PART II

WAVE PROPAGATION IN NETWORKS

CHAPTER 5

Introduction to Radio Frequency and Microwave Concepts and Applications

5.1 INTRODUCTION

This chapter lays the foundation for understanding higher-frequency wave phenomena and divides the task of active circuit design for RF/MW frequencies into specific concept blocks. These concept blocks create a gradual approach to understanding and designing RF/MW circuits and represent specific realms of knowledge that need to be mastered to become an accomplished designer.

Before we describe and analyze these types of waves we need to consider why RF/microwaves as a subject has become so important, that it is placed at the forefront of our modern technology. Furthermore, we need to expand our minds to the many possibilities that these signals can provide for peaceful practices by exploring various commercial applications useful to mankind.

5.1.1 A Short History of RF and Microwaves

Circa 1864–1873, James Clark Maxwell integrated the entirety of man's knowledge of electricity and magnetism by introducing a set of four coherent and self-consistent equations that describe the behavior of electric and magnetic fields on a classical level. This was the beginning of microwave engineering, as presented in a treatise by Maxwell at that time. He predicted, purely from a mathematical standpoint and on a theoretical basis, the existence of electromagnetic wave propagation and that light was also a form of electromagnetic energy—both completely new concepts at the time.

From 1885 to 1887, Oliver Heaviside simplified Maxwell's work in his published papers. From 1887 to 1891, a German physics professor, Heinrich Hertz, verified Maxwell's predictions experimentally and demonstrated the propagation of electromagnetic waves. He also investigated wave propagation phenomena along transmission lines and antennas and developed several useful structures. He could be called the first microwave engineer.

Marconi tried to commercialize radio at a much lower frequency for long-distance communications, but as he had a business interest in all of his work and developments, this was not a purely scientific endeavor.

Neither Hertz nor Heaviside investigated the possibility of electromagnetic wave propagation inside a hollow metal tube because it was felt that two conductors were necessary for the transfer of electromagnetic waves or energy. In 1897, Lord Rayleigh showed mathematically that electromagnetic wave propagation was possible in waveguides, both circular and rectangular. He showed that there are infinite sets of modes of the TE and TM type possible, each with its own cut-off frequency. These were all theoretical predictions with no experimental verifications.

From 1897 to 1936, the waveguide was essentially forgotten until it was rediscovered by two men, George Southworth (AT&T) and W. L. Barron (MIT), who showed experimentally that a waveguide could be used as a small bandwidth transmission medium, capable of carrying high power signals.

With the invention of the transistor in the 1950s and the advent of microwave integrated circuits in the 1960s, the concept of a microwave system on a chip became a reality. There have been many other developments, mostly in terms of application mass, that have made RF and microwaves an enormously useful and popular subject.

Maxwell's equations lay the foundation and laws of the science of electromagnetics, of which the field of RF and microwaves is a small subset. Due to the exact and all-encompassing nature of these laws in predicting electromagnetic phenomena, along with the great body of analytical and experimental investigations performed since then, we can consider the field of RF and microwave engineering a "mature discipline" at this time.

5.1.2 Applications of Maxwell's Equations

As indicated earlier in Chapter 2, *Fundamental Concepts in Electrical and Electronics Engineering*, standard circuit theory can neither be used at RF nor particularly at microwave frequencies. This is because the dimensions of the device or components are comparable to the wavelength, which means that the phase of an electrical signal (e.g., a current or voltage) changes significantly over the physical length of the device or component. Thus use of Maxwell's equations at these higher frequencies becomes imperative.

In contrast, the signal wavelengths at lower frequencies are so much larger than the device or component dimensions, that there is negligible variation in phase across the dimensions of the circuit. Thus Maxwell's equations simplify into basic circuit theory, as covered in Chapter 3, *Mathematical Foundation for Understanding Circuits*.

At the other extreme of the frequency range lies the optical field, where the wavelength is much smaller than the device or circuit dimensions. In this case, Maxwell's equations simplify into a subject commonly referred to as geometrical optics, which treats light as a ray traveling on a straight line. These optical techniques may be applied successfully to the analysis of very high microwave frequencies (e.g., high millimeter wave range), where they are referred to as "quasi-optical." Of course, it should be noted that further application of Maxwell's equations leads to an advanced field of optics called "physical optics or Fourier optics," which treats light as a wave and explains such phenomena as diffraction and interference, where geometrical optics fails completely.

The important conclusion to be drawn from this discussion is that Maxwell's equations present a unified theory of analysis for any system at any frequency, provided we use appropriate simplifications when the wavelengths involved are much larger, comparable to, or much smaller than the circuit dimensions.

5.1.3 Properties of RF and Microwaves

An important property of signals at RF, and particularly at higher microwave frequencies, is their great capacity to carry information. This is due to the large bandwidths available at these high frequencies. For example, a 10 percent bandwidth at 60 MHz carrier signal is 6 MHz, which is approximately one TV channel of information; on the other hand 10 percent of a microwave carrier signal at 60 GHz is 6 GHz, which is equivalent to 1000 TV channels.

Another property of microwaves is that they travel by line of sight, very much like the traveling of light rays, as described in the field of geometrical optics. Furthermore, unlike lower-frequency signals, microwave signals are not bent by the ionosphere. Thus use of line-of-sight communication towers or links on the ground and orbiting satellites around the globe are a necessity for local or global communications.

A very important civilian as well as military instrument is radar. The concept of radar is based on radar cross-section which is the effective reflection area of the target. A target's visibility greatly depends on the target's electrical size, which is a function of the incident signal's wavelength. Microwave frequency is the ideal signal band for radar applications. Of course, another important advantage of use of microwaves in radars is the availability of higher antenna gains as the frequency is increased for a given physical antenna size. This is because the antenna gain being proportional to the electrical size of the antenna, becomes larger as frequency is increased in the microwave band. The key factor in all this is that microwave signal wavelengths in radars are comparable to the physical size of the transmitting antenna as well as the target.

There is a fourth and yet very important property of microwaves: the molecular, atomic, and nuclear resonance of conductive materials and substances when exposed to microwave fields. This property creates a wide variety of applications. For example, because almost all biological units are composed predominantly of water and water is a good conductor, microwave technology has tremendous importance in the fields of detection, diagnostics, and treatment of biological problems or medical investigations (e.g., diathermy, scanning, etc.). There are other areas in which this basic property would create a variety of applications such as remote sensing, heating (e.g., industrial purification and cooking) and many others that are listed in a later section.

5.2 REASONS FOR USING RF/MICROWAVES

Over the past several decades, there has been a growing trend toward use of RF/microwaves in system applications. There are many reasons among which the following are prominent:

- Wider bandwidths due to higher frequency
- Smaller component size leading to smaller systems
- More available and less crowded frequency spectrum
- Better resolution for radars due to smaller wavelengths
- Lower interference due to lower signal crowding
- Higher speed of operation
- Higher antenna gain possible in a smaller space

On the other hand, there are some disadvantages to using RF/microwaves, such as: more expensive components, availability of lower power levels, existence of higher signal losses, and use of high-speed semiconductors (such as GaAs or InP) along with their corresponding less-mature technology (relative to the traditional silicon technology, which is now quite mature and less expensive).

In many RF/microwave applications the advantages of a system operating at these frequencies outweigh the disadvantages and propel engineers to a high-frequency design.

5.3 RF/MICROWAVE APPLICATIONS

The major applications of RF/microwave signals can be categorized as follows:

5.3.1 Communication

This application includes satellite, space, long-distance telephone, marine, cellular telephone, data, mobile phone, aircraft, vehicle, personal, and wireless local area network (WLAN), among others. Two important subcategories of applications need to be considered: TV and radio broadcast, and optical communications.

TV and Radio Broadcast. In this application, RF/microwaves are used as the carrier signal for audio and video signals. An example is the Direct Broadcast System (DBS), which is designed to link satellites directly to home users.

Optical Communications. In this application, a microwave modulator is used in the transmitting side of a low-loss optical fiber with a microwave demodulator at the other end. The microwave signal acts as a modulating signal with the optical signal as the carrier. Optical communication is useful in cases where a much larger number of frequency channels and less interference from outside electromagnetic radiation are desired. Current applications include telephone cables, computer network links, low-noise transmission lines, and so on.

5.3.2 Radar

This application includes air defense, aircraft/ship guidance, smart weapons, police, weather, collision avoidance, and imaging.

5.3.3 Navigation

This application is used for orientation and guidance of aircraft, ships, and land vehicles. Particular applications in this area are as follows:

- Microwave Landing System (MLS), used to guide aircraft to land safely at airports
- Global Positioning System (GPS), used to find one's exact coordinates on the globe

5.3.4 Remote Sensing

In this application, many satellites are used to monitor the globe constantly for weather conditions, meteorology, ozone, soil moisture, agriculture, crop protection from frost, forests, snow thickness, icebergs, and other factors such as monitoring and exploration of natural resources.

5.3.5 Domestic and Industrial Applications

This application includes microwave ovens, microwave clothes dryers, fluid heating systems, moisture sensors, tank gauges, automatic door openers, automatic toll collection, highway traffic monitoring and control, chip defect detection, flow meters, power transmission in space, food preservation, pest control, and so on.

5.3.6 Medical Applications

This application includes cautery, selective heating, heart stimulation, hemorrhage control, sterilization, and imaging.

5.3.7 Surveillance

This application includes security systems, intruder detection, and Electronic Warfare (EW) receivers to monitor signal traffic.

5.3.8 Astronomy and Space Exploration

In this application, gigantic dish antennas are used to monitor, collect, and record incoming microwave signals from outer space, providing vital information about other planets, stars, meteors, and other objects and phenomena in this or other galaxies.

5.3.9 Wireless Applications

Short-distance communication inside as well as between buildings in a local area network (LAN) arrangement can be accomplished using RF and microwaves. Connecting buildings via cables (e.g., coax or fiber optic) creates serious problems in congested metropolitan areas because the cable has to be run underground from the upper floors of one building to the upper floors of the other. This problem, however, can be greatly alleviated using RF and microwave transmitter/receiver systems that are mounted on rooftops or in office windows (see Figure 5.1). Inside buildings, RF and microwaves can be used effectively to create a wireless LAN in order to connect telephones, computers, and various LANs to each other. Using wireless LANs has a major advantage in office rearrangement where phones, computers, and partitions are easily moved with no change in wiring in the wall outlets. This creates enormous flexibility and cost savings for any business entity.

A summary of RF and microwave applications is shown in Table 5.1.

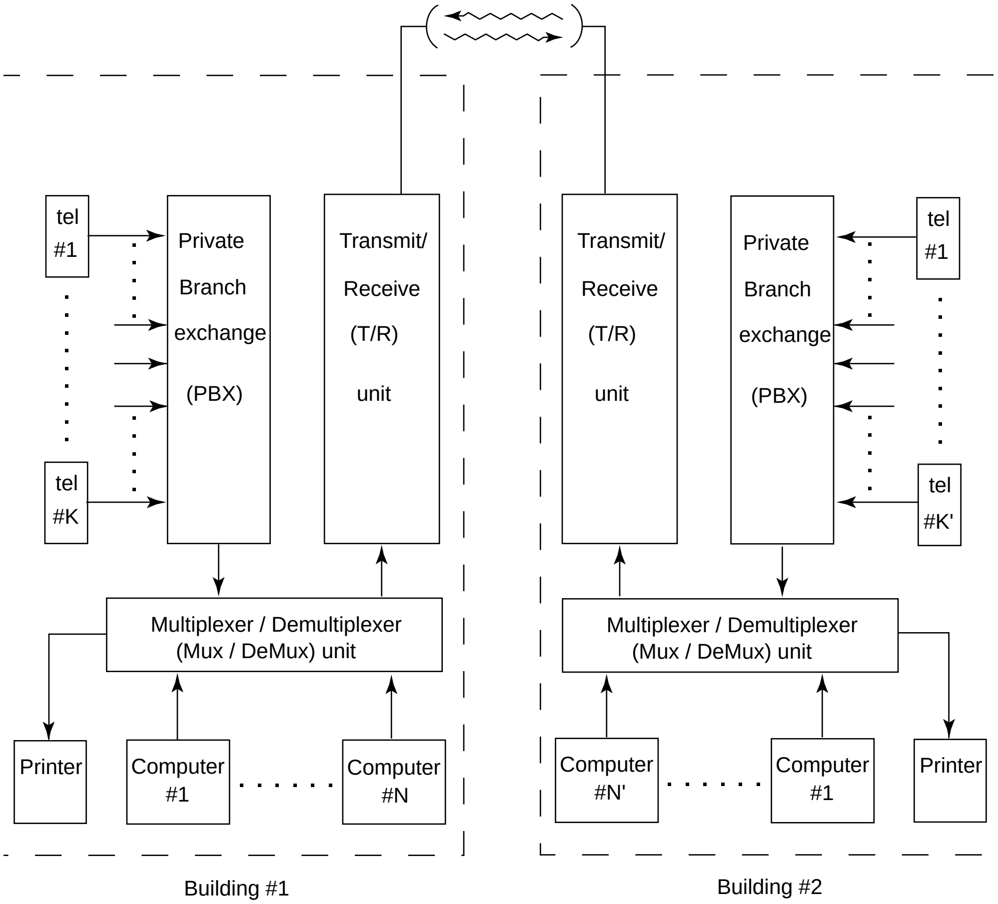


FIGURE 5.1 A typical local area network (LAN) for connectivity using microwaves.

TABLE 5.1 Summary of Applications of RF and Microwaves

Category of Application	Description
Astronomy and space exploration	Deep space probes Galactic explorations
Communication	Optical communications Telephone systems Computer networks Low-noise transmission media TV and radio broadcast Direct broadcast satellite High-definition TV
Domestic & industrial applications	Agriculture Moisture detection and soil treatment Pesticides Crop protection from freezing Automobiles Anti-theft radar or sensor Automotive telecommunication Blind spot radar Collision avoidance radar Near-obstacle detection Radar speed sensors Road-to-vehicle communication Vehicle-to-vehicle communication Highway Automatic toll collection Highway traffic control and monitoring Range and speed detection Structure inspection Vehicle detection Microwave Heating Home microwave ovens Microwave clothes dryer Industrial heating Microwave Imaging Hidden weapon detection Obstacle detection & Navigation Office Mail sorting Wireless phones and computers Power Beamed power propulsion Power transmission in space Preservation Food preservation Treated manuscript drying Production control Etching system production Industrial drying Moisture control

TABLE 5.1 Summary of Applications of RF and Microwaves *(Continued)*

Category of Application	Description
Medical applications	Cautery Heart stimulation Hemorrhaging control Hyperthermia Microwave imaging Sterilization Thermography
Radar	Air defense Navigation & position information Airport traffic control Global positioning system (GPS) Microwave landing system (MLS) Police patrol (velocity measurement) Smart weapons Tracking Weather forecast
Remote sensing	Earth monitoring Meteorology Pollution control Natural resources and exploration
Surveillance	Security system Intruder detection Security system Signal traffic monitoring
Wireless applications	Wireless local area networks (LANs)

5.4 RADIO FREQUENCY (RF) WAVES

Having briefly reviewed many of the current applications of RF/microwaves, we can see that this rapidly advancing field has great potential to be a fruitful source of many future applications.

As discussed earlier, electromagnetic (EM) waves are generated when electrical signals pass through a conductor. EM waves start to radiate from a conductor when the signal frequency is higher than the highest audio frequency, which is approximately 15 to 20 kHz. Because of this radiating property, signals of such or higher frequencies are often known as radio frequency (RF) signals.

5.4.1 RF Spectrum Bands

Because it is not practical either to design a circuit that covers the entire frequency range or to use all radio frequencies for all purposes, the RF spectrum is broken into various bands. Each band is used for a specific purpose and usually RF circuits are designed to be used in one particular band. Table 5.2 shows the most common assignment of RF commercial bands.

TABLE 5.2 Commercial Radio Frequency Band

Name of Band	Abbreviation	Frequency Range
Very low frequency	VLF	3–30 kHz
Low frequency	LF	30–300 kHz
Medium frequency	MF	300 kHz-3 MHz
High frequency	HF	3–30 MHz
Very high frequency	VHF	30–300 MHz
Ultra-high frequency	UHF	0.3–3 GHz
Super-high frequency	SHF	3–30 GHz
Extra-high frequency	EHF	30–300 GHz

Definition of Microwaves. When the frequency of operation starts to increase toward approximately 1GHz and above, a whole set of new phenomena occurs that is not present at lower frequencies. The radio waves at frequencies ranging from 1 GHz to 300 GHz are generally known as *microwaves*. Signals at these frequencies have wavelengths that range from 30 cm (at 1 GHz) to 1 millimeter (at 300 GHz). The special frequency range from 30 GHz to 300 GHz has a wavelength in the millimeter range; thus, it is generally referred to as millimeter-waves.

> **NOTE:** *In some texts, the range 300 MHz to 300 GHz is considered the microwave frequency range. This is in contrast with the microwave frequency range defined previously, where the frequency range from 300 MHz to 1 GHz is referred as the RF range.*

Microwave Bands. The microwave frequency range consisting of the three main commercial frequency bands (UHF, SHF, and EHF) can further be subdivided into several specific frequency ranges, each with its own band designation. This band subdivision and designation facilitate the use of microwave signals for specific purposes and applications.

In electronics industries and academic institutions, the most commonly used microwave bands are set forth by the Institute of Electrical and Electronics Engineers (IEEE); they are shown in Table 5.3. In this table the “Ka to G” are the millimeter-wave (mmw) bands.

TABLE 5.3 IEEE and Commercial Microwave Band Designations

Band Designation	Frequency Range (GHz)
L Band	1.0-2.0
S band	2.0-4.0
C band	4.0-8.0
X band	8.0-12.0
Ku band	12.0-18.0

TABLE 5.3 IEEE and Commercial Microwave Band Designations *(Continued)*

Band Designation	Frequency Range (GHz)
K band	18.0-26.5
Ka band (mmw)	26.5-40.0
Q band (mmw)	33.0-50.0
U band (mmw)	40.0-60.0
V band (mmw)	50.0-75.0
E band (mmw)	60.0-90.0
W band (mmw)	75.0-110.0
F band (mmw)	90.0-140.0
D band (mmw)	110.0-170.0
G band (mmw)	140.0-220.0

5.5 RF AND MICROWAVE (MW) CIRCUIT DESIGN

Because of the behavior of waves at different frequencies, basic considerations in circuit design have evolved greatly over the last few decades and generally can be subdivided into two main categories:

- RF circuit design considerations
- Microwave (MW) circuit design considerations

Each category is briefly described next.

5.5.1 Low RF Circuit Design Considerations

Low RF circuits have to go through a three-step design process. In this design process the effect of wave propagation on the circuit operation is negligible and the following facts in connection with the design process can be stated:

1. The length of the circuit (ℓ) is generally much smaller than the wavelength, (i.e., $\ell << \lambda$)
2. Propagation delay time(t_d) is approximately zero (i.e., $t_d \approx 0$).
3. Maxwell's equations simplify into all of the low-frequency laws such as KVL, KCL, and Ohm's law. Therefore, at RF frequencies, the delay time of propagation (t_d) is approximately zero when $\ell << \lambda$ and all elements in the circuit can be considered to be lumped.

The design process has the following three steps:

STEP 1. The design process starts with selecting a suitable device and performing a DC design to obtain a proper Q-point.

STEP 2. Next, the device will be characterized (through either measurement or calculations) to obtain its AC small signal parameters based on the specific DC operating point selected earlier.

STEP 3. The third step consists of designing two matching circuits that transition this device to the outside world: the signal source at one end and the load at the other. Various design considerations and criteria such as stability, gain, and noise, are included at this stage and must be incorporated in the design of the final matching networks.

The design process for RF circuits is summarized and shown in Figure 5.2.

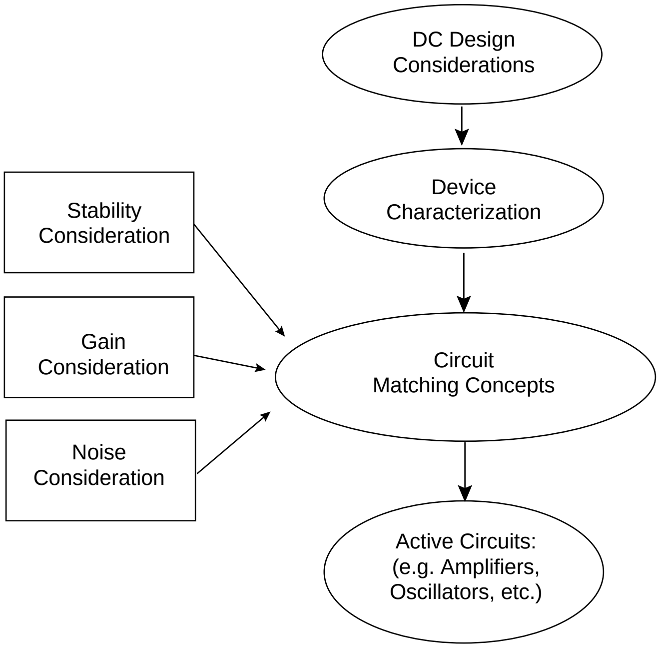


FIGURE 5.2 RF circuit design steps.

5.5.2 High RF and Microwave Circuits

To understand high RF and microwave circuits we should know that microwave circuits may have one or more lumped elements but should contain at least one distributed element. This last needs to be defined at this point:

DEFINITION-DISTRIBUTED ELEMENT: *An element whose property is spread out over an electrically significant length or area of a circuit instead of being concentrated at one location or within a specific component.*

EXAMPLE 5.1

Describe what a distributed inductor is.

Answer:

A distributed inductor is an element whose inductance is spread out along the entire length of a conductor (such as self-inductance), as distinguished from an inductor whose inductance is concentrated within a coil.

EXAMPLE 5.2

Describe what a distributed capacitor is.

Answer:

A distributed capacitor is an element whose capacitance is spread out over a length of wire and not concentrated within a capacitor, such as the capacitance between the turns of a coil or between adjacent conductors of a circuit.

Working with distributed circuits, we need to know the following facts about them:

- **a.** The wave propagation concepts as set forth by the Maxwell Equations fully apply.
- **b.** The circuit has a significant electrical length, i.e., its physical length is comparable to the wavelength of the signals propagating in the circuit.

This fact brings the next point into view:

- **c.** The time delay (t_d) due to signal propagation can no longer be neglected (i.e., $t_d \neq 0$).

To illustrate this point we will consider the following example.

EXAMPLE 5.3

How does a two-conductor transmission line (such as a coaxial line, etc.) behave at low and high frequencies?

Answer:

At low frequencies this transmission line is considered to be a short piece of wire with a negligibly small distributed resistance that can be considered to be lumped for the purpose of analysis (since $t_d \approx 0$).

At higher frequencies, however, the resistive, capacitive, and inductive properties can no longer be separated, and each infinitesimal length (Δx) of this transmission line exhibits these properties, as shown in Figure 5.3.

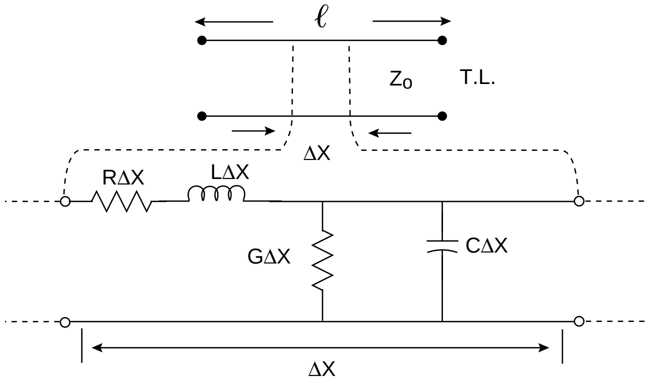


FIGURE 5.3 An infinitesimal portion of a transmission line (TL).

From this figure, we can see that the elements are: series elements (R, L) and shunt elements (G, C). These are defined as follows:

R = resistance per unit length in Ω/m
L = inductance per unit length in H/m
G = conductance per unit length in S/m
C = capacitance per unit length in F/m

This equivalent circuit is referred to as a distributed circuit model of a two-conductor transmission line and will be used in the next example to derive the governing differential equations for propagating voltage and current waves along a transmission line.

EXAMPLE 5.4

Using KVL and KCL derive the relationship between voltage and current in a transmission line at:

a. *Low frequencies*
b. *High frequencies (i.e., RF/microwave frequencies)*

Solution:

a. At low frequencies a transmission line (which can be lossy in general) can be represented as shown in Figure 5.4. In this Figure, "R" is the distributed loss resistance of the line, which can be modeled as a lumped element. The voltage and current relationship can be written as:

$$V_1 = V_2 + IR$$

NOTE: *If the line is lossless, then we have:*

$$V_1 = V_2$$

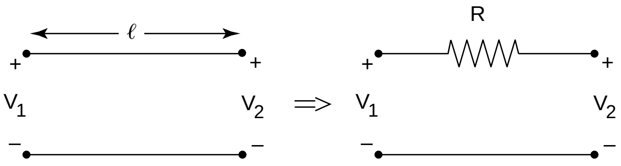


FIGURE 5.4 Equivalent circuit of a TL at low frequencies.

b. At high frequencies, based on Figure 5.3 a transmission line can be modeled as shown in Figure 5.5.

To develop the governing differential equations, we will examine one Δx section of a transmission line, as shown in Figure 5.6. Using KVL for the Δx section, we can write:

$$v(x,t) = i(x,t)\, R\Delta x + L\Delta x\, \partial i(x,t)/\partial t + v(x+\Delta x, t)$$

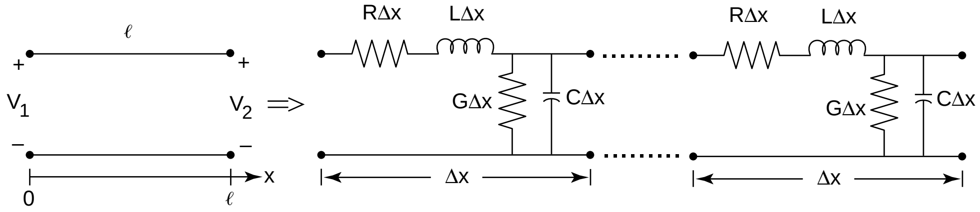
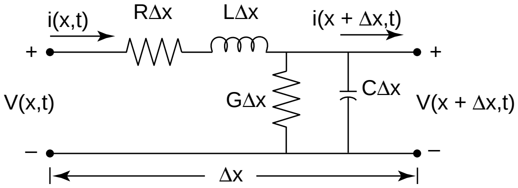


FIGURE 5.5 Equivalent circuit of a TL at high frequencies.

FIGURE 5.6 Voltage and current in an infinitesimal length of TL.



Upon rearranging terms and dividing both sides by Δx, we obtain:

$$-\frac{v(x+\Delta x, t) - v(x, t)}{\Delta x} = R\,i(x, t) + L\frac{\partial i(x, t)}{\partial t}$$

Letting $\Delta x \to 0$, yields:

$$-\frac{\partial v(x, t)}{\partial x} = R\,i(x, t) + L\frac{\partial i(x, t)}{\partial t} \tag{5.1}$$

Similarly, using KCL we can write:

$$i(x, t) = v(x+\Delta x, t)G\Delta x + C\Delta x\frac{\partial v(x+\Delta x, t)}{\partial t} + i(x+\Delta x, t)$$

Upon rearranging terms, dividing by Δx and letting $\Delta x \to 0$, we have:

$$-\frac{\partial i(x, t)}{\partial x} = G v(x, t) + C\frac{\partial v(x, t)}{\partial t} \tag{5.2}$$

Equations 5.1 and 5.2 are two cross-coupled equations in terms of v and i. These two equations can be separated by first differentiating both equations with respect to x and then properly substituting for the terms, which leads to:

$$\begin{aligned}-\frac{\partial^2 v(x, t)}{\partial x^2} &= R\frac{\partial i(x, t)}{\partial x} + L\frac{\partial^2 i(x, t)}{\partial x \partial t}\\ &= -R\left(G v(x, t) + C\frac{\partial v(x, t)}{\partial t}\right) - L\left(G\frac{\partial v(x, t)}{\partial t} + C\frac{\partial^2 v(x, t)}{\partial t^2}\right)\end{aligned}$$

or

$$\frac{\partial^2 v(x, t)}{\partial x^2} = LC\frac{\partial^2 v(x, t)}{\partial t^2} + (RC + LG)\frac{\partial v(x, t)}{\partial t} + RGv(x, t) \tag{5.3}$$

Similarly for i we can write:

$$\frac{\partial^2 i(x,t)}{\partial x^2} = LC\frac{\partial^2 i(x,t)}{\partial t^2} + (RC + LG)\frac{\partial i(x,t)}{\partial t} + RGi(x,t) \tag{5.4}$$

For sinusoidal signal variation for v and i, we can write the corresponding phasors as follows:

$$v(x,t) = Re[V(x)e^{j\omega t}]$$

$$i(x,t) = Re[I(x)e^{j\omega t}]$$

Using phasor differentiation results from Chapter 3, Equations 5.3 and 5.4 can be written as:

$$\frac{d^2V(x)}{dx^2} - \gamma^2 V(x) = 0 \tag{5.5a}$$

$$\frac{d^2I(x)}{dx^2} - \gamma^2 I(x) = 0 \tag{5.5b}$$

where

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{5.5c}$$

γ is the **propagation constant**, with real part (α) and imaginary part (β), called the **attenuation constant** (Np/m) and **phase constant** (rad/m), respectively.

The solution to the second-order differential equations, as given by Equations 5.5a and 5.5b, can be observed to be of exponential type format ($e^{\pm\gamma x}$). Thus, we can write the general solutions for $V(x)$ as follows:

$$V(x) = V^+e^{-\gamma x} + V^-e^{\gamma x} \tag{5.6a}$$

where the complex constants V^+ and V^- are determined from the boundary conditions imposed by the source voltage and the load value.

Similarly, $I(x)$ can be obtained from $V(x)$ (see Equation 5.1) as:

$$I(x) = \left(\frac{-1}{R + j\omega L}\right)\frac{dV(x)}{dx} = \frac{V^+e^{-\gamma x} - V^-e^{\gamma x}}{Z_o} \tag{5.6b}$$

where

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{5.7}$$

is the characteristic impedance of the transmission line.

Special Case: A Lossless Transmission Line

For this case, we have $R = G = 0$. This yields the following simplifications:

$$\gamma = j\omega\sqrt{LC} = j\beta$$

$$Z_o = \sqrt{L/C}$$

where $\beta = \omega\sqrt{LC}$ is the phase constant.

In this case Equation 5.5 can be written as:

$$\frac{d^2V(x)}{dx^2} + \beta^2 V(x) = 0 \tag{5.8a}$$

$$\frac{d^2I(x)}{dx^2} + \beta^2 I(x) = 0 \tag{5.8b}$$

Similar to Equations 5.6a and 5.6b, the solutions to Equation 5.8 are given by:

$$V(x) = V^+ e^{-j\beta x} + V^- e^{j\beta x} \tag{5.9a}$$

$$I(x) = \frac{V^+ e^{-\gamma\beta x} - V^- e^{\gamma\beta x}}{Z_o} \tag{5.9b}$$

NOTE 1: *Transmission line Equations 5.5 and 5.8 could all have been derived using Maxwell's equations directly from the field quantities E and H, as delineated in Appendix F, General Laws of Electricity and Magnetism, under items 14 and 19.*

It will be seen in Chapter 7, *Fundamental Concepts in Wave Propagation*, that the term $e^{-\gamma x}$ [or $e^{-j\beta x}$] represents a propagating wave in the "$+x$" direction while $e^{\gamma x}$ [or $e^{j\beta x}$] represents a propagating wave in the "$-x$" direction on a transmission line. The combination of the two comparable waves propagating in opposite directions to each other forms a standing wave on the transmission line (as discussed earlier in Chapter 2). These will be all explored further in Chapter 7.

NOTE 2: *Based on a given source voltage ($x = 0$, $V = V_1$) and a known load voltage ($x = \ell$, $V = V_2$), the constants V^+ and V^- can easily be found from the following two equations:*

$$x = 0, \quad V_1 = V^+ + V^- \tag{5.10}$$

$$x = \ell, \quad V_2 = V^+ e^{-j\beta\ell} + V^- e^{j\beta\ell} \tag{5.11}$$

EXERCISE 5.1

a. Derive expressions for V^+ and V^- from Equations 5.10 and 5.11 in terms of V_1 and V_2.

b. Given the load value as $Z = Z_L$, find V^+ and V^- in terms of V_1 and Z_L [as in part (a)].

HINT: Use $V_2 = Z_L\,[V^+ e^{-j\beta\ell} - V^- e^{j\beta\ell}]/Z_o$

5.5.3 High RF and Microwave Circuit Design Process

Circuit design process at high RF and microwaves is very similar to the low RF circuit design except for the wave propagation concepts that should be taken into account. The design process has the following three steps:

STEP 1. The design process starts with the design of the DC circuit to establish a stable operating point.

STEP 2. The next step is to characterize the device at the operating point (Q-point), using electrical waves to measure the percentage of reflection and transmission that the device presents at each port.

STEP 3. The third step consists of designing the matching networks that transition the device to the outside world such that the required specifications such as stability, overall gain, etc., are satisfied.

Except for the fact that our familiarity with wave propagation concepts becomes crucial, the microwave circuit design process is similar to the RF circuit design steps delineated in Figure 5.2.

5.6 THE UNCHANGING FUNDAMENTAL VERSUS THE EVER-EVOLVING STRUCTURE

Before we get into specific analysis and design of RF and microwave circuits, it is worthwhile first to examine a general communication system in which each circuit or component has a specific function in a bigger scheme of affairs. In general, any communication system is based on a very simple and yet extremely fundamental truth, commonly referred to as the "universal communication principle."

The "universal communication principle" is a fundamental concept that is at the heart of a wide sphere of existence called "life and livingness" or, for that matter, any of its subsets particularly the field of RF/microwaves. This principle is intertwined throughout the entire field of RF/microwaves and thus plays an important role in our understanding of this subject. Therefore it behooves us well to define it at this juncture:

THE UNIVERSAL COMMUNICATION PRINCIPLE: *This principle states that communication is the process whereby information is transferred from one point in space and time (X_1, Y_1, Z_1, t_1, called the source point), to another point in space and time (X_2, Y_2, Z_2, t_2, called the receipt point), with the intention of creating an* *exact replica of the source information at the receipt point. Usually, the receipt point at location (X_2, Y_2, Z_2) is separated by a distance (d) from the source point location (X_1, Y_1, Z_1).*

The physical embodiment of the universal communication principle is a "communication system," which takes the information from the source point and delivers an exact replica of it to the receipt point (see Figure 5.7). Thus in general, it can be seen that any communication system can be broken down into three essential elements:

Source point: A point of emanation or generation of information.

Receipt point: A point of receipt of information.

Distance (or imposed space): The space existing between the "source point" and "receipt point" through which the information travels.

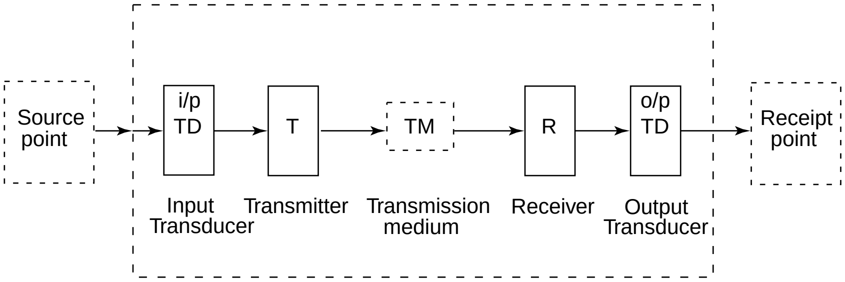


FIGURE 5.7 Depiction of a communication system.

Furthermore, it can be observed that in order to achieve effective communication between two systems, we need to have three more factors present: (a) There must be intention on the part of the source point and the receipt point to emit and to receive the information, respectively, (b) source and receipt points must have attention on each other (i.e., both being ready for transmission and reception), and (c) duplication (i.e., an exact replica) must occur at the receipt point of what emanated from the source point.

Use of the universal communication principle in practice creates a one-way communication system (such as radio and TV broadcast), and it forms one leg of a two-way communication system (such as CB radio or telephone), where this process is reversed to create the second leg of the communication action.

An important application of the universal communication principle is in a radar communication system where the source point (X_1, Y_1, Z_1) is at the same physical location as the receipt point (X_2, Y_2, Z_2), i.e., $X_1 = X_2$, $Y_1 = Y_2$, $Z_1 = Z_2$; however, the times of sending and reception are different ($t_1 \neq t_2$). Otherwise no communication would take place. This brings us to the obvious conclusion that we can not have a condition where the source and the receipt points are the same, simultaneously!

Based on this simple concept of communication, the most complex communication systems can be understood, analyzed, and designed. Figure 5.8 is a simple and yet very generalized block diagram of such a practical communication system in use today.

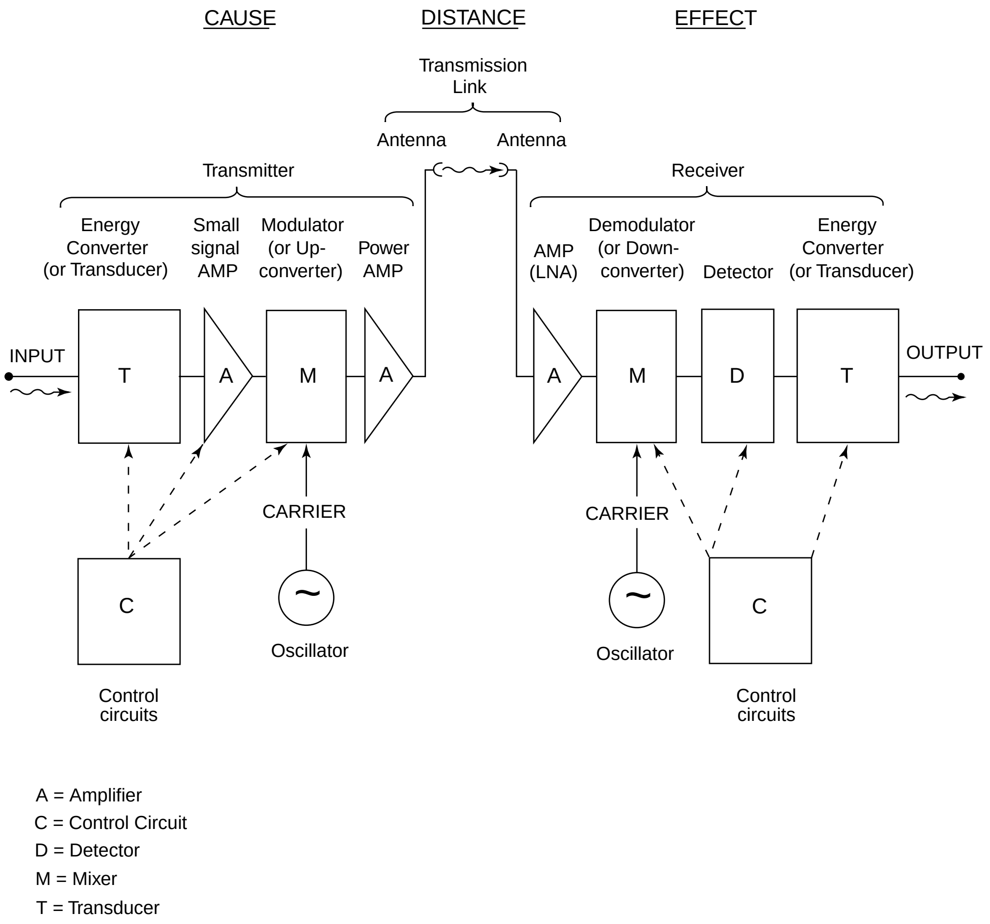


FIGURE 5.8 Block diagram of a general communication system.

It should be noted that the design and structure of this communication system can change and evolve into a more efficient system with time, whereas the universal communication principle will never change. Of course, this should be no surprise to workers in the field because the foundation (fundamental postulates, axioms, and natural laws) and basic concepts (theorems, analytical techniques, and theory of operation) of any science are far superior in importance to any designed circuitry, machinery, or network. This observation brings us to the following conclusion:

> *Fundamentals of any science are superior and dictate the designed forms, structures, or in general the entire application mass of that science, and not vice versa.*

This is true in all aspects of design: While the underlying principle remains constant, the structure, which is the electronic circuit, constantly undergoes improvement with new designs and evolves in time toward a more efficient circuitry.

This can best be described as “engineering principle as a constant” versus “the application mass as a constantly evolving structure” that approaches closer and closer to a perfect embodiment of the underlying principle with each improvement.

Even though, rarely, new discoveries may bring new underlying fundamentals to the forefront, nevertheless the fundamentals, as a general rule, remain invariant.

For example, between 1864 and 1873 James Clerk Maxwell interrelated all of the known data about electricity and magnetism in classical laws of electromagnetics. Since that time, which is over a century, tremendous technological changes and advances have happened all over the globe, yet Maxwell’s equations have not changed an iota. This set of celebrated equations has remained timeless!

Of course, it should be noted that quantum mechanics, dealing with subatomic particles, may be considered by some, to have generalized these equations and shown that energy is not continuous but quantized. Nevertheless, Maxwell’s equations at the classical level of observation have not been surpassed and are still true today; they currently form the foundation of “electromagnetics” as a science—the backbone of electronics and electrical engineering.

Now to build a communication system in the physical universe that works and is practical, we must satisfy two conditions:

- First, it must be based on the fundamental concept of “the universal communication principle” and then Maxwell’s equations—both in combination form a static that is unchanging!
- Second, it must follow and conform to the current state of technology in terms of manufacturing, materials, device fabrication, circuit size, and structure—a kinetic and constantly evolving! These two prerequisites, in essence, clearly demonstrate and confirm the interplay of *static versus kinetic*, which is interwoven throughout our entire world of science and technology.

The previous two steps of system design set up the blueprint for any general engineering system design. We must heed these points carefully before we go very far in the quest for workable knowledge.

5.7 GENERAL ACTIVE-CIRCUIT BLOCK DIAGRAMS

Considering Figure 5.8, we note several stages from left to right:

Energy conversion stage: This is a simple transducer causing the incoming energy (e.g., sound, etc.) to be converted to electrical energy. An example for this stage could be a microphone.

Amplification stage: This is a high-gain small-signal amplifier causing a higher signal to compensate for losses in the energy conversion stage.

Frequency conversion stage (also called modulation or up-conversion): This stage follows the amplification stage and causes a carrier wave to be modulated by the amplified signal.This is the stage that prepares the signal for transmission for long distance by increasing its frequency because higher-frequency signals travel further and require smaller antennas. A local oscillator is needed to produce the carrier wave before the modulation process can take place.

Power amplification stage: This is the stage where the signal power level is boosted greatly so that a higher range of reception is allowed.

Transmission link: This is the transmission media in which the modulated signal is transported from "cause or source point" to the "effect or receipt point."

Low-noise amplification stage: This is the first stage (or front-end) of the receiver wherein the modulated signal is amplified and prepared by a low-noise amplifier (LNA) in such a way that the effect of noise that could possibly be added to the signal by later stages, is minimized.

Frequency conversion stage (or demodulation or down-conversion): This stage demodulates the signal and brings the carrier frequency down to workable levels. Just as in the modulation stage, a local oscillator of a certain frequency is needed to make the demodulation process effective.

NOTE: *If the local oscillator is tunable, then the same receiver can be used to receive signals from other sources at other frequencies (a heterodyne receiver!).*

Detector stage: This stage removes the carrier wave and reconstructs the original signal.

Energy conversion stage: This stage converts the electrical signal back to its original form (e.g., sound). An example for this stage could be a speaker.

Control stage: This is where all the decisions with regard to circuit connection/disconnection, routing, switching, and so on, take place. A control stage is present at both the source and the receipt points of the communication system.

In the remainder of this book, we will explore and focus on techniques for analysis and design of circuits used in all stages of an RF/microwave communication system. To gain a full conceptual understanding of different types of circuit designs we need to have an overall idea of "how different components fit together." To bring this point into a realm of practicality each specific type of microwave circuit has been cast into an exact block diagram that clearly depicts the relationship of the device with other circuit components and sections. The circuits considered for the purpose of the block diagram are defined as follows:

Amplifier: An electronic circuit capable of increasing the magnitude or power level of an electrical signal without distorting the wave-shape of the quantity. The block diagram for this circuit is shown in Figure 5.9.

Oscillator: An electronic circuit that converts energy from a DC source to a periodically varying electrical signal. The block diagram for this circuit is shown in Figure 5.10.

Mixer: An electronic circuit that generates an output frequency equal to the sum and difference of two input frequencies; (also called a frequency converter). The block diagram for this circuit is shown in Figure 5.11.

Detector: An electronic circuit concerned with demodulation; it extracts a signal that has modulated a carrier wave. The block diagram for this circuit is shown in Figure 5.12.

From these block diagrams we can see that the device forms the "heart" or "engine" of the circuit around which all other circuit components should be properly designed to control the input/output flow of signals and eventually obtain optimum performance. Furthermore, these four block diagrams show the irresistible fact that the knowledge gained in earlier chapters is essential in the design of these complicated circuits.

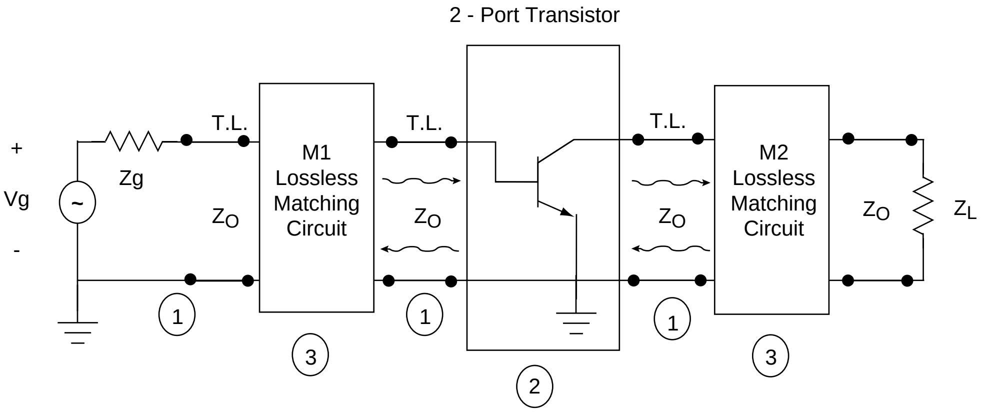


FIGURE 5.9 An amplifier circuit block diagram.

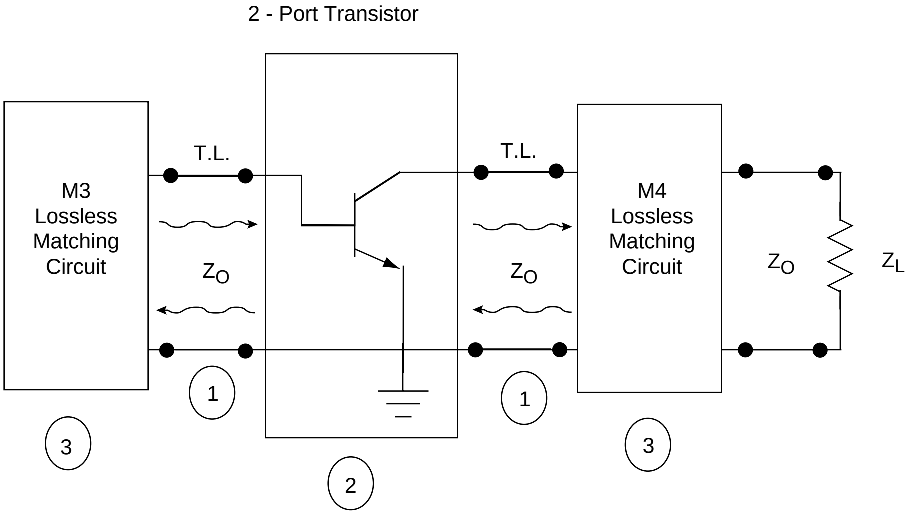


FIGURE 5.10 An oscillator circuit block diagram.

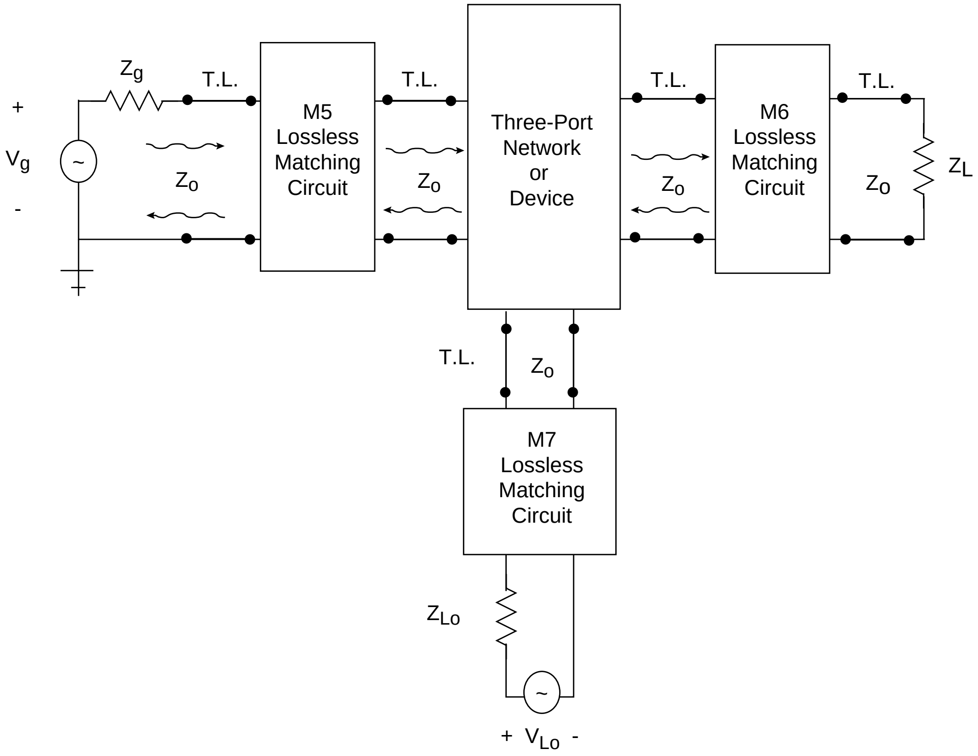


FIGURE 5.11 A mixer circuit block diagram.

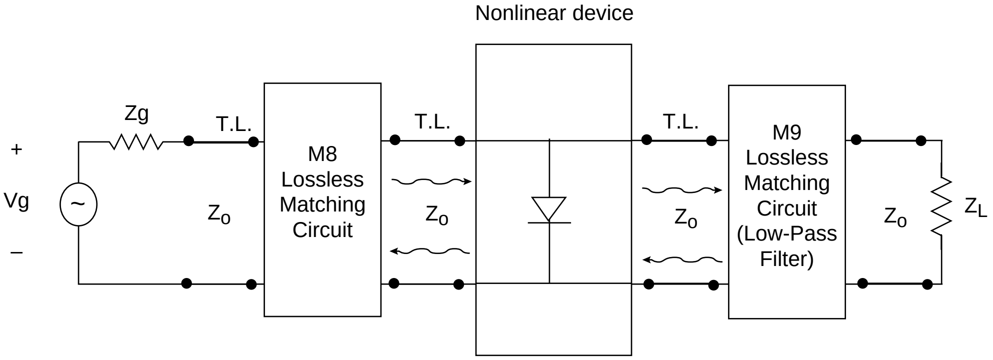


FIGURE 5.12 A detector circuit block diagram.

5.8 SUMMARY

To be proficient at higher frequency circuits (analysis or design), we need to master, on a gradient scale, all of the underlying principles and develop a depth of knowledge before we can be called a skilled microwave practitioner.

Figure 5.13 depicts the gradient scale of concepts that need to be fully understood to achieve a mastery of circuit design skills at higher frequencies. As shown in this figure, we start with the fundamental axioms of sciences, fundamental concepts in electronics, and we progress toward high-frequency electronic circuit design by learning the DC and low-frequency concepts first, then wave propagation concepts, device-circuit characterization, matching concepts, and we eventually arrive at the final destination of RF/MW active circuit design concepts, originally set forth as the goal of this book. Knowing this progressive series of concepts will enable us to design amplifiers, oscillators, mixers, detectors, control circuits, and integrated circuits with relative ease and proficiency at RF/MW frequencies.

LIST OF SYMBOLS/ABBREVIATIONS

A symbol will not be repeated again once it has been identified and defined in an earlier chapter, as long as its definition remains unchanged.

ℓ	Length of a component or circuit
t_d	Time delay
λ	Wavelength

PROBLEMS

5.1 What is the difference between a lumped element and a distributed element?

5.2 How many steps are required to design an RF circuit? A microwave circuit? Describe the steps.

5.3 What are the similarities and difference(s) between an RF and a microwave circuit design procedure?

5.4 Describe: (a) What is meant by “fundamentals versus application mass”? (b) What is meant by timelessness of a fundamental truth? Give an example. (c) What part of a system constantly evolves? (d) What are the prerequisites for any general system design?

5.5 What is at the heart of an amplifier, an oscillator, a mixer, or a detector block diagrams?

5.6 What are the main concepts we need to master to design an RF or a microwave circuit?

5.7 Why is it necessary to understand low-frequency electronics fully before trying to master RF/microwave electronics?

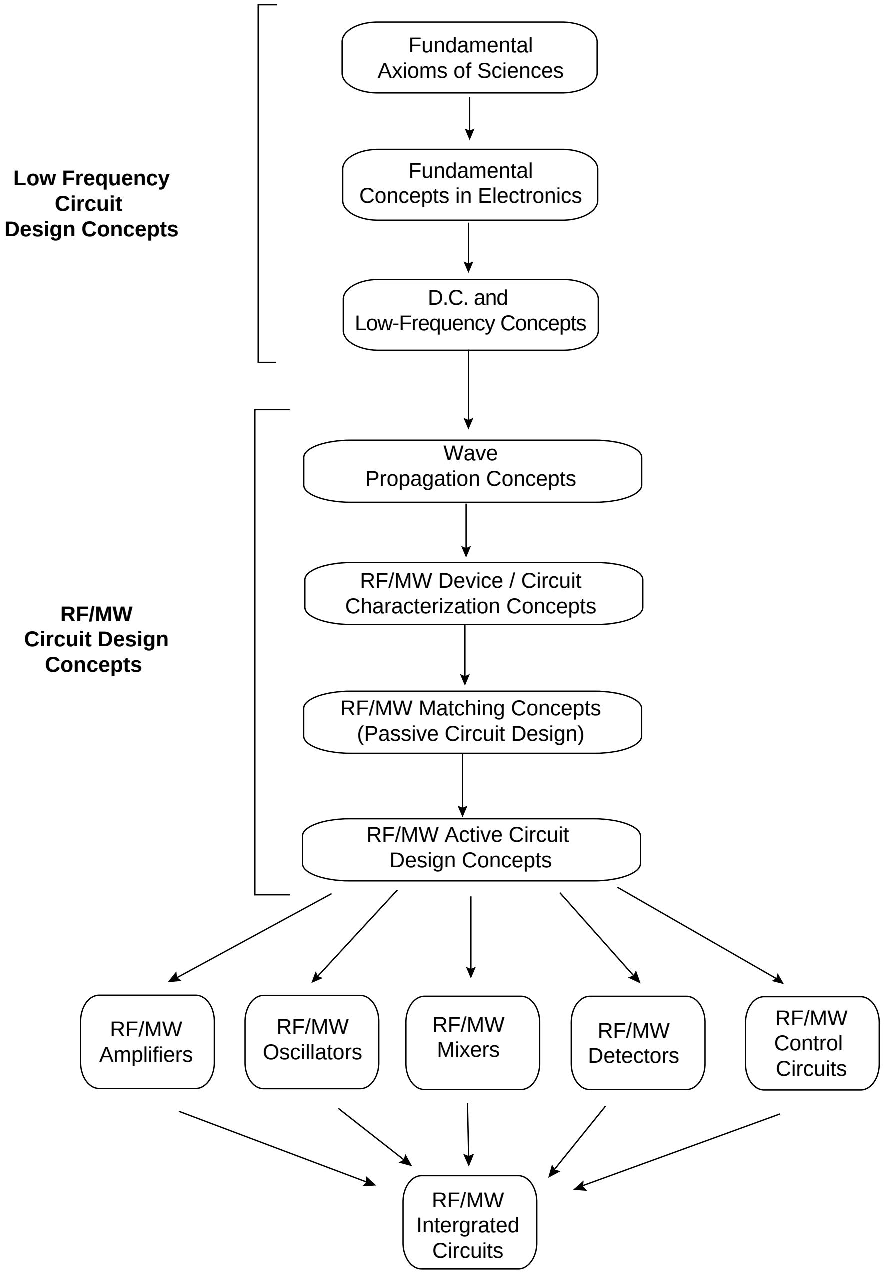


FIGURE 5.13 The gradient scale of concepts in RF/MW circuit design.

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