1 INTRODUCTION AND SURVEY OF THE ELECTROMAGNETIC SPECTRUM

How does electromagnetic theory tie together such broad phenomena as electronics, radio waves, and light? Explaining this question in the context of electronics design is the main goal of this book. The basic philosophy of this book is that by developing an understanding of the fundamental physics, you can develop an intuitive feel for how electromagnetic phenomena occur. Learning the physical foundations serves to build the confidence and skills to tackle real-world problems, whether you are an engineer, technician, or physicist.

The many facets of electromagnetics are due to how waves behave at different frequencies and how materials react in different ways to waves of different frequency. Quantum physics states that electromagnetic waves are composed of packets of energy called photons. At higher frequencies each photon has more energy. Photons of infrared, visible light, and higher frequencies have enough energy to affect the vibrational and rotational states of molecules and the electrons in orbit of atoms in the material. Photons of radio waves do not have enough energy to affect the bound electrons in a material. Furthermore, at low frequencies, when the wavelengths of the EM waves are very long compared to the dimensions of the circuits we are using, we can make many approximations leaving out many details. These low-frequency approximations give us the familiar world of basic circuit theory.

THE NEED FOR ELECTROMAGNETICS

So why would an electrical engineer need to know all this theory? There are many reasons why any and all electrical engineers need to understand electromagnetics. Electromagnetics is necessary for achieving electromagnetic compatibility of products, for understanding high-speed digital electronics, RF, and wireless, and for optical computer networking.

Certainly any product has some electromagnetic compatibility (EMC) requirements, whether due to government mandated standards or simply for the product to function properly in the intended environment. In most EMC problems, the product can be categorized as either an aggressor or a victim. When a product is acting as an aggressor, it is either radiating energy or creating stray reactive fields at power levels high enough to interfere with other equipment. When a product is acting as a victim, it is malfunctioning due to interference from other equipment or due to ambient fields in its environment. In EMC, victims are not always blameless. Poor circuit design or layout can create products that are very sensitive to ambient fields and susceptible to picking up noise. In addition to aggressor/victim problems, there are other problems in which noise disrupts proper product operation. A common problem is that of cabling, that is, how to bring signals in and out of a product without also bringing in noise and interference. Cabling problems are especially troublesome to designers of analog instrumentation equipment, where accurately measuring an external signal is the goal of the product.

Moreover, with computers and networking equipment of the 21st century running at such high frequencies, digital designs are now in the RF and microwave portion of the spectrum. It is now crucial for digital designers to understand electromagnetic fields, radiation, and transmission lines. This knowledge is necessary for maintaining signal integrity and for achieving EMC compliance. High-speed digital signals radiate more easily, which can cause interference with nearby equipment. High-speed signals also more often cause circuits within the same design to interfere with one another (i.e., crosstalk). Circuit traces can no longer be considered as ideal short circuits. Instead, every trace should be considered as a transmission line because reflections on long traces can distort the digital waveforms. The Internet and the never-ending quest for higher bandwidth are pushing the speed of digital designs higher and higher. Web commerce and applications such as streaming audio and video will continue to increase consumer demand for higher bandwidth. Likewise, data traffic and audio and video conferencing will do the same for businesses. As we enter the realm of higher frequencies, digital designs are no longer a matter of just ones and zeros.

Understanding electromagnetics is vitally important for RF (radio frequency) design, where the approximations of electrical circuit theory start to break down. Traditional viewpoints of electronics (electrons flowing in circuits like water in a pipe) are no longer sufficient for RF designs. RF design has long been considered a “black art,” but it is time to put that myth to rest. Although RF design is quite different from low-frequency design, it is not very hard to understand for any electrical engineer. Once you understand the basic concepts and gain an intuition for how electromagnetic waves and fields behave, the mystery disappears.

Optics has become essential to communication networks. Fiber optics are already the backbone of telecommunications and data networks. As we exhaust the speed limits of electronics, optical interconnects and possibly optical computing will start to replace electronic designs. Optical techniques can work at high speeds and are well suited to parallel operations, providing possibilities for computation rates that are orders of magnitude faster than electronic computers. As the digital age progresses, many of us will become “light engineers,” working in the world of photonics. Certainly optics is a field that will continue to grow.

THE ELECTROMAGNETIC SPECTRUM

For electrical engineers the word *electromagnetics* typically conjures up thoughts of antennas, transmission lines, and radio waves, or maybe boring lectures and “all-nighters” studying for exams. However, this electrical word also describes a broad range of phenomena in addition to electronics, ranging from X-rays to optics to thermal radiation. In physics courses, we are taught that all these phenomena concern electromagnetic waves. Even many nontechnical people are familiar with this concept and with the electromagnetic spectrum, which spans from electronics and radio frequencies through infrared, visible light, and then on to ultraviolet and X-rays. We are told that these waves are all the same except for frequency. However, most engineers find that even after taking many physics and engineering courses, it is still difficult to see much commonality across the electromagnetic spectrum other than the fact that all are waves and are governed by the same mathematics (Maxwell’s equations). Why is visible light so different from radio waves? I certainly have never encountered electrical circuits or antennas for visible light. The idea seems absurd. Conversely, I have never seen FM radio or TV band lenses for sale. So why do light waves and radio waves behave so differently?

Of course the short answer is that it all depends on frequency, but on its own this statement is of little utility. Here is an analogy. From basic chemistry, we all know that all matter is made of atoms, and that atoms contain a nucleus of protons and neutrons with orbiting electrons. The characteristics of each element just depend on how many protons the atom has. Although this statement is illuminating, just knowing the number of protons in an atom doesn't provide much more than a framework for learning about chemistry. Continuing this analogy, the electromagnetic spectrum as shown in Figure 1.1 provides a basic framework for understanding electromagnetic waves, but there is a lot more to learn.

To truly understand electromagnetics, it is important to view different problems in different ways. For any given frequency of a wave, there is also a corresponding wavelength, time period, and quantum of energy. Their definitions are given below, with their corresponding relationships in free space.

frequency, f, *the number of oscillations per second*
wavelength, λ, *the distance between peaks of a wave*:

$$\lambda = \frac{c}{f}$$

time period, T, *the time between peaks of a wave*:

$$T = \frac{1}{f}$$

photon energy, E, *the minimum value of energy that can be transferred at this frequency*:

$$E = h \times f$$

where c equals the speed of light and h is Planck's constant.

Depending on the application, one of these four interrelated values is probably more useful than the others. When analyzing digital transmission lines, it helps to compare the signal rise time to the signal transit time down the transmission line. For antennas, it is usually most intuitive to compare the wavelength of the signal to the antenna length. When examining the resonances and relaxation of dielectric materials it helps to compare the frequency of the waves to the resonant frequency of the material's microscopic dipoles. When dealing with infrared, optical, ultraviolet, and X-ray interactions with matter, it is often most useful to talk about the energy of each photon to relate it to the orbital energy of electrons in atoms. Table 1.1 lists these four values at various

Figure 1.1 The electromagnetic spectrum.

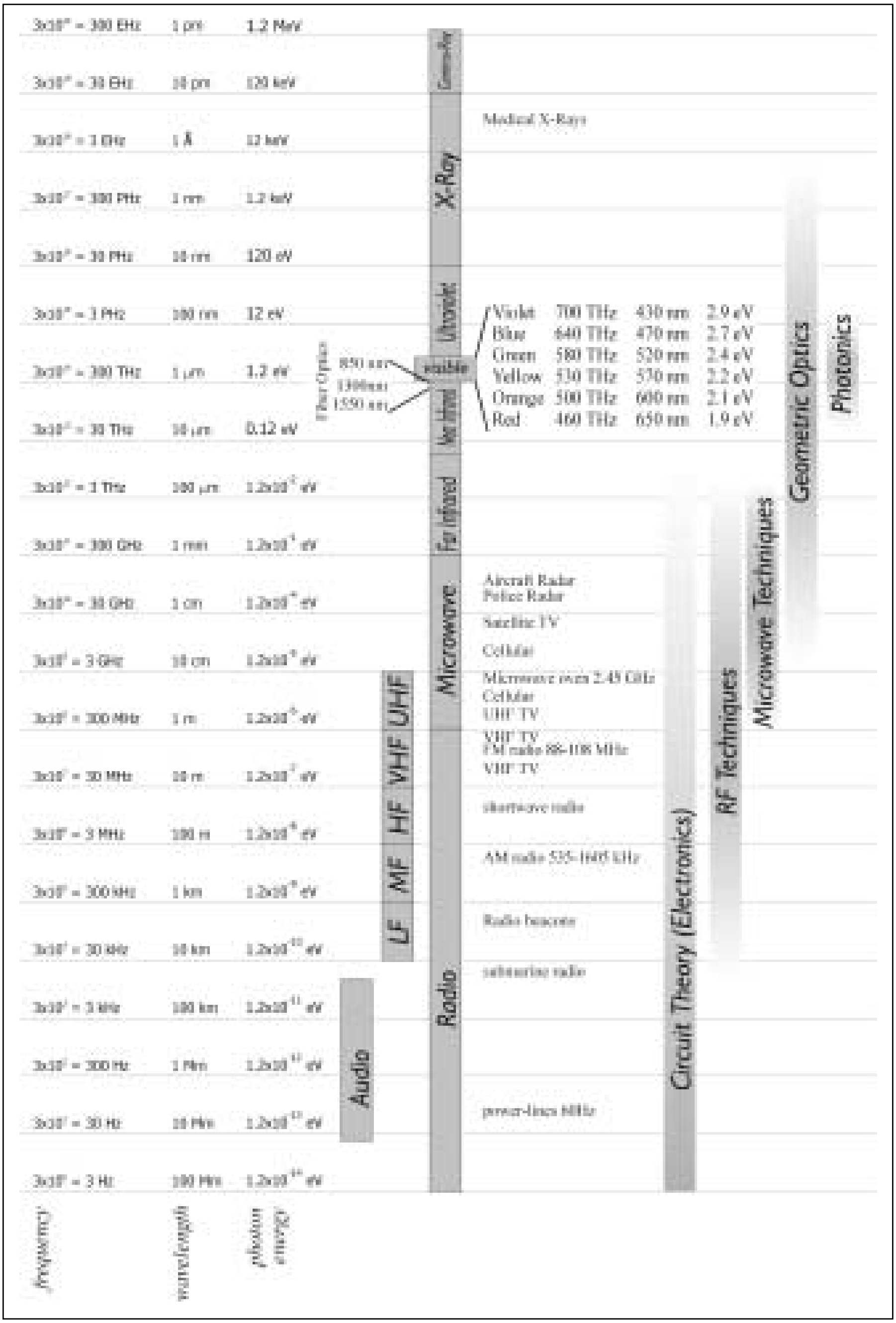


Table 1.1 Characteristics of Electromagnetic Waves at Various Frequencies

Frequency	*Wavelength*	*Photon Energy*	*Period*	*Copper Skin Depth*	*Copper Propagation Phase Angle*
60 Hz *Power line frequency*	5000 km	2.48×10^{-13} eV	16.7 msec	8.4 mm	45° (conductor)
440 Hz *audio*	681 km	1.82×10^{-12} eV	2.27 msec	3.1 mm	45° (conductor)
1 MHz *AM radio*	300 km	4.14×10^{-9} eV	1.00 µsec	65 µm	45° (conductor)
100 MHz *FM radio*	3.00 m	4.14×10^{-7} eV	10.0 nsec	6.5 µm	45° (conductor)
2.45 GHz *Microwave oven*	12.2 cm	1.01×10^{-7} eV	40.8 psec	1.3 µm	45° (conductor)
160 GHz *Cosmic background radiation ("Big Bang") peak*	1.87 mm	6.62×10^{-4} eV	6.25 psec	0.16 µm	46° (conductor)
4.7 THz *Relaxation resonance of copper*	63.8 µm	1.94×10^{-2} eV	213 fsec	27.3 nm	68°
17.2 THz *Room temperature Blackbody infrared peak*	17.4 µm	7.11×10^{-2} eV	5.81 fsec	21.8 nm	82°
540 THz *Center of visible band*	555 nm	2.23 eV	1.85 fsec	21.8 nm	90° (reflecting plasma)
5000 THz *Ultraviolet*	60.0 nm	20.7 eV	0.60 fsec	89 µm	0° (transparent plasma)
1×10^{7} THz *Diagnostic x-ray*	30 pm	4.14×10^{4} eV	1.00×10^{-19} sec	400 m	0° (transparent plasma)
1×10^{8} THz *Gamma ray from ^{198}Hg nucleus*	3.0 pm	4.15×10^{5} eV	1.00×10^{-20} sec	40 km	0° (transparent plasma)

Dipole Radiation Field Border	*Blackbody Characteristic Radiation Temperature*	*Photon Rate for 1 mW Source*	*Aperture for Human Quality Imaging*	*Aperture for Minimal Quality Imaging*
795 km	<1°K	2.5×10^{28} photons/sec	2.7×10^{10} m	7.0×10^{7} m
108 km	<1°K	3.4×10^{27} photons/sec	3.7×10^{9} m	9.5×10^{6} m
47.7 m	<1°K	1.5×10^{24} photons/sec	1.6×10^{6} m	4200 m
47.7 cm	<1°K	1.5×10^{22} photons/sec	1600 m	42 m
1.95 cm	<1°K	6.2×10^{20} photons/sec	660 m	1.7 m
298 µm	2.72°K (temperature of outer space)	9.4×10^{18} photons/sec	10 m	2.6 cm
40.2 µm	80°K	3.2×10^{17} photons/sec	35 cm	0.89 mm
2.77 µm	20°C	8.8×10^{16} photons/sec	9.4 cm	0.24 mm
88.4 nm	9440°K	2.8×10^{15} photons/sec	3.0 mm	7.8 µm
9.54 nm	85,000°K	3.0×10^{14} photons/sec	0.32 mm	840 nm
4.77 pm	1.7×10^{8}°K	1.5×10^{11} photons/sec	160 nm	420 pm
0.477 pm	1.7×10^{9}°K	1.5×10^{10} photons/sec	16 nm	42 pm

parts of the electromagnetic spectrum, and also includes some other relevant information. If some of these terms are unfamiliar to you, don't fret—they'll be explained as you progress through the book.

ELECTRICAL LENGTH

An important concept to aid understanding of electromagnetics is electrical length. Electrical length is a unitless measure that refers to the length of a wire or device at a certain frequency. It is defined as the ratio of the physical length of the device to the wavelength of the signal frequency:

$$\text{Electrical length} = \frac{L}{\lambda}$$

As an example, consider a 1-meter long antenna. At 1 kHz this antenna has an electrical length of about 3×10^{-6}. An equivalent way to say this is in units of wavelength; that is, a 1 meter antenna is $3 \times 10^{-6}\,\lambda$ long at 1 kHz. At 1 kHz this antenna is electrically short. However, at 100 MHz, the frequency of FM radio, this antenna has an electrical length of 0.3 and is considered electrically long. In general, any device whose electrical length is less than about 1/20 can be considered electrically short. (Beware: When working with wires that have considerable loss or large impedance mismatches, even electrical lengths of 1/50 may not be electrically short.) Circuits that are electrically short can in general be fully described by basic circuit theory without any need to understand electromagnetics. On the other hand, circuits that are electrically long require RF techniques and knowledge of electromagnetics.

At audio frequencies and below (<20 kHz), electromagnetic waves have very long wavelengths. The wavelength is typically much larger than the length of any of the wires in the circuit used. (An exception would be long telephone lines.) *When the wavelength is much longer than the wire lengths, the basic rules of electronic circuits apply and electromagnetic theory is not necessary.*

THE FINITE SPEED OF LIGHT

Another way of looking at low-frequency circuitry is that the period (the inverse of frequency) of the waves is much larger than the delay through the wires. "What delay in the wires?" you might ask. When we are involved in low-frequency circuit design it is easy to forget that the electrical signals are carried by waves and that they must travel at the speed of light, which is very fast (about 1 foot/nsec on open air wires), but not infinite. So, even when you turn on a light switch there is a delay before the light bulb receives the voltage. The same delay occurs between your home stereo and its speakers. This delay is typically too small for humans to perceive, and is ignored whenever you approximate a wire as an ideal short circuit. The speed of light delay also occurs in telephone lines, which can produce noticeable echo (>50 msec) if the connection spans a large portion of the earth or if a satellite feed is used. Long distance carriers use echo-cancellation electronics for international calls to suppress the effects. The speed of light delay becomes very important when RF or high-speed circuits are being designed. For example, when you are designing a digital system with 2 nsec rise-times, a couple feet of cable amounts to a large delay.

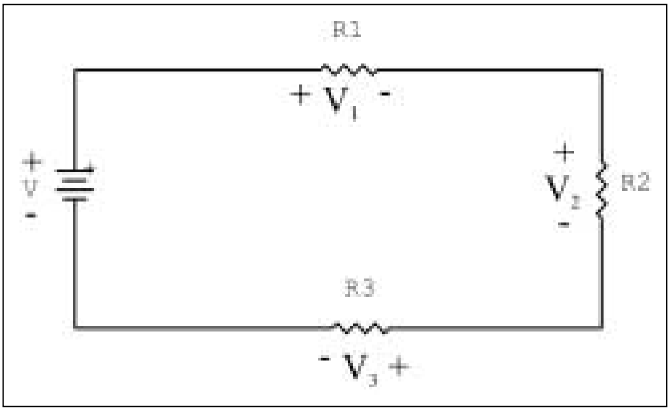
ELECTRONICS

Electronics is the science and engineering of systems and equipment that utilize the flow of electrons. Electrons are small, negatively charged particles that are free to move about inside conductors such as copper and gold. Because the free electrons are so plentiful inside a conductor, we can often approximate electron flow as fluid flow. In fact, most of us are introduced to electronics using the analogy of (laminar) flow of water through a pipe. Water pressure is analogous to electrical voltage, and water flow rate is analogous to electrical current. Frictional losses in the pipe are analogous to electrical resistance. The pressure drop in a pipe is proportional to the flow rate multiplied by the frictional constant of the pipe. In electrical terms, this result is Ohm's law. That is, the voltage drop across a device is equal to the current passing through the device multiplied by the resistance of the device:

$$\text{Ohm's law: } V = I \cdot R$$

Now imagine a pump that takes water and forces it through a pipe and then eventually returns the water back to the tank. The water in the tank is considered to be at zero potential—analogous to an electrical ground or common. A pump is connected to the water tank. The pump produces a pressure increase, which causes water to flow. The pump is like a voltage source. The water flows through the pipes, where frictional losses cause the pressure to drop back to the original "pressure potential." The water then returns to the tank. From the perspective of energy

Figure 1.2 A simple circuit demonstrating Kirchhoff's voltage law ($\boldsymbol{V = V_1 + V_2 + V_3}$).



flow, the pump sources energy to the water, and then in the pipes all of the energy is lost due to friction, converted to heat in the process. Keep in mind that this analogy is only an approximation, even at DC.

Basic circuit theory can be thought of in the same manner. The current flows in a loop, or circuit, and is governed by Kirchhoff's laws (as shown in Figures 1.2 and 1.3). Kirchhoff's voltage law (KVL) says that the voltages in any loop sum to zero. In other words, for every voltage drop in a circuit there must be a corresponding voltage source. Current flows in a circle, and the total of all the voltage sources in the circle or circuit is always equal to the total of all the voltage sinks (resistors, capacitors, motors, etc.). KVL is basically a consequence of the conservation of energy.

Kirchhoff's current law (KCL) states that when two or more branches of a circuit meet, the total current is equal to zero. This is just conservation of current. For example, if 5 amps is coming into a node through a wire, then 5 amps must exit the node through another wire(s). In our water tank analogy, this law implies that no water can leave the system. Current can't just appear or disappear.

Additional rules of basic circuit theory are that circuit elements are connected through ideal wires. Wires are considered perfect conductors with no voltage drop or delay. The wires between components are therefore all considered to be at the same voltage potential and are referred to as a node. This concept often confuses the beginning student of electronics. For an example, refer to Figure 1.4. In most schematic diagrams, the wire connections are in fact considered to be ideal. This method of representing electronic circuits is termed "lumped element" design.

Figure 1.3 A simple circuit demonstrating Kirchhoff's current law ($I_1 = I_2 + I_3$).

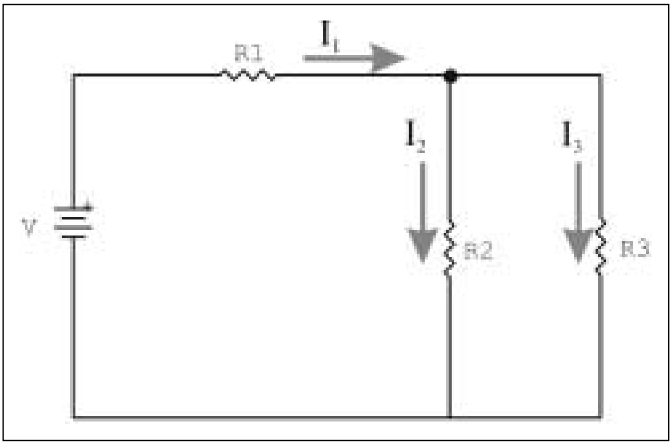
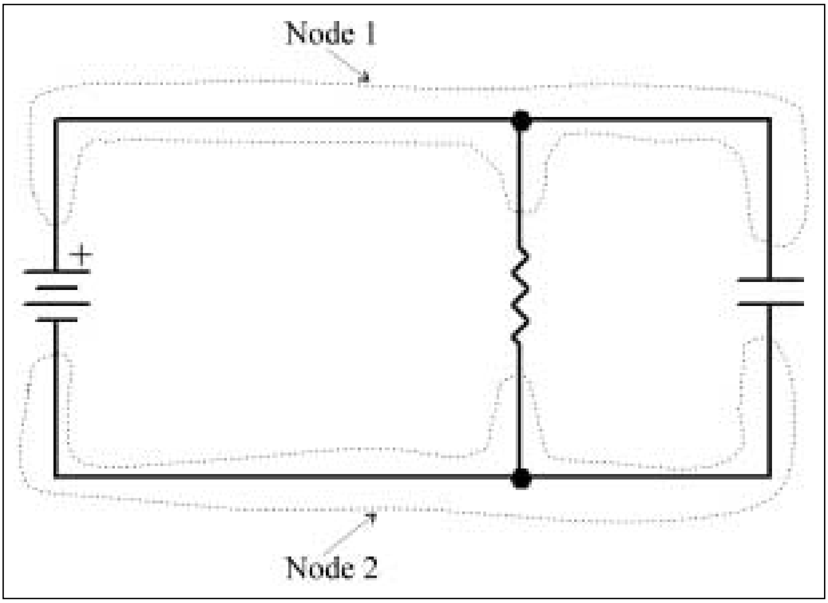


Figure 1.4 A simple circuit demonstrating the voltage node principle. The voltage is the same everywhere inside each of the dotted outlines.



The ironic thing about this is that the beginning student is taught to ignore the shape and length of wires, but at RF frequencies the length and shape of the wires become just as important as the components. Engineering and science are filled with similar situations where you must develop a simplified understanding of things before learning all the exceptions and details. Extending the resistance concept to the concept of AC (alternating current) impedance allows you to include capacitors and inductors. That is circuit theory in a nutshell. There are no antennas or transmission lines. We can think of the circuit as electrons flowing through wires like water flowing through a pipe. Electromagnetics is not needed.

ANALOG AND DIGITAL SIGNALS

Electronics is typically divided into the categories of analog and digital. Analog signals are continuously varying signals such as audio signals. Analog signals typically occupy a specific bandwidth and can be decomposed in terms of sinusoids using Fourier theory. For example, signals carrying human voice signals through the telephone network occupy the frequency band from about 100 Hz to about 4000 Hz.

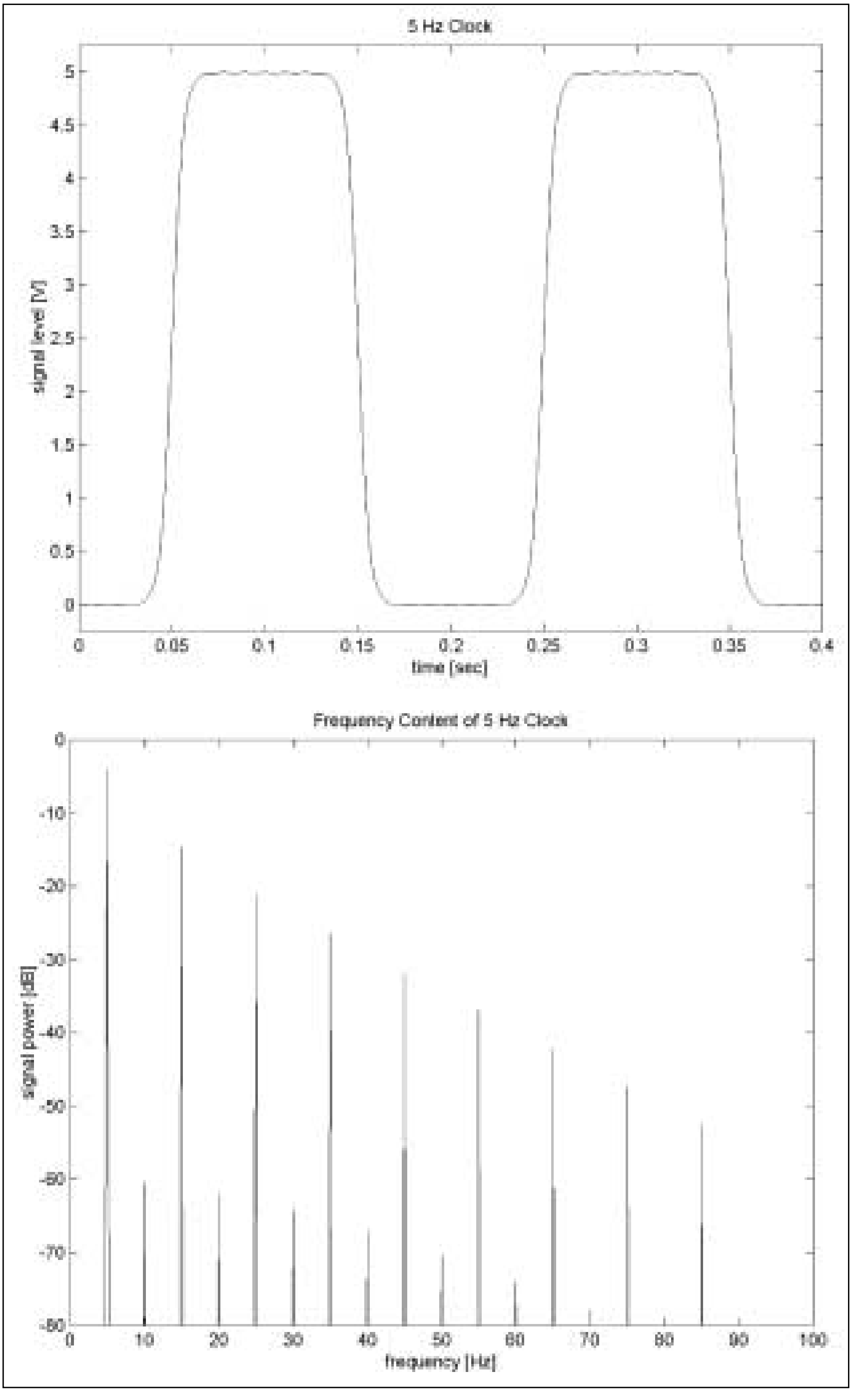
Digital signals, on the other hand, are a series of ones and zeroes. A typical method to represent a digital signal is to use 5 V for a one and 0 V for a zero. A digital clock signal is shown as an example in Figure 1.5. Fourier theory allows us to create such a square wave by summing individual sine waves. The individual sine waves are at multiples or harmonics of the clock frequency.* To create a perfectly square signal (signal rise and fall times of zero) requires an infinite number of harmonics, spanning to infinite frequency. Of course, this is impossible in reality, so all real digital signals must have rise and fall times greater than zero. In other words, no real digital signal is perfectly square. *When performing transmission line and radiation analysis for digital designs, the rise and fall times are the crucial parameters.*

RF TECHNIQUES

At higher frequencies, basic circuit theory runs into problems. For example, if wires are electrically long, transmission line effects can occur.

*Rock musicians may find it interesting to know that the signal of an electric guitar with distortion looks very similar to Figure 1.5. The distortion effect for guitars is created by “squaring off” the sine waves from the guitar, using a saturated amplifier.

Figure 1.5 A 5 Hz clock signal and its frequency content.

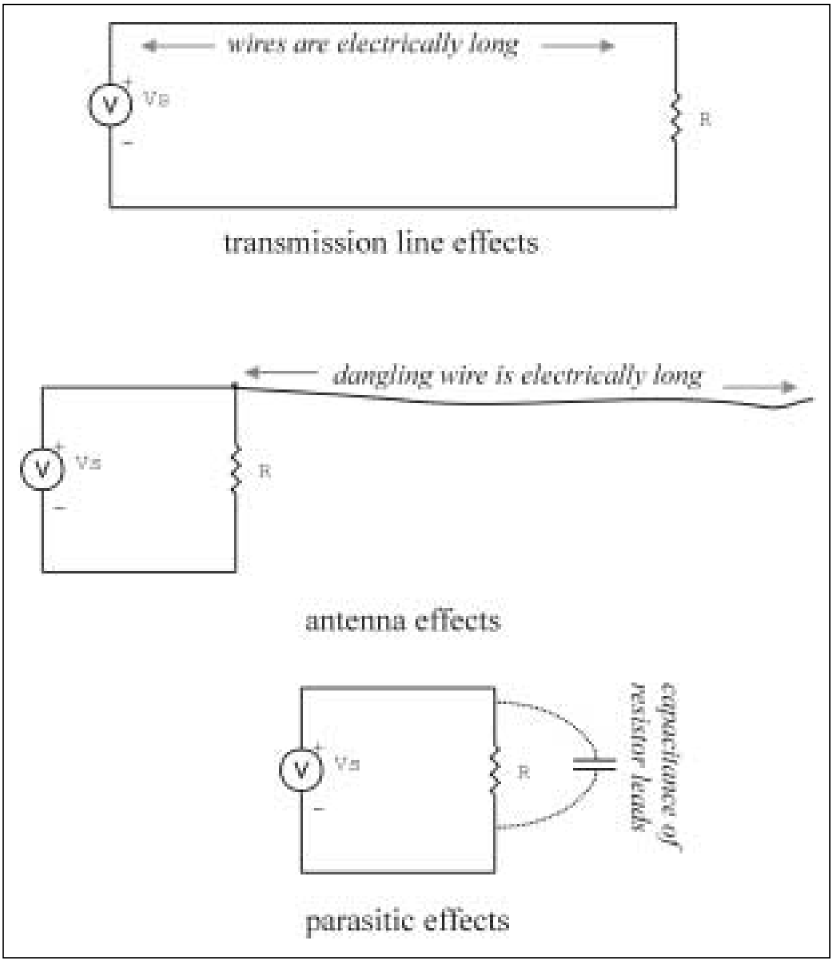


The basic theory no longer applies because electromagnetic wave reflections bouncing back and forth along the wires cause problems. These electromagnetic wave reflections can cause constructive or destructive interference resulting in the breakdown of basic circuit theory. In fact, when a transmission line has a length equal to one quarter wavelength of the signal, a short placed at the end will appear as an open circuit at the other end! Certainly, effects like this cannot be ignored. Furthermore, at higher frequencies, circuits can radiate energy much more readily; that is circuits can turn into antennas. Parasitic capacitances and inductances can cause problems too. No component can ever be truly ideal. The small inductance of component leads and wires can cause significant voltage drops at high frequencies, and stray capacitances between the leads of the component packages can affect the operation of a high-frequency circuit. These parasitic elements are sometimes called "the hidden schematic" because they typically are not included on the schematic symbol. (The high-frequency effects just mentioned are illustrated in Figure 1.6.)

How do you define the high-frequency regime? There is no exact border, but when the wavelengths of the signals are similar in size or smaller than the wire lengths, high-frequency effects become important; in other words, when a wire or circuit element becomes electrically long, you are dealing with the high-frequency regime. An equivalent way to state this is that when the signal period is comparable in magnitude or smaller than the delay through the interconnecting wires, high-frequency effects become apparent. *It is important to note that for digital signals, the designer must compare the rise and fall times of the digital signal to the wire delay*. For example, a 10 MHz digital clock signal may only have a signal period of 100 nsec, but its rise time may be as low as 5 nsec. Hence, the RF regime doesn't signify a specific frequency range, but signifies frequencies where the rules of basic circuit theory breakdown. *A good rule of thumb is that when the electrical length of a circuit element reaches 1/20, RF (or high-speed digital) techniques may need to be used.*

When working with RF and high-frequency electronics it is important to have an understanding of electromagnetics. At these higher frequencies, you must understand that the analogy of electrons acting like water through a pipe is really more of a myth than a reality. In truth, circuits are characterized by metal conductors (wires) that serve to guide electromagnetic energy. The circuit energy (and therefore the signal) is carried between the wires, and not inside the wires. For an example, consider the power transmission lines that deliver the electricity to our homes at 60 Hz. The electrons in the wires do not directly transport the energy from the power plant to our homes. On the contrary, the energy

Figure 1.6 Some effects that occur in high-frequency circuits.



is carried in the electromagnetic field between the wires. This fact is often confusing and hard to accept for circuit designers. The wire electrons are not experiencing any net movement. They just slosh back and forth, and through this movement they propagate the field energy down the wires. A good analogy is a "bucket brigade" that people sometimes use to fight fires. A line of firefighters (analogous to the electrons) is set up between the water source (signal source) and the fire (the load). Buckets of water (the electromagnetic signal) are passed along the line from firefighter to firefighter. The water is what puts out the fire. The people are just there to pass the water along. In a similar manner, the electrons just serve to pass the electromagnetic signal from source to load. This statement is true at all electronic frequencies, DC, low frequency, and RF.

MICROWAVE TECHNIQUES

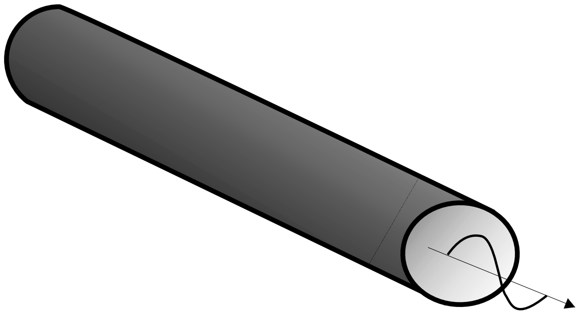
At microwave frequencies in the GHz range, circuit theory is no longer very useful at all. Instead of thinking about circuits as electrons flowing through a pipe, it is more useful to think about circuits as structures to guide and couple waves. At these high frequencies, lumped elements such as resistors, capacitors, and inductors are often not viable. As an example, the free space wavelength of a 30 GHz signal is 1 cm. Therefore, even the components themselves are electrically long and do not behave as intended. Voltage, current, and impedance are typically not used. In this realm, electronics starts to become similar to optics in that we often talk of power transmitted and reflected instead of voltage and current. Instead of impedance, reflection/transmission coefficients and S-parameters are used to describe electronic components. Some microwave techniques are shown in Figure 1.7.

INFRARED AND THE ELECTRONIC SPEED LIMIT

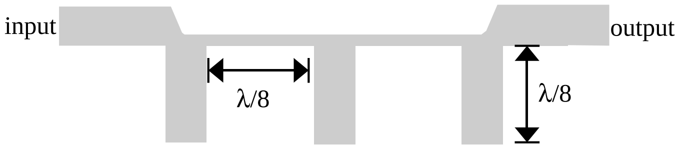
The infrared region is where the spectrum transitions from electronics to optics. The lower-frequency portion of the infrared is termed the "far infrared," and is the extension of the microwave region. Originally, the edge of the microwave band (300 MHz) was considered the highest viable frequency for electronics. As technology progresses, the limit of electronics extends further into the infrared. Wavelengths in the infrared are under 1 mm, implying that even a 1 mm wire is electrically long, readily radiating energy from electrical currents. Small devices are therefore mandatory.

At the time of publishing of this book, experimental integrated circuit devices of several terahertz (10^{12} Hz) had been achieved, and 40 GHz digital devices had become commercially available for communications applications. (Terahertz devices were created decades ago using vacuum tube techniques, but these devices are obviously not viable for computing devices.) Certainly digital devices in the hundreds of gigahertz will become commercially viable; in fact, such devices have already been demonstrated by researchers. Making digital devices past terahertz speeds will be a very difficult challenge. To produce digital waveforms,

Figure 1.7 Examples of microwave techniques.



Waveguide: a hollow metal tube for guiding electromagnetic waves



Top view of a lowpass filter implemented using microstrip transmission lines (copper strips above a ground plane)

you need an amplifier with a bandwidth of at least 3 to 5 times the clock frequency. Already researchers are pursuing special semiconductors such as Indium Phosphide (InP) electron spin, single-electron, and quantum devices, as well as molecular electronics. Only time will tell what the ultimate “speed limit” for electronics will be.

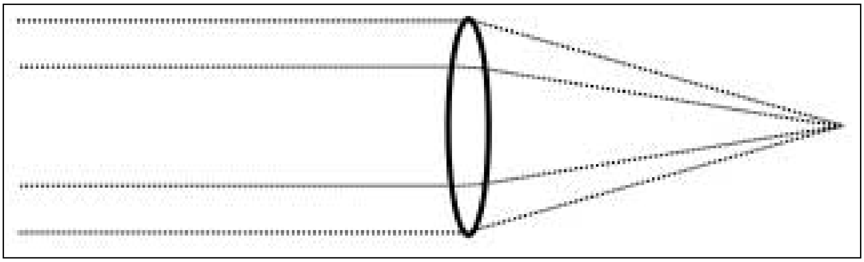
What is almost certain is that somewhere in the infrared frequencies, electronics will always be impossible to design. There are many problems in the infrared facing electronics designers. The speed of transistors is limited by their size; consequently, to probe higher frequencies, the state of the art in integrated circuit geometries must be pushed to smaller and smaller sizes. Quantum effects, such as tunneling, also cause problems. Quantum tunneling allows electrons to pass through the gate of very small MOSFET transistors. This effect is a major problem facing researchers trying to further shrink CMOS technology. Furthermore, the properties of most materials begin to change in the infrared. The conductive properties of metals begin to change. In addition, most dielectric materials become very lossy. Even dielectrics that are transparent in the visible region, such as water and glass, become opaque in the portions of the infrared. Photons in the infrared are very energetic compared to photons at radio frequencies and below. Consequently, infrared photons can excite resonant frequencies in materials. Another characteristic of the infrared is that the maximum of heat radiation occurs in the infrared for materials between room temperature (20°C) and several thousand degrees Celsius. These characteristics cause materials to readily absorb and emit radiation in the infrared. For these reasons, we can readily feel infrared radiation. The heat we feel from incandescent lamps is mostly infrared radiation. It is absorbed very easily by our bodies.

VISIBLE LIGHT AND BEYOND

At the frequencies of visible light, many dielectrics become less lossy again. Materials such as water and glass that are virtually lossless with respect to visible light are therefore transparent. Considering that our eyes consist mostly of water, we are very fortunate that water is visibly transparent. Otherwise, our eyes, including the lens, would be opaque and quite useless. A striking fact of nature is that the absorption coefficient of water rises more than 7 decades (a factor of 10 million) in magnitude on either side of the visible band. So it is impossible to create a reasonably sized, water-based eye at any other part of the spectrum. All creatures with vision exploit this narrow region of the spectrum. Nature is quite amazing!

At visible frequencies, the approximations of geometric optics can be used. These approximations become valid when the objects used become much larger than a wavelength. This frequency extreme is the opposite of the circuit theory approximations. The approximation is usually called ray theory because light can be approximated by rays or streams of particles. Isaac Newton was instrumental in the development of geometric optics, and he strongly argued that light consisted of particles and not waves. The physicist Huygens developed the wave theory of light and eventually experimental evidence proved that Huygens was correct. However, for geometrical optics, Newton's theory of particle streams works quite well. An example of geometrical optics is the use of a lens to concentrate or focus light. Figure 1.8 pro-

Figure 1.8 A lens that focuses rays of light.



vides a lens example. Most visible phenomena, including our vision, can be studied with geometrical optics. The wave theory of light is usually needed only when studying diffraction (bending of light around corners) and coherent light (the basis for lasers). Wave theory is also needed to explain the resolution limits of optical imaging systems. A microscope using visible light can only resolve objects down to about the size of a wavelength.

At the range of ultraviolet frequencies and above (X-rays, etc.) each photon becomes so energetic that it can kick electrons out of their atomic orbit. The electron becomes free and the atom becomes ionized. Molecules that absorb these high-energy photons can lose the electrons that bond the molecules together. Ions and highly reactive molecules called *free radicals* are produced. These highly reactive ions and molecules cause cellular changes and lead to biological tissue damage and cancer. Photons of visible and infrared light, on the other hand, are less energetic and only cause molecular heating. We feel the heat of the infrared radiation from the sun. We see the light of visible radiation from the sun. Our skin is burned and damaged by the ultraviolet radiation from the sun.

X-ray photons, being higher in energy, are even more damaging. Most materials are to some degree transparent to X-rays, allowing the use of X-ray photography to “see through” objects. But when X-rays are absorbed, they cause cellular damage. For this reason, limited X-ray exposure is recommended by physicians. The wavelengths of high-energy X-rays are about the same size as the atomic spacing in matter. Therefore, to X-rays, matter cannot be approximated as continuous, but rather is “seen” as lumps of discrete atoms. The small wavelength makes X-rays useful for studying crystals such as silicon, using the effects of diffraction. Above X-rays in energy are gamma rays and cosmic rays. These extremely high-energy waves are produced only in high-energy phenomena such as radioactive decay, particle physics collisions, nuclear power plants, atomic bombs, and stars.

LASERS AND PHOTONICS

Electronic circuits can be created to transmit, amplify, and filter signals. These signals can be digital bits or analog signals such as music or voices. The desire to push electronics to higher frequencies is driven by two main applications: computers and communication links. For computers, higher frequencies translate to faster performance. For communication links, higher frequencies translate to higher bandwidth. Oscillator circuits serve as timing for both applications. Computers are in general synchronous and require a clock signal. Communications links need a carrier signal to modulate the information for transmission. Therefore, a basic need to progress electronics is the ability to create oscillators.

In the past few decades, photonics has emerged as an alternative to electronics, mostly in communication systems. Lasers and fiber optic cables are used to create and transmit pulses of a single wavelength (frequency) of light. In the parlance of optics, single-frequency sources are known as coherent sources. Lasers produce synchronized or coherent photons; hence, the name photonics. The light that we encounter every day from the sun and lamps is noncoherent light. If we could look at this light on an oscilloscope, it would look like noise. In fact, the visible light that we utilize for our vision is noise—the thermal noise of hot objects such as the sun or the filament in a light bulb. The electrical term “white noise” comes from the fact that optical noise contains all the visible colors (frequencies) and appears white. The white noise of a light bulb extends down to electronic frequencies and is the same white noise produced by resistors and inherent in all circuits. Most imaging devices, like our eyes and cameras, only use the average squared-field amplitude of the light received. (Examination at the quantum level reveals imaging devices to be photon detectors/counters.) Averaging allows us to use “noisy” signals for vision, but because of averaging all phase information is lost. To create sophisticated communication devices, such light is not suitable. Instead the coherent, single-frequency light of lasers is used. Lasers make high-bandwidth fiber optic communication possible.

Until recently, the major limitation of photonics was that the laser pulsed signals eventually had to be converted to electronic signals for any sort of processing. For instance, in data communications equipment, major functions include the switching, multiplexing, and routing of data between cables. In the past, only electronic signals could perform these functions. This requirement limited the bandwidth of a fiber optic cable to the maximum available electronic bandwidth. However, with recent advances in optical multiplexing and switching, many tasks can now be performed completely using photonics. The upshot has been an exponential increase in the data rates that can be achieved with fiber optic technology. The ultimate goal for fiber optics communication is to create equipment that can route Internet protocol (IP) datapackets using only photonics. Such technology would also lead the way for optical computing, which could provide tremendous processing speeds as compared with electronic computers of today.

SUMMARY

Different techniques and approximations are used in the various portions of the electromagnetic spectrum. Basic circuit theory is an approximation made for low-frequency electronics. The circuit theory approximations work when circuits are electrically small. In other words, circuit theory is the limit of electromagnetics as the wavelength becomes infinitely larger than the circuit. RF theory takes circuit theory and adds in some concepts and relations from electromagnetics. RF circuit theory accounts for transmission line effects in wires and for antenna radiation. At microwave frequencies it becomes impossible to design circuits with lumped elements like resistors, capacitors, and inductors because the wavelengths are so small. Distributed techniques must be used to guide and process the waves. In the infrared region, we can no longer design circuits. The wavelengths are excessively small, active elements like transistors are not possible, and most materials become lossy, readily absorbing and radiating any electromagnetic energy. At the frequencies of visible light, the wavelengths are typically much smaller than everyday objects, and smaller than the human eye can notice. In this range, the approximations of geometrical optics are used. Geometrical optics is the limit of electromagnetic theory where wavelength becomes infinitely smaller than the devices used. At frequencies above light, the individual photons are highly energetic, able to break molecular bonds and cause tissue damage.

With the arrival of the information age, we rely on networked communications more and more every day, from our cell phones and pagers to our high-speed local-area networks (LANs) and Internet connections. The hunger for more bandwidth consistently pushes the frequency and complexity of designs. The common factor in all these applications is that they require a good understanding of electromagnetics.

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