# 1 Introduction to Microwaves

**Objectives**

- Understand the propagation, properties and classification of radio waves.
- Learn the method of generation, modulation, transmission and reception of radio waves.
- Understand the electromagnetic spectrum and microwave bands.
- Obtain an idea of the development and applications of microwaves.

## 1.1 INTRODUCTION

Every electrical circuit carrying alternating current radiates a certain amount of electrical energy in the form of electromagnetic waves. But the amount of energy thus radiated is extremely small since the dimensions of the circuit are much less when compared to its wavelength. Thus, for a power line, carrying 50 Hz current with 6 m spacing between the conductors, will radiate practically no energy because the wavelength at 50 Hz is 6 million meters and 6 m is negligible in comparison to this. On the other hand, a coil of 6 m diameter carrying a 3 MHz current will radiate a considerable amount of energy because 6 m is comparable with 100 m wavelength of the radiated wave. It is thus apparent that the size of the radiator required is *inversely proportional* to the frequency. Therefore, low frequency waves require a large antenna system for effective radiation whereas a small size radiator can radiate high frequency waves.

Every radiator has directional characteristics. Hence, it radiates stronger power in certain directions than others. Directional characteristics of antennas are utilized to concentrate the radiation towards the desired direction or to favour the reception of energy from a particular direction. This property is the basis for *microwave* (MW) *communication*.

## 1.2 PROPAGATION OF ELECTROMAGNETIC WAVES

The electrical energy that has been radiated into free space exists in the form of electromagnetic (EM) waves. These waves are known as *radio waves*. They travel with the velocity of light. They consist of magnetic and electric fields that are perpendicular to each other and also at right angles to the direction of travel or *propagation*. If these fields could actually be seen, the wave would appear as indicated in Fig. 1.1. One half of the electrical energy contained in the wave is in the form of *electric energy* and the other half is in the form of *magnetic energy*.

## 1.3 PROPERTIES OF RADIO WAVES

The important properties of radio waves are *frequency*, *intensity*, *direction of propagation* and *plane of polarization*. The radio waves will vary in intensity with the frequency of the current and will therefore be alternately *positive* and *negative* as shown in Fig. 1.1(b). The distance occupied by one complete cycle of the wave is called *wavelength* $\lambda$ and is equal to the velocity of the wave or light divided by the frequency $f$. The relationship between the velocity $c$ in meters/sec, wavelength $\lambda$ in meters and the frequency $f$ in Hz is given by

$$\lambda = c/f = 300 \times 10^6/f \tag{1.1}$$

It can be seen from Eq. (1.1), that a low frequency wave has a long wavelength while a high frequency wave has a short wavelength.

The strength of a radio wave is measured in terms of the voltage stress produced in space by the electric field. It is usually expressed in $\mu$V/m. It is also exactly the same voltage induced in a conductor 1 m long by the magnetic field sweeping across the conductor with the velocity of light. The minimum field strength required for satisfactory reception of a radio wave depends upon a number of factors such as frequency, type of signal involved and the amount of interference present. Under certain conditions, radio waves with signal strength as low as 0.1 $\mu$V/m are adequate. Occasionally, signal strengths exceeding 1000 $\mu$V/m are required to ensure satisfactory reception at all times. In most cases, the useful signal strength lies between these two extremes.

A plane parallel to the mutually perpendicular lines of the electric and magnetic flux is called the *wave front*. The wave always travels in a direction perpendicular to the wave front. But whether it is forward or backward direction depends on the relative direction of the lines of electric and magnetic flux. If the direction of either the magnetic flux or the electric flux is reversed, the direction of travel is reversed. However, reversing both the sets of flux has no effect. The direction of electric lines of flux is called the direction of *polarization* of the wave. If the electric flux lines are vertical as shown in Fig. 1.1, the wave is vertically polarized. If the electric flux lines are horizontal and the electromagnetic flux lines are vertical, then it is horizontally polarized.

As radio waves travel away from their point of origin, they get attenuated due to (i) spreading of the waves, (ii) absorption by the ground or ionosphere, and (iii) reflection or refraction by ionosphere or lower atmosphere or ground. The resulting situation is quite complex and differs greatly depending on the frequency of radio waves. Table 1.1 summarizes the bahaviour of different classes of radio waves.

**Example 1.1:** Find the range of wavelength for very low frequency range 10 kHz to 30 kHz.

**Solution:** From Eq. (1.1), the wavelength is given by

$$\lambda = c/f = 300 \times 10^6/f \text{ m}$$

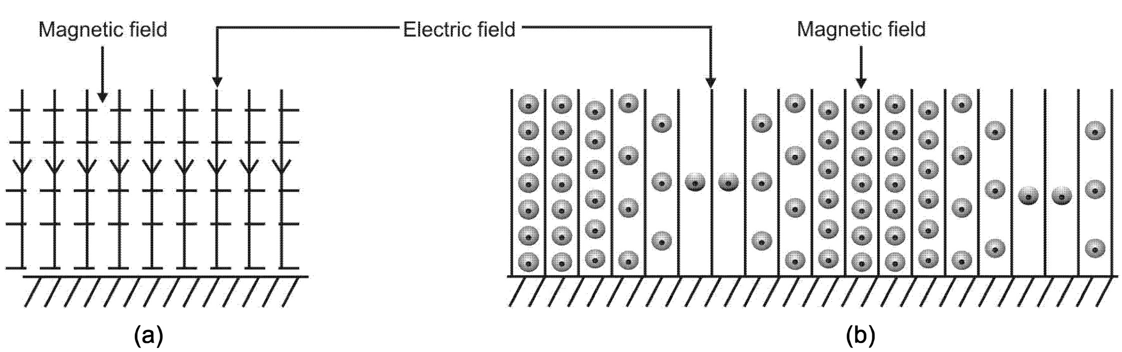



**Fig. 1.1:** Vertically polarized wave (a) Front view (b) Side view

**Table 1.1:** Classification of radio waves

| *Class* | *Frequency range* | *Wavelength range* | *Propagation characteristics* | *Typical uses* |
|---|---|---|---|---|
| Very low frequency (VLF) | 10 kHz–30 kHz | 30,000 m – 10,000 m | Low attenuation; very reliable | Long distance point-to-point communication |
| Low frequency (LF) | 30 kHz–300 kHz | 10,000 m – 1,000 m | Night propagation same as VLF; day time absorption greater; less reliable | Long distance point-to-point comunication, marine communication navigational aids |
| Medium frequency (MF) | 300 kHz–3 MHz | 1,000 m – 100 m | Low night and high day attenuation | Broadcasting; marine navigational aids |
| High frequency (HF) | 3 MHz–30 MHz | 100 m – 10 m | Ionosphere propagation; varies with time of the day, season and frequency | All types of moderate to long distance communication |
| Very high frequency | 30 MHz–300 MHz | 10 m – 1 m | Line of sight propagation; not affected by ionosphere | Short distance communication, TV, FM, radar, aircraft navigation |
| Ultra-high frequency (UHF) | 300 MHz–3 GHz | 100 cm – 10 cm | Same as above | Short distance communication, TV, FM, radar, aircraft navigation, radio relay system |
| Super-high frequency (SHF) | 3 GHz–30 GHz | 10 cm – 1 cm | Same as above | Radar, navigation, radio relay systems |
| Extra-high frequency (EHF) | 30 GHz–300 GHz | 1 cm – 1 mm | Same as above | Radar, navigation, radio relay systems |

For $f_1 = 10{,}000$ Hz,

$$\lambda_1 = 300 \times 10^6/10{,}000 = \mathbf{30{,}000}\text{ m}$$

For $f_2 = 30{,}000$ Hz,

$$\lambda_2 = 300 \times 10^6/30{,}000 = \mathbf{10{,}000}\text{ m}$$

**Example 1.2:** Find the range of wavelength for low frequency range 30 kHz to 300 kHz.

**Solution:** From Eq. (1.1), the wavelength is given by

$$\lambda = c/f = 300 \times 10^6/f \text{ m}$$

For $f_1 = 30{,}000$ Hz

$$\lambda_1 = 300 \times 10^6/30{,}000 = \mathbf{10{,}000}\text{ m}$$

For $f_2 = 300{,}000$ Hz,

$$\lambda_2 = 300 \times 10^6/300{,}000 = \mathbf{1000}\text{ m}$$

**Example 1.3:** Find the range of wavelength for medium frequency range 300 kHz to 3 MHz.

**Solution:** From Eq. (1.1), the wavelength is given by

$$\lambda = c/f = 300 \times 10^6/f \text{ m}$$

For $f_1 = 300{,}000$ Hz,

$$\lambda_1 = 300 \times 10^6/300{,}000$$
$$= \mathbf{1000} \text{ m}$$

For $f_2 = 3 \times 10^6$ Hz,

$$\lambda_2 = 300 \times 10^6/3 \times 10^6$$
$$= \mathbf{100} \text{ m}$$

**Example 1.4:** Find the range of wavelength for high frequency range 3 MHz to 30 MHz.

**Solution:** From Eq. (1.1), the wavelength is given by

$$\lambda = c/f = 300 \times 10^6/f \text{ m}$$

For $f_1 = 3 \times 10^6$ Hz,

$$\lambda_1 = 300 \times 10^6/3 \times 10^6$$
$$= \mathbf{100} \text{ m}$$

For $f_2 = 30 \times 10^6$ Hz,

$$\lambda_2 = 300 \times 10^6/30 \times 10^6$$
$$= \mathbf{10} \text{ m}$$

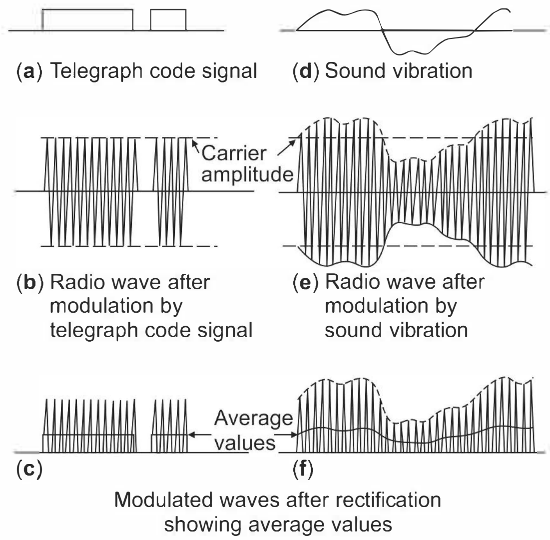



**Fig. 1.2:** (a) Telegraph code signal (b) Modulated wave (c) Detected wave of (b) with average value (d) Acoustic wave (e) Modulated wave and (f) Detected wave of (e) with average value

## 1.4 GENERATION OF RADIO WAVES

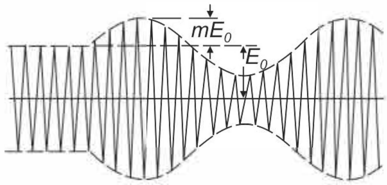
The radio frequency power required by a transmitter is always obtained from vacuum tube or solid-state oscillators. These devices convert dc power into RF power. At frequencies over 1 GHz, the power generated is of the order of kilowatts.

## 1.5 MODULATION

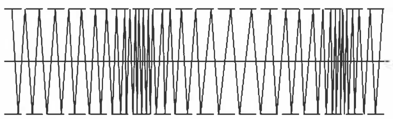
If an RF wave is to convey a message, some features of the wave must be varied in accordance with the information or message to be transmitted. The process of performing this is called *modulation*. There are two important and common types of modulation: *amplitude modulation* and *frequency modulation*. In amplitude modulation, the amplitude of the high frequency carrier wave is varied in accordance with the instantaneous value of the message wave. For example, in radiotelegraphy, the RF transmitter is turned ON and OFF in accordance with the telegraph code as illustrated in Figs 1.2 (a) and (b). In radiotelephony, the RF signal amplitude is varied in accordance with the strength of the sound wave being transmitted as shown in Figs. 1.2 (d) and (e). Figures 1.2 (c) and (f) show the waves after detection along with the average values that are similar to the telegraph and sound signals. Similarly, in picture transmission, the RF signal amplitude is varied in accordance with the light intensity of the part of the picture that is being transmitted at that instant. In the frequency modulation, the RF signal frequency is varied in accordance with the instantaneous value of the message signal. The frequency modulation is widely used in high frequency communication systems. Figure 1.3 shows the amplitude and frequency modulated waves by a single frequency sine wave for the purpose of comparison.

## 1.6 NATURE OF MODULATED WAVE

A modulated wave is a mixer of several waves of different frequencies superimposed upon each other. The actual nature of the modulated wave can be studied by analyzing its equation mathematically. Thus, with a sine wave amplitude modulation as in




(a) Amplitude-modulated wave



(b) Same information transmitted by frequency-modulated wave

**Fig. 1.3:** (a) Amplitude-modulated wave (b) Frequency-modulated wave

Fig. 1.3 (a), the amplitude of RF oscillation is given by $V = V_c + mV_c \sin 2\pi f_s t$. $V_c$ represents the amplitude of the carrier wave, $f_s$ is the signal or message frequency and $m$ is the *degree of modulation* or *modulation index*. Hence, the amplitude-modulated wave can be mathematically represented by

$$v = V_c(1 + m \sin 2\pi f_s t) \sin 2\pi f_c t \qquad (1.2)$$

where $f_c$ is the carrier frequency. Eq. (1.2) may be written as

$$v = V_c \sin 2\pi f_c t + m \sin 2\pi f_s t \sin 2\pi f_c t \quad (1.3)$$

By expanding the last term in Eq. (1.2), we get

$$v = V_c \sin 2\pi f_c t + (mV_c/2) \cos 2\pi (f_c - f_s)t$$
$$- (mV_c/2) \cos 2\pi (f_c + f_s)t \qquad (1.4)$$

Thus, the amplitude-modulated (AM) wave consists of *three separate waves*. One of them is the carrier wave. Its amplitude is independent of the presence or absence of modulation. The magnitude of the other two components are the same but their frequencies differ, one of them is less than the carrier frequency by the signal or message or *modulating* frequency and the other one is more than the carrier frequency by the signal or message or *modulation* frequency. These two frequencies are called *sideband frequencies*. The lower frequency band is called *lower sideband* and the higher frequency band is called *upper sideband* frequencies. Both the sidebands carry the message or intelligence that is being transmitted. The frequency of the sideband components relative to the carrier frequency is determined by the modulation frequency. The relative amplitudes of the sideband components is determined by the amplitude of the modulation signal, or in other words, on the modulation index.

When the modulation signal is more complex than a simple sine wave, it results in the occurrence of additional sideband frequencies. Thus, if the modulation signal has a frequency band of 300 Hz to 3,500 Hz and the carrier frequency is 1000 kHz, then the modulated wave will contain two sidebands, the lower sideband will be from 996.5 kHz to 999.7 kHz, and the upper sideband will be from 1000.3 kHz to 1003.5 kHz.

The analysis of the frequency-modulated (FM) wave is more complex. However, the result is analogous to amplitude modulation. The principal difference is that the frequency-modulated wave contains not only the same sideband frequencies as that of amplitude-modulated wave but also contains higher order sidebands. For example, if the modulation signal has a frequency of 1000 Hz and the carrier frequency is 1000 kHz, then the modulated wave will not only contain two sidebands of 999 kHz and 1001 kHz but also contain 998 kHz and 1002 kHz sidebands and possibly 997 kHz to 1003 kHz sidebands. The amplitudes of the various sidebands will depend on the extent and the rate of frequency variation.

## 1.7 SIGNIFICANCE OF SIDEBANDS

The carrier and sideband frequencies are present in the modulated wave and can be separated from each other by suitable filters. The sideband frequencies are generated as a result of modulation. Their magnitude and frequency are dependent upon the type of the modulation. Thus, it is seen that the transmission of message requires the use of a band of frequencies rather than a single frequency. The frequency components involved in standard broadcasting of speech and quality music are from 100 Hz to 5000 Hz. When modulated, the total bandwidth required is 10 kHz. Hence, each transmitting station would have been assigned a carrier frequency with a bandwidth of 5 kHz on either side of the carrier frequency. If this entire band of frequencies is not fully received due to attenuation in propagation paths, then the quality of reception will be poor.

## 1.8 TRANSMISSION OF RADIO SIGNALS

The modulated wave is further amplified and its power is boosted to the required level. Then, it is radiated into the space by means of transmitting antenna. In this way, a number of broadcasting stations will be transmitting the electromagnetic waves into the space. Each broadcasting station has been assigned a specific carrier frequency and a bandwidth of 10 kHz. Signals will be simultaneously available in the space from all these stations. The desired station program is selected at the receiver end by means of tuning.

## 1.9 RECEPTION OF RADIO SIGNALS

To receive radio signals, it is first necessary to abstract energy from the radio waves passing the receiving point. Any antenna capable of radiating electrical energy is also able to absorb energy from the passing radio waves. This is because the electromagnetic flux of the wave cuts across the antenna and induces in the antenna a voltage that varies in time in exactly the same way as the current flowing in the transmitting antenna. The induced voltage and the associated current produced represent the radio frequency energy absorbed from the passing wave.

Every wave passing the receiving antenna induces its own voltage in the antenna. Therefore, it is necessary that the radio receiver is capable of selecting the desired signal from all the signals that are inducing voltages in the antenna. This selection is made on the basis of the difference in carrier frequency assigned to various transmitting stations. This selection process is carried out by the use of resonant circuits. The ability to discriminate between radio waves of different frequencies is called *selectivity* and the process of adjusting circuits to resonance with the frequency of the desired signal is known as *tuning*.

Radio signals at the receiving antennae will be very weak as the broadcasting stations are thousands of kilometers away from the receiving point. For satisfactory reproduction, the received signal needs to be amplified further. If the amplification takes place before detection, it is radio-frequency amplification and if the amplification takes place after detection, it is audio-frequency amplification. The amplification of the signals is necessary for the satisfactory reception of signals from waves that are otherwise too weak to produce audible response. This amplification can be obtained by using vacuum tubes or transistors.

## 1.10 DETECTION OF RADIO SIGNALS

The process by which the transmitted message or intelligence is retrieved from the modulated wave is called *demodulation* or *detection* and the circuit is known as *detector* or *demodulator*. With amplitude-modulated waves, the detection is accomplished by rectifying the wave to produce a current that varies in accordance with the modulation of the received wave. Thus, when the modulated wave shown in Fig. 1.2(e) is rectified, the resulting current has an average value that varies in accordance with the instantaneous value of the original signal as shown in Fig. 1.2(f). In the case of telegraph codes, rectified current reproduces the dots and dashes of the telegraph code as shown in Fig. 1.2(c) and can be used to operate a telegraph sounder.

The detection of a frequency-modulated wave is accomplished by passing the wave through a circuit in which the relative response depends on the frequency. This circuit is known as a *frequency discriminator*. The average value of the output of the discriminator varies in accordance with the instantaneous value of the original signal.

**Example 1.5:** A carrier frequency of 1.5 MHz is amplitude modulated by a low frequency signal of 1 kHz. Find the sideband frequencies.

**Solution:** $f_c = 1500$ kHz; $f_m = 1$ kHz.

Lower sideband (LSB) frequency is given by

$$\text{LSB} = f_c - f_m = 1{,}500 - 1 = 1499 \text{ kHz.}$$

Upper sideband (USB) frequency is given by

$$\text{USB} = f_c + f_m = 1{,}500 + 1 = 1501 \text{ kHz.}$$

**Example 1.6:** A carrier frequency of 1.5 MHz is amplitude modulated by a low frequency signal of frequencies 500 Hz to 3 kHz. Find the sideband frequencies.

**Solution:** $f_c = 1500$ kHz;

$$f_{m_1} = 0.5 \text{ kHz and } f_{m_2} = 3 \text{ kHz}$$

Lower sideband (LSB) frequencies are given by

$$\text{LSB}_1 = f_c - f_{m_1}$$
$$= 1{,}500 - 0.5 = 1499.5 \text{ kHz.}$$
$$\text{LSB}_2 = f_c - f_{m_2}$$
$$= 1{,}500 - 3 = 1497 \text{ kHz.}$$

Thus, LSB = 1497 kHz to 1499.5 kHz.

Upper sideband (USB) frequencies are given by

$$\text{USB}_1 = f_c + f_{m_1}$$
$$= 1{,}500 + 0.5 = 1500.5 \text{ kHz.}$$
$$\text{USB}_1 = f_c + f_{m_1}$$
$$= 1{,}500 + 3 = 1503 \text{ kHz}$$

Thus, USB = **1500.5 kHz to 1503 kHz.**

**Example 1.7:** If the carrier power and modulation index of amplitude modulated wave are 10 kW and 0.6 kW respectively, find the power in each sideband.

**Solution:** The power in each sideband is given by

$$P_{sb} = (m^2/4)\, P_c$$
$$m = 0.6,\ P_c = 10 \text{ kW}$$
$$P_{sb} = (0.6^2/4) \times 10 \text{ kW} = \mathbf{0.9} \text{ kW}$$

## 1.11 REPRODUCTION OF RADIO SIGNALS

The detected waves are audio frequency waves. They are still weak signals. Hence they are further amplified by a series of voltage amplifiers and finally by a power amplifier. The output of the power amplifier is fed to a loudspeaker. The loudspeaker converts the varying audio frequency current in its coil into acoustic waves or into an audible response that is almost same as the original message or information.

## 1.12 MICROWAVE FREQUENCIES

The term *microwave* is used to describe electromagnetic (EM) waves with wavelengths ranging from 30 cm to 3 mm. The microwave (MW) frequency range is from 1 GHz ($10^9$ Hz) to 100 GHz ($10^{11}$ Hz). Electromagnetic waves with wavelengths ranging from 1 mm to 10 mm are known as millimeter waves. The free space is characterized by the following electrical medium parameters: (i) Permittivity $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m, (ii) Conductivity $\sigma_0 = 10^{-14}$ mho/m and (iii) Permeability $\mu_0 = 4\pi \times 10^{-7}$ H/m. Figure 1.4 shows the electromagnetic frequency spectrum. Because of short wavelengths, microwaves are not reflected by the ionosphere. During World War II, there was tremendous development in the field of microwaves for defense purposes.

Different classification schemes are used to designate MW frequency bands. Table 1.2 shows the new and old US military MW bands and IEEE MW frequency bands and their designations.[1]

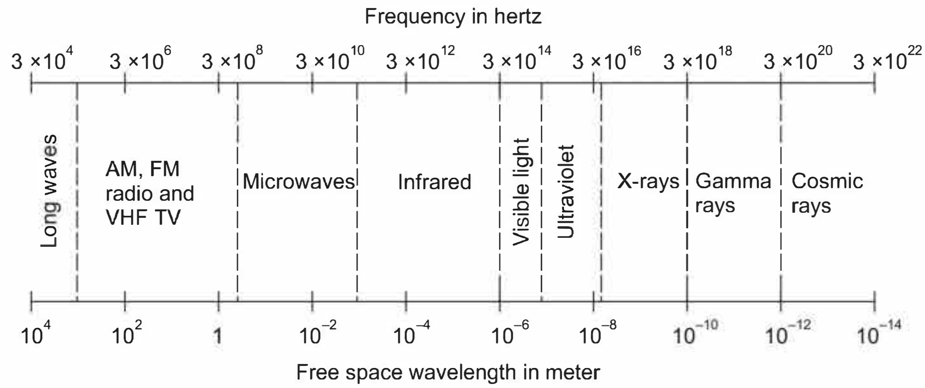



**Fig. 1.4:** The electromagnetic spectrum

## 1.13 CHARACTERISTICS OF MICROWAVES

There are three important characteristics that differentiate MW engineering from low and optical frequencies. They are:

(i) The size of most of the MW components is comparable with wavelengths at MW frequencies.

(ii) Currents at MW frequencies tend to flow along the surface of conductors. This increases dramatically the resistive effect. Therefore, special techniques are required to minimize the circuit losses at MW frequencies. Hence, silver-plating and polishing of metallic surfaces of certain MW components are essential.

(iii) At MW frequencies, voltages and currents are uniquely defined and hence cannot be measured directly as in the case of low-frequency circuits.

## 1.14 MICROWAVE DEVICES

Conventional lines will radiate considerable amount of power because of their comparable lengths with the wavelengths of the microwaves. This results in losses in micro-

**Table 1.2:** Classification of MW frequencies

| *US Military MW bands* | | | | *IEEE MW band* | |
|---|---|---|---|---|---|
| *New bands* | *Frequency range (GHz)* | *Old bands* | *Frequency range (GHZ)* | *Band* | *Frequency range (GHZ)* |
| **A** band | **0.10–0.25** | **P** band | **0.225–0.390** | **HF** band | **0.003–0.030** |
| **B** band | **0.25–0.50** | **L** band | **0.390–1.550** | **VHF** band | **0.030–0.300** |
| **C** band | **0.50–1.00** | **S** band | **1.550–3.900** | **UHF** band | **0.300–1.000** |
| **D** band | **1.00–2.00** | **C** band | **3.900–6.200** | **L** band | **1.000–2.000** |
| **E** band | **2.00–3.00** | **X** band | **6.200–10.900** | **S** band | **2.000–4.000** |
| **F** band | **3.00–4.00** | **K** band | **10.900–36.00** | **C** band | **4.000–8.000** |
| **G** band | **4.00–6.00** | **Q** band | **36.00–46.00** | **X** band | **8.000–12.000** |
| **H** band | **6.00–8.00** | **V** band | **46.00–56.00** | **Ku** band | **12.000–18.000** |
| **I** band | **8.00–10.00** | **W** band | **56.00–100.00** | **K** band | **18.000–27.000** |
| **J** band | **10.00–20.00** | | | **Ka** band | **27.000–40.000** |
| **K** band | **20.00–40.00** | | | Millimeter | **40.000–300.000** |
| **L** band | **40.00–60.00** | | | Submillimeter | **> 300.000** |
| **M** band | **60.00–100.00** | | | | |

wave energy. Therefore special active and passive devices are required for the generation and transmission of signals at microwave frequencies. The microwaves can be generated using vacuum tubes such as reflex klystron, magnetrons and backward wave oscillators or solid-state devices such as Gunn diodes, tunnel diodes and varactor diodes. They are amplified using multi-cavity klystron and traveling wave tube amplifiers or solid-state amplifiers such as parametric amplifiers and metal-semiconductor field effect transistors (MESFETs).

Microwaves are transmitted through coaxial lines, waveguides, strip lines, microstrip lines and other devices such as attenuators, phase shifters, circulators, isolators and directional couplers. All these devices will be described in the text.

## 1.15 MICROWAVE SYSTEMS

A microwave system normally consists of a transmitting subsystem and a receiver subsystem. The transmitting system includes a microwave source or oscillator, waveguides and a transmitting antenna. The receiver system includes a receiving antenna, transmission lines or waveguide, a microwave amplifier and a receiver. A typical microwave system is shown in Fig. 1.5.

## 1.16 MICROWAVE UNITS

Different units are used in microwave measurements. Of these, the meter-kilogram-second units (the International System of Units) are used internationally. We shall follow this system throughout. Table 1.3 shows the most commonly used MKS units.

**Table 1.3:** MKS units

| *Quantity* | *Unit* | *Symbol* |
|---|---|---|
| Resistance | Ohm | Ω |
| Conductance | Mho | ℧ |
| Inductance | Henry | H |
| Capacitance | Farad | F |
| Voltage | Volt | V |
| Current | Ampere | A |
| Power | Watt | W |
| Charge | Coulomb | Q |
| Field | Volt/meter | E |
| Flux linkage | Weber | ψ |
| Frequency | Hertz | Hz |
| Length | Meter | m |
| Time | Second | s |
| Velocity | Meter/Second | v |

## 1.17 HISTORICAL BACKGROUND

In this section, we shall deal with the important milestones in the development of MW engineering.[2,3,4]

**1845:** Michael Faraday studied the effect of magnetic field on the propagation of light through glass. He established the existence of relationship between electromagnetic waves and light. He speculated that light might have wave like characters.

**1865:** James Clerk Maxwell published a paper "A dynamical theory of the electromagnetic

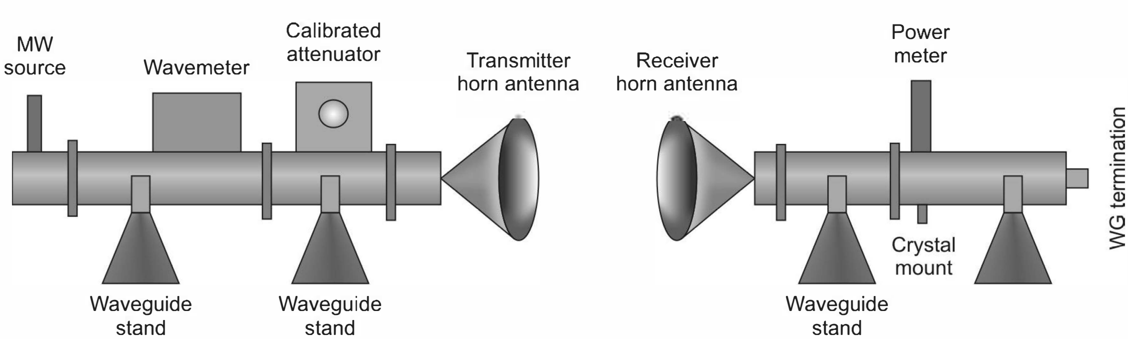



**Fig. 1.5:** A typical microwave system

field". He developed four basic equations known as Maxwell's equations and demonstrated that the electromagnetic fields travel at the speed of light.

**1888: Heinrich Hertz** generated 30 MHz signal and validated the Maxwell's theory. Established the relationship $f\,\lambda_0 = c$, where $\lambda_0$ is the free space wavelength and $c$ is the velocity of light ($3 \times 10^8$ m/s.).

**1893: Heinrich Hertz** demonstrated that parabolic reflectors concentrate the EM energy, thus improving the efficiency of transmission. Parabolic reflectors are used even today as efficient MW antennas.

**1895: Guglielmo Marconi** transmitted radio signals over 1 mile; thus demonstrating the first practical application of EM waves in the field of communication. The transmission distance was increased to 4 miles by using parabolic reflectors with an operating frequency of 1.2 GHz.

**1897: Lord Rayleigh** theoretically proved that EM waves could propagate through hollow metal tubes (waveguides).

**1897: Oliver Lodge** demonstrated EM wave propagation in waveguides at 1.5 and 4 GHz.

**1901: Guglielmo Marconi** transmitted successfully the first transatlantic wireless message from England to Newfoundland at a distance of 3,000 miles.

**1919: Barkhausen and Kurz** developed positive grid MW oscillators.

**1921: Hull** developed smooth bore Magnetron for MW signal generation.

**1921 to 1930:** Remarkable progress in wireless transmission was achieved. Frequencies from hundreds of kHz to hundreds of MHz were used to transmit messages over thousands of miles through space.

**1937: Varian Brothers** developed Klystron that continues to be an excellent source of MW power.

**1938: Hansen** invented cavity resonator.

**1939: Randall and Boot** developed cavity magnetrons to produce 400 W of power at 3 GHz.

**1944: R Kompfner** developed helix-type traveling wave tube.

**1957: L Esaki** developed tunnel diode.

**1958: WT Reed** developed IMPATT-type oscillators.

**1963: JB Gunn** developed Gunn-effect diodes.

**1965: MW transistors** were developed.

**1966: Mead** proposed **metal semiconductor FET**

**1969: Middlebrook** realized MESFET (metal-oxide semiconductor field effect transistor).

With the development of MW repeater stations and satellite communication, microwave technology has been recognized as a major field for commercial and military purposes.

## 1.18 MICROWAVE APPLICATIONS

Two of the earliest MW uses are for point-to-point communication and radars. Some of the most important uses of MW are discussed below:

(i) **Point-to-point communication:** For point-to-point communication, it is important that the transmitted signal is sharply focused and aimed at the receiving antenna. Since these abilities can easily be achieved at MW frequencies, they are ideally suited for point-to-point communication. The function of the radio and TV broadcasting is to *broadcast* the radio signals over as *broad* an area as possible. Therefore, AM, FM and TV broadcast frequencies are much lower than those in the MW range.

A series of repeater stations spaced along the line of sight (LOS) paths can provide a communication link between cities far away. The combination of MW transmitters and satellites enable to communicate between continents. The satellite receives the signal, amplifies and retransmits it to a large area. Since atmospheric noise is low in the frequency band 3 to 6 GHz, most satellite communication systems operate within this frequency band.

Communication theory states that the amount of information that can be transmitted is directly proportional to the available bandwidth. The MW spectrum contains a wide band of frequencies. This is advantageous for use in transmitting information. It can therefore accommodate many more communication channels than the conventional radio and TV frequencies.

(ii) **Radar systems:** Another major application of microwaves is radar systems. They are used to detect enemy aircrafts and guide missiles, to control flight traffic at airports and to observe and track weather patterns. Radars are also used in garage-door openers, burglar alarms and vehicle speed detectors. MW is extremely useful in radar systems because it can be sharply focused. For instance, an airport-radar must be able to detect separate planes in the traffic pattern. Hence, the radar beam must be sufficiently narrow so that the received signal is reflected from one aircraft only and not from any other in the vicinity of 15°. This necessitates the use of a very narrow beam and therefore MW frequencies are used. Sharply focused MW beams from an aircraft are also used to map the terrain of a large area.

(iii) **Commercial and industrial applications:** MW ovens are typical examples of commercial and industrial applications. In MW ovens, the entire volume of food is heated directly and uniformly. As a result, the cooking time is reduced. Heating property of microwaves is also used in drying potato chips, grains, paper, coffee beans etc. Microwaves are used to measure precisely the thickness of metal sheets in rolling mills and also to determine moisture content in substances. Because MW penetrates the ionosphere, they are used in radio astronomy and for communication with space vehicles.

## 1.19 ADDITIONAL EXAMPLES

**Example 1.8:** Find the wavelength of the MW signal at 1 GHz.

**Solution:** From Eq. (1.1), the wavelength is given by

$$\lambda = c/f = 300 \times 10^6/f \text{ m}$$
$$f = 10^9 \text{ Hz}$$
$$\lambda = 300 \times 10^6/10^9 = 0.3 \text{ m} = \mathbf{30} \text{ cm.}$$

**Example 1.9:** Find the range of wavelength of the X-band MW signal (8 to 12 GHz).

**Solution:** From Eq. (1.1), the wavelength is given by

$$\lambda = c/f = 300 \times 10^6/f \text{ m}$$
$$f_1 = 8 \times 10^9;\ f_2 = 12 \times 10^9$$
$$\lambda_1 = 300 \times 10^6/8 \times 10^9 = 0.0375 \text{ m}$$
$$= \mathbf{3.75} \text{ cm}$$
$$\lambda_2 = 300 \times 10^6/12 \times 10^9 = 0.0275 \text{ m}$$
$$= \mathbf{2.75} \text{ cm}$$

Range of wavelength is from 2.75 cm to 3.75 cm.

**Example 1.10:** Find the wavelength of the MW signal at 300 GHz.

**Solution:** From Eq. (1.1), the wavelength is given by

$$\lambda = c/f = 300 \times 10^6/f \text{ m}$$
$$f = 300 \times 10^9 \text{ Hz}$$
$$\lambda = 300 \times 10^6/300 \times 10^9 = 0.001 \text{ m}$$
$$= 1 \text{ mm.}$$

**Example 1.11:** The carrier frequency in amplitude modulation is 2 MHz and the modulation frequency is 1 kHz. Find the sideband frequencies.

**Solution:** Given: $f_c$ = 2000 kHz; $f_m$ = 1 KHz. The sideband frequencies are given by

$$f_{\text{sideband}} = f_c \pm f_m = 2000 \pm 1$$
$$= \mathbf{1999} \text{ and } \mathbf{2001} \text{ kHz.}$$

**Example 1.12:** If the 2 MHz carrier-frequency is modulated by a band of frequencies from 1 kHz to 4 kHz, find the sideband frequencies.

**Solutions:** Given:

$$f_c = 2000 \text{ kHz}; \ f_m = 1 \text{ to } 4 \text{ kHz}$$

$$f_{\text{sideband}} = f_c \pm f_m = 2000 \pm (1 \text{ to } 4)$$

The lower sideband is given by

$$\text{LSB} = 2000 - (1 \text{ to } 4)$$

$$= \mathbf{1996} \text{ to } \mathbf{1999} \text{ kHz}$$

The upper sideband is given by

$$\text{USB} = 2000 + (1 \text{ to } 4)$$

$$= \mathbf{2001} \text{ to } \mathbf{2004} \text{ kHz}$$

**Example 1.13:** The amplitude of the carrier is two times that of modulation signal, find the modulation index and amplitude of each sideband.

**Solution:** Given: $\boldsymbol{V_c/V_m} = 2$

The modulation index is given by

$$m = \boldsymbol{V_m}/\text{amplitude of each sideband}$$

$$= 1/2 = \mathbf{0.5}$$

The amplitude of each sideband is given by

$$\boldsymbol{V}_{\text{sideband}} = (m/2)\boldsymbol{V_c} = \mathbf{0.25}\boldsymbol{V_c}$$

**Example 1.14:** If the modulation index $m = 0.4$, find the power in each sideband.

**Solution:** Given: $m = 0.4$

The power in each sideband is given by

$$\boldsymbol{P}_{\text{sideband}} = (m^2/4)\, \boldsymbol{P_c} = \mathbf{0.04}\, \boldsymbol{P_c}$$

**Example 1.15:** The sideband frequencies of a transmitting station is 10.005 and 9.995 MHz. What is its carrier frequency?

**Solution:** The sideband frequencies are given by

$$\text{LSB} = f_c - f_m = \mathbf{9.995} \text{ MHz}$$

$$\text{USB} = f_c + f_m = \mathbf{10.005} \text{ MHz}$$

$$\text{LSB} + \text{USB} = 2f_c = 20 \text{ MHz}.$$

$$\therefore \qquad f_c = 10 \text{ MHz}.$$

## KEY POINTS

- A small size radiator can radiate considerable energy at high frequencies. The wavelength of the radio waves (RF) is short and comparable with the dimensions of the RF components.
- Every radiator radiates stronger power in certain directions than others.
- RF waves are radiated into free space in the form of electromagnetic (EM) waves at the velocity of light.
- Important properties of radio waves: frequency, intensity, direction of propagation and plane of polarization.
- $\lambda = \lambda c/f$; $\lambda$ is in meters, $c = 300 \times 10^6$ and $f$ is in Hz.
- The strength of a radio wave is measured in mV/m.
- Wave front is a plane parallel to the mutually perpendicular lines of the electric and electromagnetic flux.
- The direction of wave polarization is the direction of electric lines of flux.
- The radio frequency power is generated using vacuum tube or solid-state oscillators.
- The process of varying a feature of a carrier wave is called modulation.
- In amplitude modulation, the amplitude of the high frequency carrier wave is varied in accordance with the instantaneous value of the message wave and its frequency remains constant.
- The amplitude-modulated wave consists of the carrier wave and two sidebands. The magnitudes of the two sidebands are the same but the frequencies differ. Both the sidebands carry the message or intelligence. The process by which the transmitted message or intelligence is retrieved from the modulated wave is called demodulation or detection.
- In the frequency modulation, the RF signal frequency is varied in accordance with the instantaneous value of the message signal and its amplitude remains constant.
- The detection of a frequency-modulated wave is accomplished by passing the wave through a circuit in which the relative response depends on the frequency. This circuit is known as frequency discriminator.
- Loudspeakers convert the varying audio frequency current in its coil into acoustic waves.

- Microwaves are electromagnetic (EM) waves with wavelengths ranging from 30 cm to 3 mm. The microwave (MW) frequency range is from 1 GHz ($10^9$ Hz) to 100 GHz ($10^{11}$ Hz).
- An antenna radiates electrical energy and also absorbs energy from the passing radio waves.

## FURTHER READINGS

1. Altman JL (1962). *Microwave Circuits*, New Jersey, Van Nostrand.
2. Atwater HA (1962). *Introduction to Microwave Theory*, New York: McGraw Hill.
3. Collin, RE (1966). *Foundations of Microwave Engineering*, New York: McGraw Hill.
4. Historical Perspectives of Microwave Engineering – Special centennial issue, *IEEE Trans*. Vol. MTT – 32, Sept., 1984.
5. Gandhi OP (1981). *Microwave Engineering*, New York: McGraw Hill.
6. Pozar DM (1990), *Microwave Engineering*, Addison-Wesley, Mass.

## REVIEW QUESTIONS

1.1 Why does an electrical transmission line not radiate considerable amount of energy?
1.2 At higher frequencies, considerable energy is radiated. Explain.
1.3 What is meant by directional characteristic?
1.4 What are the components of radio waves? What is their velocity of propagation?
1.5 Mention the important properties of a radio wave.
1.6 Write down the relationship between wave length and the frequency.
1.7 In what units the strength of a radio wave is measured.
1.8 What is a wave front?
1.9 What is meant by polarization?
1.10 Define modulation.
1.11 Mention the two common types of modulation.
1.12 Define amplitude modulation.
1.13 Define modulation index.
1.14 Define frequency modulation.
1.15 How many sidebands are present in amplitude modulation?
1.16 How many sidebands are present in frequency modulation?
1.17 Name the circuits used for detection.
1.18 What are microwaves?
1.19 Mention the MW bands with their frequency range.
1.20 Mention the different classification of frequency spectrum.
1.21 What is the important property of MW used in communication?
1.22 What is the important property of MW used in radar systems?
1.23 What is the important property of MW used in MW oven?
1.24 Mention four uses of MW in domestic and industrial applications.

## DESCRIPTIVE QUESTIONS

1.1 Explain briefly the propagation of radio waves.
1.2 Describe the process of modulation.
1.3 Describe the process of detection.
1.4 Explain the nature of the modulated wave and the significance of sidebands.
1.5 Draw the electromagnetic frequency spectrum and indicate the relevant details.
1.6 Explain the classification of radio waves with their frequency range, wavelength range, characteristics and uses.
1.7 Give the classification of microwaves and their most important properties.
1.8 Explain the applications of microwaves in (i) point-to-point communication, (ii) radar systems and (iii) commercial applications.

## PRACTICE PROBLEMS

1.1 Find the range of wavelength for very high frequency range 30 MHz to 300 MHz.
(**Ans:** 1 m to 10 m)
1.2 Find the range of wavelength for ultra-high frequency range 300 MHz to 3 GHz.
(**Ans:** 10 cm to 1 m)
1.3 Find the range of wavelength for super-high frequency range 3 GHz to 30 GHz.
(**Ans:** 1 cm to 10 cm)
1.4 Find the range of wavelength for extra-high frequency range 30 GHz to 300 GHz.
(**Ans:** 1 cm to 1 mm)
1.5 The carrier frequency in amplitude modulation is 1 MHz and the modulation frequency is 1 kHz. Find the sideband frequencies.
(**Ans:** 999 and 1001 kHz)

1.6 If the 1 MHz carrier frequency is modulated by a band of frequencies from 500 Hz to 4 kHz, find the sideband frequencies.
(**Ans:** 996 to 999.5 kHz and 1000.5 to 1004 kHz)

1.7 The amplitude of the carrier is four times that of modulating signal, find the modulation index and amplitude of each sideband.
(**Ans:** 0.25 , 0.125 $V_c$)

1.8 If the modulation index $m$ = 0.6, find the power in each sideband.
(**Ans:** 0.09 $P_c$)

1.9 A transmission line having a solid dielectric reduces the phase velocity to $2 \times 10^8$ m/s from its free space value. Find the wavelength of a 500 MHz sine wave on the line.
(**Ans:** 40 cm)

1.10 A 500 MHz sine wave is propagated over a matched transmission line that has air dielectric. The phase velocity in the air is $3 \times 10^8$ m/s. Find the wavelength of the signal on the line.
(**Ans:** 60 cm)

## REFERENCES

1. Terman FE (1955). *Electronic and Radio Engineering*, New York, McGraw Hill Intl. Ed.
2. Liao SY (2003). *Microwave Devices and Circuits*, Pearson, India.
3. Das A and Das SK (2004). *Microwave Engineering*, TMH, New Delhi.
4. Historical Perspectives of Microwave Engineering – Special centennial issue, IEEE Trans. Vol. MTT – 32, Sept. 1984.