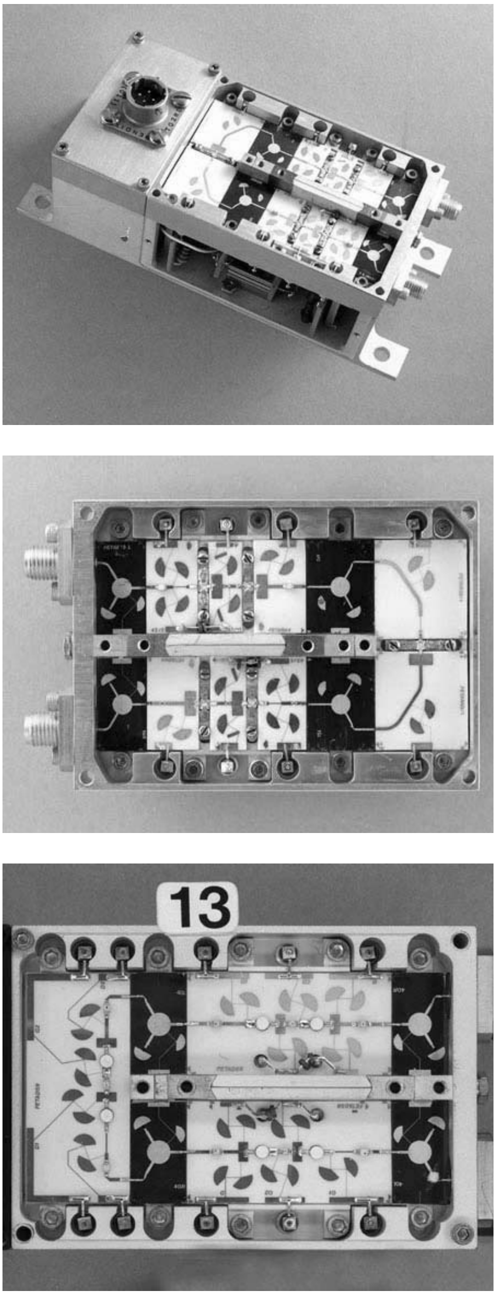


FIGURE 1.1 First GaAs MESFET amplifiers for 12-GHz satellite application for direct broadcast TV. (Courtesy of Rene Douville [1.18–1.20].)

high-volume production: 10 cents, insignificant for the RF portion. When the cellular RF analog transceiver has been reduced to this small size, the digital content, case, and antenna will become the virtual cost of the mobile telephone, which will be hopefully within the reach of most of the world.

Of course, there is also a great deal of RF/microwave engineering going on today for the entertainment industry, largely digital TV, the next consumer product. The integration of analog and digital functions on the same silicon chip is expected to significantly reduce costs for all consumer products.

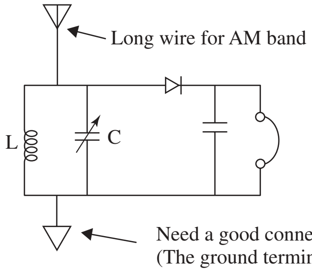
Almost 100 years ago the simplest radio receiver was the crystal radio receiver shown in Figure 1.2, which uses no battery. The diode (or crystal) demodulates the amplitude-modulated (AM) carrier to excite the headphones into sound. This circuit is also called "the foxhole radio" because of its use during World War II. In this case the components were the antenna (a length of wire), the LC tank, the detector, which was made from pencil lead touching a Gillette razor blade, and a headphone set. The capacitor of 1000 pF in parallel with the headphones is an RF ground for the carrier frequency. The headphones detect the envelope of the received signal, which is the desired information. This type of receiver is the simplest of all, and there are numerous web sites which can sell you one for your evaluation.

A similar invention which also uses no battery is the telephone [1.22]. The detector is a diaphragm which transmits sound to the human ear drum, which has a threshold sensitivity of one hydrogen atom displacement [1.23], where the frequency is roughly 5 kHz.

The frequency spectrum of a receiver is shown in Figure 1.3, where the image signal may also produce an unwanted IF output, so the image should be filtered. The image signal is the mirror image of the desired RF signal.

The radio is a tuned resonant tank circuit at the carrier frequency, which maximizes the input voltage to the heterodyne receiver shown in Figure 1.4. The incoming signal is converted to a lower intermediate frequency (IF) by the local oscillator (LO), where the pertinent mathematics is

$$\begin{aligned}\cos\alpha\cos\beta &= 0.5\cos(\alpha-\beta)+0.5\cos(\alpha+\beta)\\ &= 0.5\cos(\omega_{\mathrm{IF}}t)+0.5\cos(\omega_{\mathrm{RF}}t+\omega_{\mathrm{LO}}t)\end{aligned} \tag{1.1}$$



Long wire for AM band

L: Approx. 250 µH

C: Approx. 40-400pF to tune AM band

Headphones need to be high-Z (> a few kΩ)

Need a good connection to earth ground for best results
(The ground terminal of an AC power outlet often works okay, but be sure to hook things upright, or there could be some measure of unpleasantness)

FIGURE 1.2 Crystal radio receiver or Foxhole Radio [1.12].

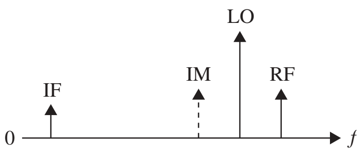
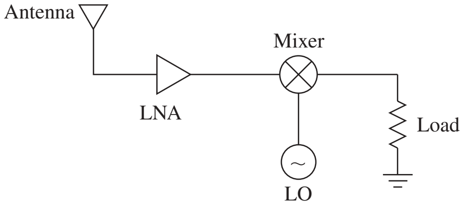
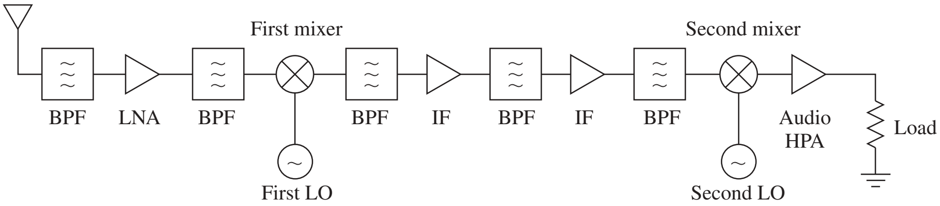


FIGURE 1.3 Frequency spectrum of radio receiver.



(*a*) Heterodyne receiver, if $f_{\mathrm{LO}} = f_{\mathrm{RF}}$, homodyne or direct-conversion receiver



(*b*) Superheterodyne receiver

FIGURE 1.4 Heterodyne receiver, single-conversion superheterodyne receiver, double-conversion superheterodyne receiver [1.26].

where α and β are the RF and LO frequencies. The frequency spectrum is shown in Figure 1.3, where the image signal may also produce an unwanted IF output, so the image should be filtered. The image signal is the mirror image of the desired RF signal.

The basic heterodyne receiver invented by Armstrong in 1917 is given in Figure 1.4. The modulated carrier is amplified, converted to an IF, demodulated, and amplified at baseband (audio). This gives a single tuning control (the LO) and allows high gain and selectivity at the IF. A superheterodyne receiver has two (or more) mixers, so the frequency is converted once or twice to a lower frequency. Most of the gain is done at the first or second IF, where the cost is generally lower.

Most electrical engineers have worked in various aspects of RF or microwave design. This book is addressed to the designers of these circuits. The circuits are organized into three frequency ranges:

RF	1 MHz (or less) to 1 GHz
Microwave	1–30 GHz
Millimeter wave	30–300 GHz (or higher)

The word *wireless* was used by Marconi in 1901, and it reoccurred as a replacement for the word *radio* in about 1991. The design techniques tend to be different for these three groups, but there are many similarities. A single CAD package such as Ansoft Design Suite (which is provided in the jacket of this book), Agilent ADS (Advanced Design System), or Advanced Wave Research (AWR) Microwave Office (MWO) may be used for all three groups.

Another summary of wireless applications is given in Table 1.2 [1.24]. These applications include all three frequency groups as well as communications, radar, navigation, remote sensing, RF identification, broadcasting, automobiles and highways, sensors, surveillance, medical, and astronomy and space exploration.

TABLE 1.2 Wireless Applications [1.24]

1. *Wireless communications*: space, long-distance, cordless phones, cellular telephones, mobile, PCS, local-area networks (LANs), aircraft, marine, citizen's band (CB) radio, vehicle, satellite, global, etc.
2. *Radar (standing for radio detection and ranging)*: airborne, marine, vehicle, collision avoidance, weather, imaging, air defense, traffic control, police, intrusion detection, weapon guidance, surveillance, etc.
3. *Navigation*: microwave landing system (MLS), global positioning system (GPS), beacon, terrain avoidance, imaging radar, collision avoidance, auto-pilot, aircraft, marine, vehicle, etc.
4. *Remote sensing*: Earth monitoring, meteorology, pollution monitoring, forest, soil moisture, vegetation, agriculture, fisheries, mining, desert, ocean, land surface, clouds, precipitation, wind, flood, snow, iceberg, urban growth, aviation and marine traffic, surveillance, etc.
5. *RF identification*: security, antitheft, access control, product tracking, inventory control, keyless entry, animal tracking, toll collection, automatic checkout, asset management, etc.
6. *Broadcasting*: amplitude- and frequency-modulated (AM, FM) radio, TV, direct broadcast satellite (DBS), universal radio system, etc.
7. *Automobiles and highways*: collision warning and avoidance, GPS, blind-spot radar, adaptive cruise control, autonavigation, road-to-vehicle communications, automobile communications, near-obstacle detection, radar speed sensors, vehicle RF identification, intelligent vehicle and highway system (IVHS), automated highway, automatic toll collection, traffic control, ground penetration radar, structure inspection, road guidance, range and speed detection, vehicle detection, etc.
8. *Sensors*: moisture sensors, temperature sensors, robotics, buried-object detection, traffic monitoring, antitheft, intruder detection, industrial sensors, etc.
9. *Surveillance and electronic warfare*: spy satellites, signal or radiation monitoring, troop movement, jamming, antijamming, police radar detectors, intruder detection, etc.
10. *Medical*: magnetic resonance imaging, microwave imaging, patient monitoring, etc.
11. *Radio astronomy and space exploration*: radio telescopes, deep-space probes, space monitoring, etc.
12. *Wireless power transmission*: space-to-space, space-to-ground, ground-to-space, ground-to-ground power transmission.

At low frequency, we use lumped components with transistors and diodes as needed, that is, R, L, and C. When the components become about $\lambda/8$ long, about 500 MHz to 1 GHz, we may add transmission line components (usually microstripline) in addition to lumped components. The transition from lumped elements to distributed elements will be covered in Chapter 2. When the free-space wavelength becomes less than 1 mm (millimeter wave), the designers are usually forced to use distributed transmission line elements where possible. Other forms of transmission are also used due to the limitations of transverse-electromagnetic (TEM) stripline/microstripline transmission lines [1.25], such as waveguides, surface modes, slotline, coplanar waveguide, inverted microstripline, and suspended microstripline [1.26]. The geometry for these forms of TEM, transverse-electric (TE), and transverse-magnetic (TM) lines is given in Figure 1.5. It is useful to keep in mind that two wires (or conductors) are needed for TEM and only one conductor is required for TE and TM waves, which are generally at higher frequencies.

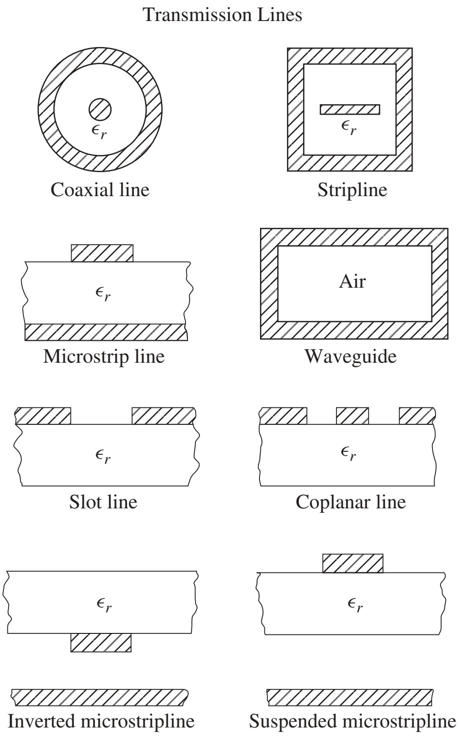


FIGURE 1.5 Geometry for microwave transmission.

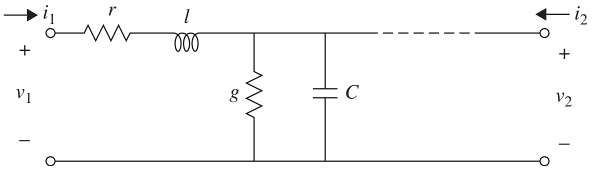


FIGURE 1.6 Lumped-element equivalent circuit of transmission line.

Transmission lines may be modeled as in Figure 1.6, which leads to the telegrapher equations, which are a time-domain description of the line:

$$\frac{\partial v(z,t)}{\partial z} = -RI(z,t) - L\frac{\partial I(z,t)}{\partial t} \tag{1.2}$$

$$\frac{\partial I(z,t)}{\partial z} = -Gv(z,t) - C\frac{\partial v(z,t)}{\partial t} \tag{1.3}$$

For sinusoidal steady-state conditions, this may be simplified to

$$\frac{dV(z)}{dz} = -(R + j\omega L)I(z) \tag{1.4}$$

$$\frac{dI(z)}{dz} = -(G + j\omega C)V(z) \tag{1.5}$$