1, 2, 3, 6

1

Introduction

This chapter presents a description of microwaves and some of its many applications. Significant historical developments related to the advancement of microwave engineering are also presented. Students of engineering are urged to study the history of science, mathematics, and engineering. I have observed that those possessing a *sense of history* develop a deeper understanding of new concepts and are more creative problem solvers (see Ref. 1–10). Besides, it's fun! The chapter concludes with a review of the units and notation used throughout the text.

1–1 THE MICROWAVE SPECTRUM

Microwaves are electromagnetic waves whose frequencies range from approximately 300 megahertz (MHz) to 1000 gigahertz (GHz). Most applications of microwave technology make use of frequencies in the 1 to 40 GHz range. The letter designations for the most commonly used microwave bands are listed in Table 1–1.

TABLE 1–1 Commonly Used Microwave Frequency Bands

LETTER DESIGNATION	FREQUENCY RANGE
L band	1 to 2 GHz
S band	2 to 4 GHz
C band	4 to 8 GHz
X band	8 to 12 GHz
K_u band	12 to 18 GHz
K band	18 to 26 GHz
K_a band	26 to 40 GHz

The diagram of the electromagnetic spectrum in Fig. 1–1 illustrates that the lower end of the microwave region borders radio and television frequencies, while the upper end is adjacent to the infrared and optical spectrums. As a result, microwave engineers often employ ideas and techniques derived from both of these well-established disciplines. For example, optical techniques are used to design microwave antennas and lenses, while microwave circuit design usually involves concepts associated with ac network theory.

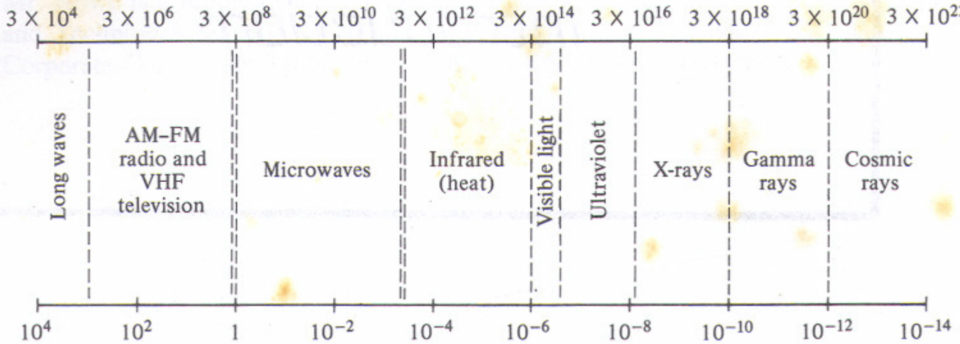


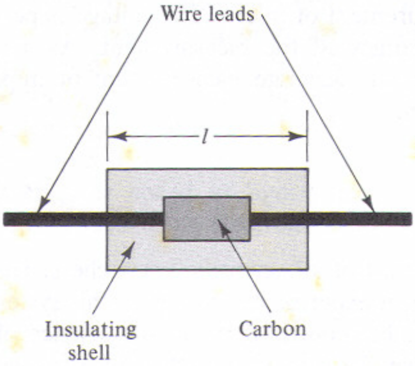
Figure 1–1 The electromagnetic spectrum.

There are three important characteristics that differentiate microwave engineering from its low-frequency and optical counterparts. First, the size of most microwave components and circuits are within an order of magnitude of the operating wavelength.[1] This is not the case for ordinary optical devices and conventional electric circuits. For example, the validity of the ray concept in optics stems from the fact that components, such as lenses and mirrors, are much larger than the operating wavelength. On the other hand, the application of ac network theory requires that all dimensions of the circuit elements be much smaller than the wavelength. To verify this statement, consider the carbon resistor and its model illustrated in Fig. 1–2. A basic assumption of ac theory is that the current entering the resistor exactly equals that leaving it, both in amplitude and phase. However, they cannot be exactly equal since it takes a finite time for the wave associated with the current to travel the length l. Since phase delay is merely a normalized way of expressing the time delay of a sinusoid, the conclusion is that the phase of $\boldsymbol{I}_2$ will not necessarily be the same as $\boldsymbol{I}_1$. Thus the statement $\boldsymbol{I}_1 = \boldsymbol{I}_2$ assumes that the time delay t_d is negligible compared to the period T of the ac signal.[2] Expressed mathematically $t_d = l/v \ll T = 1/f$. Since all waves are governed by the relationship

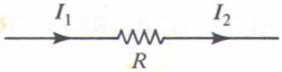
$$f\lambda = v \tag{1–1}$$

[1] It is interesting to note that the size of many audio components, such as speakers and microphones, are comparable to the wavelength of audible sound waves. Consequently, audio engineering techniques are also useful to the microwave engineer.

[2] All symbols and their SI units are listed in Appendix A.



(a) Cross-section of a carbon resistor



(b) Circuit model

Figure 1–2 The resistance model.

where, in this case, v is the electromagnetic wave velocity, the inequality may be rewritten as $l \ll \lambda$. In other words, an alternate way of expressing the underlying assumption of ac theory is that the dimensions of the circuit elements must be small compared to the operating wavelength. In Chapter 3, transmission-line methods will be explored which partially circumvent the restrictiveness of this assumption and hence are very useful in the design and analysis of microwave circuits.

It should be noted that even when the actual circuit element is small compared to the wavelength, it may not behave as expected. For example, to the designer of low-frequency networks, an ordinary low-power carbon resistor may be modeled as a simple resistance. For the microwave designer, however, an accurate representation must include the shunt capacitance due to the insulating shell and the series inductance associated with the wire leads. In many cases, the reactances associated with this capacitance and inductance obscure the resistive properties making it unsuitable for microwave applications. Specially designed microwave resistors are commercially available that minimize these unwanted or *parasitic* reactances. The same holds true for diodes, transistors, and other elements.

A second phenomenon that is of particular concern to the microwave engineer is that of skin effect. Skin depth, defined precisely in Chapter 2, is a measure of the degree to which an electromagnetic field penetrates a conducting material. This effect is a function of frequency, the depth of penetration decreasing with increasing frequency. For example, at 1000 MHz, the skin depth for copper is only a few microns. As a result, microwave currents tend to flow along the surface of a conductor, which dramatically increases its resistive effect. At microwave frequencies, the resistance of a copper wire can easily be a thousand times greater than its low-frequency value. Therefore, the use of special techniques for minimizing circuit losses are particularly important at microwaves. In some cases the silver-plating and polishing of metallic surfaces is necessary.

The third unique characteristic of microwave work is associated with the measurement techniques used. At low frequencies, the properties of a circuit or system are determined by measuring voltages and currents. This approach is not applicable to microwave circuits since oftentimes these quantities are not uniquely defined. Even when the direct measurement of microwave voltage is possible, noise fluctuations usually degrade the accuracy of the measurement. As a result, most microwave experimentation involves the accurate measurement of impedance and power rather than voltage and current.

1–2 HISTORICAL BACKGROUND

Michael Faraday was one of the greatest of all scientific researchers. His careful attention to the detail and organization of experiments, as well as his systematic analysis of data resulted in many remarkable contributions to the science of electricity and magnetism. In 1845, for example, he studied the effect of a magnetic field on the propagation of light through glass. He observed that when the magnetic field was aligned with the direction of propagation, the plane of polarization of the light beam rotated slightly. This observation suggested the existence of a relationship between electromagnetism and light. In his "Thoughts on Ray Vibrations," Faraday speculated that light might be a transverse magnetic disturbance with *wavelike* characteristics. Twenty years later, James Clerk Maxwell published "A Dynamical Theory of the Electromagnetic Field." In this remarkable paper, and later in his definitive work, *Electricity and Magnetism,* Maxwell formally developed the electromagnetic theory of light. Starting with four basic relationships, now called Maxwell's equations, he proved mathematically that electromagnetic waves could propagate through a nonconducting medium. Furthermore, he demonstrated that the electric and magnetic fields are transverse to the direction of propagation and travel at the speed of light. In fact, his predicted value of wave velocity was so near the known speed of light, that he stated, "we have strong reason to conclude that light itself is an electromagnetic disturbance in the form of waves . . ." Maxwell's theory of electromagnetic waves was not readily accepted by all physicists. Many scientists subscribed to the Weber theory which held that electric and magnetic fields merely represented "instantaneous action-at-a-distance."

In the early 1880s, Heinrich Hertz set out to determine which of the two theories was correct. Through a brilliant series of experiments, he succeeded in verifying Maxwell's theory of electromagnetic waves. These experiments are described in two papers, published in 1888, entitled "On Electromagnetic Waves in Air, and Their Reflection" and "On Electric Radiation." A detailed description of these experiments may be found in Refs. 1–1 and 1–2. In the Hertz experiments, the electromagnetic generator consisted of a spark gap connected to an induction coil. The interruption of current in the coil produced a high voltage, causing a spark to appear across the gap. This effect was oscillatory with a frequency in the megahertz range. For a detector, Hertz used a circular loop of thick wire with the ends separated by a very tiny gap. He reasoned that the induced voltage in the loop would be sufficient to cause a small observable spark across the tiny gap. This experiment was conducted in a room where one wall was covered with a large sheet of zinc to reflect the waves (if they existed). At the time, the principle that wave reflections caused a standing wave pattern was well known, the spacing between successive nulls being one-half the wavelength. By moving the detector about, he was able to determine the location of the nulls and hence measure the wavelength. The observed peaks and nulls were considered proof of the existence of electromagnetic waves. Furthermore, since Hertz knew the frequency of his generator (about 30 MHz), the measurement of wavelength allowed him to calculate the velocity of these waves. The wavelength was determined to be about 10 m, from which the velocity was calculated to be 3×10^8 m/s. This value of velocity was that predicted by Maxwell (namely, the speed of light), hence validating Maxwell's theory of electromagnetism. Thus, for an electromagnetic wave in free space, Eq. (1–1) becomes

$$f\lambda_0 = c \tag{1–2}$$

where λ_0 is the free space wavelength and c denotes the velocity of light in free space. The value of c and other physical constants are listed in Table 1–3.

In further experiments, described in his second paper, Hertz used a generator having a frequency of approximately 450 MHz. He employed parabolic reflectors to concentrate the electromagnetic energy which improved the efficiency of transmission. Reflectors of this type continue to be used today as efficient microwave antennas.

The first practical application of electromagnetic waves was in the field of communications. The major figure in this endeavor was the dynamic Guglielmo Marconi of Italy. In 1895, he succeeded in transmitting radio signals over a distance of 1 mile. By using parabolic reflectors, he increased the transmission distance to 4 miles. In this particular demonstration, the operating wavelength was 25 cm. In 1901, with considerably improved equipment, he successfully transmitted the first transatlantic wireless message from England to Newfoundland, a distance of about 3000 miles. Over the next 30 years, the progress in wireless transmission was remarkable. Frequencies from hundreds of kilohertz up to hundreds of megahertz were transmitted through space over thousands of miles.

While all these achievements were taking place, another method of transmitting signals had developed and grown. The sending of telegraph and telephone signals along wires, in fact, predated much of the work in wireless communication. Samuel Morse's telegraph was put into operation between Baltimore and Washington in 1844. In the early 1850s, the possibility of laying a transatlantic submarine cable to provide a direct telegraphic link between England and America was proposed. Sir William Thomson (later Lord Kelvin) was retained as a consultant by the Atlantic Cable Company to study the problem of electrical transmission along the cable. In 1855, his studies led to the first distributed circuit analysis of a transmission line. His model for the line consisted of uniformly distributed series resistances and shunt capacitances. This was the beginning of transmission-line theory. Although Thomson was aware that the line also contained series inductance and shunt conductance, he concluded that they were not significant in this particular application.

With the invention of the telephone in 1876 by Bell and Gray, a more detailed study of electrical signals on transmission lines was required. This project was undertaken by the brilliant mathematician and engineer, Oliver Heaviside of England. His analysis was so thorough that it appears practically unaltered in today's textbooks. Twenty-one years later, Lord Rayleigh presented theoretical proof that electromagnetic waves could propagate through hollow metal pipes (waveguides). At about the same time, Oliver Lodge demonstrated propagation in waveguides at the Royal Institution in London. The operating frequencies for Lodge's experiments were reported to be 1.5 and 4.0 GHz. Due to the lack of dependable microwave generators, the study of waveguide transmission lay dormant for the next 30 years.

Thanks to the pioneering work of Barkhausen and Kurz on positive-grid oscillators (1919) and Hull on the smooth-bore magnetron (1921), reliable microwave sources became a reality. A tube with 20 watts output at 3 GHz was constructed by British scientists in 1936. A year later, the Varian brothers at Stanford conceived the idea of velocity modulating an electron beam. This discovery led to the invention of the klystron which continues to be an excellent source of microwave power. In 1939, a team of British researchers led by Randall and Boot used the cavity resonator principle to develop a new microwave oscillator, the cavity magnetron. With an applied magnetic field of 1000 oersteds and a dc voltage of 16,000 volts, the magnetron produced an amazing 400 watts at 3 GHz. Significant contributions to the development of both the klystron and magnetron were made by the tireless W. W. Hansen of Stanford University, the inventor of the cavity resonator. Microwave tube development in the 1930s was given great impetus by the threatening war clouds over Europe. Britain's concern over the German threat prompted the British to install radars along their coastline. This effort was directed by Robert Watson-Watt. The use of such radars to insure early detection of enemy aircraft was a decisive factor in the defeat of the German Luftwaffe in the Battle of Britain.

With the availability of microwave sources, theoretical and experimental waveguide development proceeded rapidly. Southworth at Bell Labs and Chu and Barrow at MIT not only demonstrated wave propagation through hollow pipes, but also proved that in many cases it was superior to the recently developed coaxial line. During the next several years, Southworth and his colleagues at Bell Labs developed many waveguide components. These and many other microwave devices are described in Southworth's book (Ref. 1–5). In a later book (Ref. 1–6), Southworth gives a historical perspective of the development of microwave techniques. It makes fascinating reading.

Precipitated by events surrounding World War II, the MIT Radiation Laboratory was established in 1940. Many of the greatest scientists in the United States worked long and hard at this facility to further the development of radar systems. The contributions of men like Schwinger, Marcuvitz, Ragan, Montgomery, Dicke, Purcell, Pound, Smullin, Slater, and many others resulted in major advances in the theory and practice of microwaves. The twenty-seven volumes of the MIT Radiation Lab Series is still a reliable source of information for practicing engineers.

Despite the disbanding of the Radiation Lab at the end of World War II, research and development efforts continued at a rapid pace, particularly in microwave magnetics and electronics. For example, the successful development of ferrite materials led to the realization of passive, nonreciprocal components. One of the first, developed by C. L. Hogan, was a microwave gyrator based on the Faraday rotation principle. A major advance in the field of low-noise receivers was achieved with the development of varactor-type parametric amplifiers and upconverters by M. Hines, A. Uhlir, Jr., and their coworkers at Bell Labs and also by H. Hefner and G. Wade at Stanford. Other significant achievements in the field of microwave amplification included the development of the helix-type traveling-wave tube by R. Kompfner, the CW maser described by N. Bloembergen, and the tunnel diode by L. Esaki.

The developments in passive components were equally spectacular, particularly in the area of filter and coupler design. The fine work of the engineering group at the Stanford Research Institute, led by S. Cohn and others, must be acknowledged. The results of their efforts are well known by those in the microwave field.

The early 1960s saw the emergence of two more major development areas, microwave integrated circuits and solid-state microwave sources. The pioneering efforts of J. B. Gunn, W. T. Read, B. C. DeLoach, and many others led to the successful development of Gunn-effect and Impatt-type oscillators. The research in these and other areas, such as microwave transistors, is ongoing and offers exciting possibilities for the future. The special centennial issue of MTT (Ref. 1–11) provides a fascinating historical account of the many advances in microwave technology.

With the development of satellite communication, microwave relay stations, and the further growth in commercial and military radars, microwave technology has become a billion-dollar industry. The recognition of microwaves as a major field in electrical engineering resulted in the creation of the IRE group on Microwave Theory and Techniques (MTT) in 1952.[3] Prime movers during its formative years included B. Warriner, A. G. Clavier, W. W. Mumford, D. D. King, G. C. Southworth, and others. The International MTT Symposium and the Transactions of the MTT are major sources of information on developments in the theory and practice of microwave engineering. These publications are available in most technical libraries.

1–3 MICROWAVE APPLICATIONS

Microwaves are used to satisfy many functions in our modern society. These run the gamut from sending a television signal across continents to cooking an oven roast in minutes. As indicated in the previous section, two of the earliest uses of electromagnetic waves were for point-to-point communication and radar. One might ask, "What is the advantage of microwave frequencies in these applications?" The ability to focus a radio wave is a function of the antenna size and the operating wavelength. For a fixed antenna size, the focusing ability improves as the wavelength decreases. For instance, the width of a radio beam from a parabolic antenna 1 meter in diameter is about 50 degrees at 1 GHz but only 5 degrees at 10 GHz. To communicate efficiently between two points, it is important that the transmitted signal be sharply focused and aimed at the receiving antenna. Since microwave frequencies have this ability, they are ideally suited for wireless type point-to-point communication. An analysis of point-to-point communication systems is presented in Appendix F. It is interesting to note that the function of ordinary radio and television broadcasting is

[3] In 1963, the Institute of Radio Engineers (IRE) and the American Institute of Electrical Engineers (AIEE) merged to form the Institute of Electrical and Electronics Engineers (IEEE).

not to focus but to *cast* the radio signal over as *broad* an area as possible. For that reason, AM, FM, and TV broadcast frequencies are much lower than those in the microwave range.

There are many examples of point-to-point communications at microwave frequencies. A sight familiar to highway travelers is the microwave repeater station shown in Fig. 1–3. A series of these stations spaced along line-of-sight paths can provide a communication link between any two cities in the country. The repeater station collects the microwave signal with one antenna, passes it through an amplifier and transmits the amplified signal via a second antenna to the next repeater station. Usual distances between stations are 25 to 75 miles. A link of many such stations can, for example, deliver a TV signal originating in New York to any other city in the United States and Canada. These links are also used by Western Union, the telephone companies, railroads, public utilities, and many large industries.

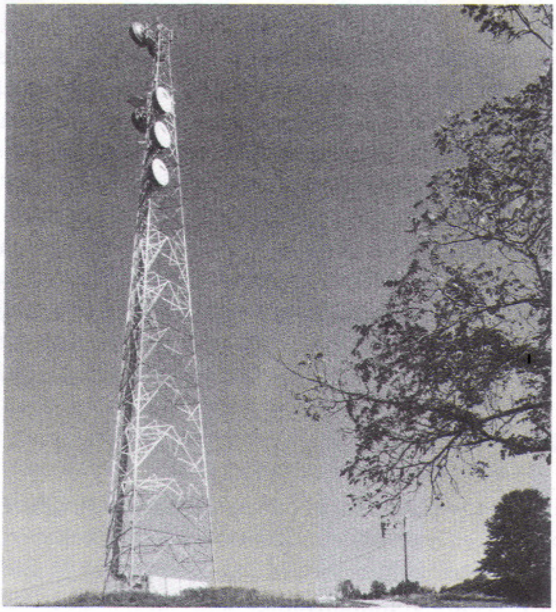
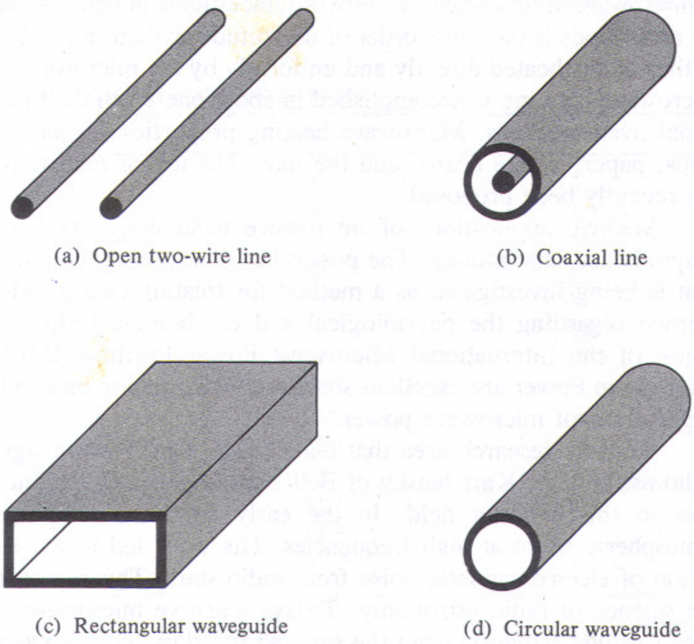


Figure 1–3 A typical microwave repeater station. (Courtesy of Andrew Corp., Orland Park, Ill.)

The combination of satellites and point-to-point microwave transmission results in the ability to communicate between continents. For example, a TV signal originating in Europe can be transmitted to a satellite via a large ground-based antenna. The satellite receives, amplifies, and retransmits the signal to a large receiving antenna, possibly located in the eastern United States. In effect the satellite simulates a repeater station with a 500 mile high tower! Since atmospheric noise is particularly low in the 3 to 6 GHz range, most satellite communication systems operate within this frequency band.

The microwave spectrum contains a wide band of frequencies, which is advantageous for use in transmitting information. Communication theory holds that the amount of information that can be transmitted is directly proportional to the available bandwidth. Thus the microwave spectrum can accommodate many more communication channels than the radio and television bands. With the ever-expanding need to transmit information, microwave communications has become increasingly common in our society.

Transmitting microwave signals is sometimes accomplished with transmission lines rather than antenna systems.[4] Some typical lines are pictured in Fig. 1–4. The open two-wire line is used mainly at the lower frequencies over short distances, an example being the TV twin-lead used to connect an antenna to a television receiver. Its main disadvantage is that it is unshielded and hence tends to radiate energy. On the other hand, the coaxial and waveguide configurations are inherently shielded and therefore are the more popular choices for low-loss microwave transmission. One of the major uses of coaxial lines is the mushrooming cable TV industry.



(a) Open two-wire line (b) Coaxial line

(c) Rectangular waveguide (d) Circular waveguide

Figure 1–4 Typical microwave transmission lines.

Radar systems represent another major application of microwaves. They are used to detect aircraft, guide supersonic missiles, observe and track weather patterns, and control flight traffic at airports. Radar is also used in burglar alarms, garage-door openers, and in the speed detectors utilized by law enforcement officials. The ability to sharply focus a radiated wave is what makes microwaves so useful in radar applications. For example, an airport radar must be able to discern separate airplanes in the traffic pattern. Consequently, the radar beam must be sufficiently narrow so that when the antenna is aimed at one airplane, the received signal represents a reflected wave from that aircraft and not from another one, say,

[4] The two methods of electromagnetic transmission are compared in Appendix F.

15 degrees away. This angular resolution of reflected signals requires a narrow beam and hence the use of microwave frequencies. Sharply focused microwaves from an aircraft radar can also be used to map the terrain of a large ground area. This has both civilian and military application.

The heating properties of microwave power is useful in a wide variety of commercial and industrial applications. The microwave oven is a well-known example. In ordinary ovens, food is heated by infrared. Since the skin depth of foodstuffs is small at infrared frequencies, the heat is absorbed by the surface of the substance. This heat is delivered to the inside of the foodstuff by conduction, a relatively slow process. Hence, it takes a few hours for the center of an average-sized roast to be cooked properly. At the same time, the air in the oven becomes quite hot. In comparison, the air in a microwave oven remains cool since it is a very low-loss medium at microwave frequencies. Moreover, since the skin depth at microwave frequencies for most foods is the same order of magnitude as their dimensions, the entire volume of the food is heated directly and uniformly by the microwave radiation. As a result, microwave cooking is accomplished in about one-tenth the time required by conventional oven methods. Microwave heating properties are also used in drying potato chips, paper, coffee beans, and the like. The use of microwaves for drying clothes has recently been proposed.

Medical applications of microwave technology are being explored in many hospitals and laboratories. The possibility of exposing malignant cells to microwave heat is being investigated as a method for treating cancer. Much more needs to be learned regarding the physiological and psychological effects of microwaves. The digest of the International Microwave Power Institute (IMPI) and the Journal of Microwave Power are excellent sources of information on commercial and industrial applications of microwave power.

Another research area that makes use of microwave signals and techniques is radio astronomy. Karl Jansky of Bell Labs is generally credited with being the pioneer in this exciting field. In the early 1930s he made an extensive study of atmospheric noise at high frequencies. His work led to the discovery and identification of electromagnetic noise from radio stars. This represented the beginning of the science of radio astronomy. Today, sensitive microwave receivers are not only used to study radiation from the sun and the stars, but also as a passive navigational aid to ships at sea.

Two other investigative areas that utilize microwave techniques are material science and high-energy particle physics. Many substances exhibit atomic and molecular resonances in the microwave range. The analysis and interpretation of these resonances, called microwave spectroscopy, is an important vehicle in the scientific effort to understand the fundamental nature of solids, liquids, and gases. In the field of high-energy physics, it is often necessary to accelerate electron beams to velocities within an order of magnitude of the speed of light. Periodically loaded waveguide structures are often employed to slow an electromagnetic wave so that it can efficiently interact with an electron beam. In this manner, electromagnetic energy from a microwave source can be used to increase the kinetic energy of the electron beam.

While current methods of using microwaves are certainly exciting and dynamic, the real challenge and satisfaction for future microwave engineers lies in the applications and techniques yet to be envisioned. I hope you will be a participant in these exciting new developments.

1–4 STANDARD NOTATION, PREFIXES, AND PHYSICAL CONSTANTS

Unless otherwise indicated, the International System of Units (SI) is employed throughout the text. Appendix A contains a compilation of symbols and units for the various quantities that will be encountered. Table 1–2 lists the standard prefixes as adopted by the IEEE and used here. Some of the more common physical constants are given in Table 1–3.

TABLE 1–2 Standard Prefixes and Their Symbols

Prefix	Factor	Symbol
tera	10^{12}	T
giga	10^{9}	G
mega	10^{6}	M
kilo	10^{3}	k
hecto	10^{2}	h
deka	10	da
deci	10^{-1}	d
centi	10^{-2}	c
milli	10^{-3}	m
micro	10^{-6}	μ
nano	10^{-9}	n
pico	10^{-12}	p
femto	10^{-15}	f
atto	10^{-18}	a

TABLE 1–3 Commonly Used Physical Constants

DESCRIPTION	SYMBOL	VALUE
Boltzmann's Constant	k	1.38×10^{-23} J/°K
Electron volt	eV	1.60×10^{-19} J
Electron charge	q_e	1.60×10^{-19} C
Electron mass	m_e	9.11×10^{-31} kg
Permeability of free space	μ_0	$4\pi \times 10^{-7}$ H/m
Permittivity of free space	ϵ_0	8.854×10^{-12} F/m $\approx 10^{-9}/36\pi$ F/m
Planck's constant	h	6.626×10^{-34} J-s
Velocity of light in free space	c	2.998×10^{8} m/s $\approx 3.00 \times 10^{8}$ m/s