## 1.1 Introduction

Microwave is a descriptive term used to identify electromagnetic waves in the frequency spectrum ranging approximately from 1 GHz (wavelength $\lambda = 30$ cm) to 300 GHz ($\lambda = 1$ mm). For wavelength from 1.00 to 0.3 mm, i.e. for frequencies 300–1000 GHz, the EM waves are called millimetre waves (Fig. 1.1) and sub-millimetre waves.

Microwaves are so called as they are normally defined in terms of their wavelength. In fact beyond audio waves, all are electromagnetic waves having E-vector and H-vector which are perpendicular to each other.

These microwaves have several interesting and unusual features, not found in other portions of the electromagnetic frequency spectrum. These features make microwaves uniquely suitable for several useful applications.

Since the wavelengths are small, the phase varies rapidly with distance in the guided media; therefore, the techniques of circuit analysis and design, measurements of power generation and amplification at these frequencies are different from those at lower frequencies.

Analysis based on Kirchhoff's laws and Ohm's law (voltage–current) concepts is not easily possible for describing the circuit's behaviour at microwave frequencies. It is necessary to analyse the circuit or the component in terms of electric and magnetic fields associated with it. For this reason, microwave engineering is also known as electromagnetic engineering or applied electromagnetic. A background of electromagnetic theory is a prerequisite for understanding microwaves.

The complete spectrum of electromagnetic waves is given in Figs. 1.1, 1.2, and 1.3 giving frequency and corresponding wavelength. It also gives names of different frequency bands (e.g. IEEE band, millimetre band, sub-millimetre of UHF and VHF), different applications, guided media of application, etc. The IEEE-defined band is also given separately in Table 1.1.

## 1.2 History of Microwaves

One of the first attempts to deduce the fundamental law of electromagnetic action in terms of an electric field propagating at finite velocity was done by Karl Friedrick Gauss (1777–1855), a German mathematician. However, the genesis of microwave and electromagnetic waves in general can be taken from Michael Faraday's (1848) experiments on propagation of magnetic disturbance (EM waves), which later got theoretical formulation by James Clerk Maxwell (1865), popularly known as Maxwell's Field Equations. Thereafter, Marconi and Hertz in their experiments (1888) proved Maxwell's theory of RF signal being an EM wave and travel with the velocity of light ($c = \lambda \cdot f = 3 \times 10^8$ m/s). In 1885, J. C. Bose developed a circuit for generating microwave power and in 1898 developed horn antenna, polariser, and detector of RF signal, which is used even today. The slow but steady development in the area of transmission line, transmitters, etc., continued till 1930, but thereafter it got accelerated. The genesis of microwave propagation through waveguides was from the success of Dr. Southworth (1933) of AT and T Labs, USA, when he was able to transmit signal through metal pipe of 4″ diameter. Thereafter, the requirements of World Wars I and II further boosted through the development of microwave tubes—Klystron by Varian brothers (1936) of Stanford University, magnetron by Randel and Boots of UK (1939), Radar by Henry Tizard (UK) during 1940, etc. Thereafter, also the development continued and ferrite devices, TWT, etc., came in 1950s. In 1960s, Solid State Microwave sources, e.g. Gunn diodes, avalanche diodes, microwave transistors came in full swing, which takes very small space and has very low dc power requirements for generating microwave power. Now application of microwaves has entered all the segments of Communication and Telemetry control (audio, video, text, and data), whether it is for use in civilian systems or in defence systems or for space applications. It has other applications also, e.g. heating (in industrial processes or domestic appliances or cancer treatment), microwave spectroscopy, radio astronomy, satellite communication.

Today for microwave power requirements below 5 W, we can use sources of semiconductor devices like IMPATT diode, while for higher power requirements, we use microwave tubes like klystron, magnetron, Travelling Wave Tube (TWT).

## 1.3 Characteristic Features and Advantages of Microwaves

Unique features leading to advantages of microwave over low-frequency signal are as:

1. **Increased band width availability**: It has large band width because of high frequency. Normally the maximum bandwidth can be 10% of the base signal. A 10% band width at 3 GHz implies availability of 300 MHz band width and hence much more information can be transmitted.
2. **Lower fading and reliability**: Fading effect is high at low frequency, while in microwave due to line-of-sight propagation and high frequency, there is less fading effect and hence microwave communication is more reliable.

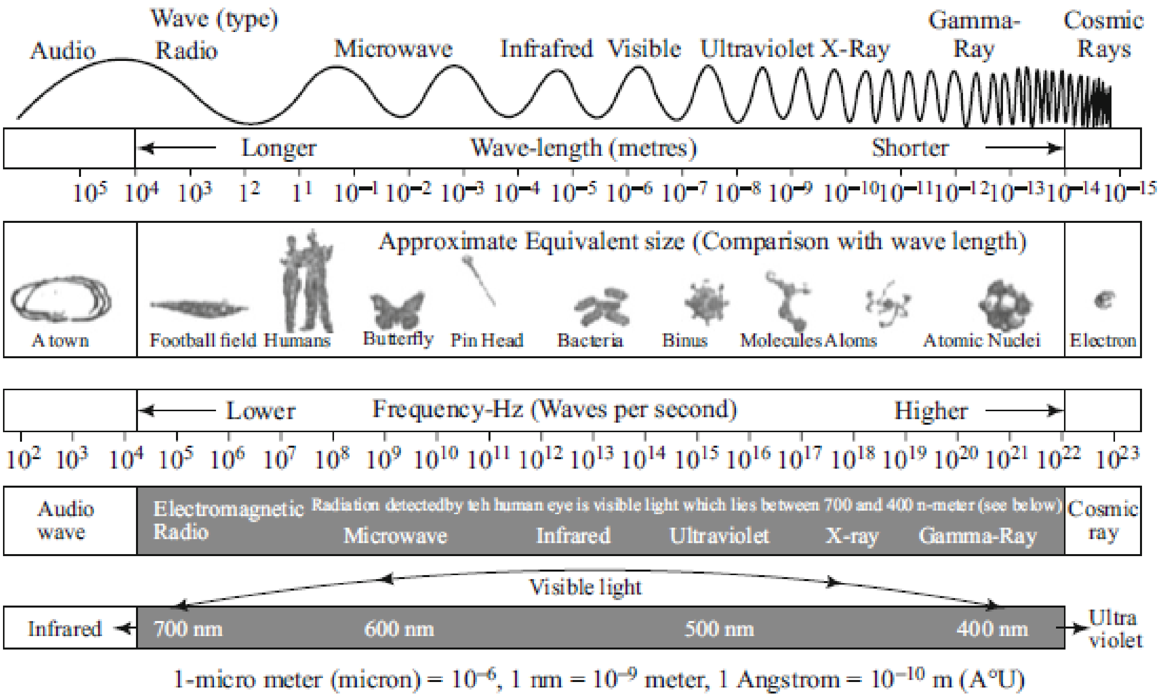



**Fig. 1.1** Comparative visualisation of the complete spectrum of EM wavelengths and its frequencies

3. **Transparency property**: It has transparency property, i.e. it can easily propagate through air, space, even through an ionised layer surrounding the earth and atmosphere, leading to important applications like:
   - Astronomical research of space.
   - Duplex communication between ground station and speed vehicles.

The only 58–60 GHz frequency band which is used less due to molecule resonance ($H_2O$ and $O_2$) and hence absorption. Above 400 GHz, some frequencies are blocked by ozone in the atmosphere due to similar reasons.

4. **Low-power requirements**: The dc power required by the transmitter and receiver at microwave frequency is quite low as compared to low-frequency operations especially due to its directivity and low attenuation in space as well as in any guided media like wave guides.

**Table 1.1** Microwave frequency band IEEE names

| Frequency | Band (old name) | Band (new name) |
|---|---|---|
| 3–30 MHz | HF | HF |
| 30–300 MHz | VHF | VHF |
| 0.3–1.0 GHz | UHF | C |
| 1–2 GHz | L | D |
| 2–3 GHz | S | E |
| 3–4 GHz | S | F |
| 4–6 GHz | C | G |
| 6–8 GHz | C | H |
| 8–10 GHz | X | I |
| 10–12.4 GHz | X | J |
| 12.4–18.6 GHz | Ku (upper to K) | J |
| 18–20 GHz | K | J |
| 20–26.5 GHz | K | K |
| 26.5–40 GHz | Ka (after K) | K |
| 40–300 GHz | Millimetre | Millimetre |
| >300.00 GHz | Sub-millimetre | Sub-millimetre |

5. **Higher power radiated and higher gain of receiving antenna, at higher frequencies**: In radar system, the power radiated $P_r$ from a tower antenna and the gain $G$ of a receiving antenna for signals reflected from the target, are high, being proportional to the square of the frequency as given below:

$$P_r = m_0 \pi^2 I_0^2 l^2 f^2 / c^2 \quad (1.1)$$

$$G = 4\pi\rho_a \cdot A \cdot f^2 / c^2 \quad (1.2)$$

where $I_0$ = ac current; $l$ = length of transmitting antenna,
$A$ = area of the receiving dish antenna,
$\rho_a$ = antenna aperture efficiency.

As $E = h\nu$, the energy of the wave increases with frequency ($\nu$); Fig. 1.3 may be referred for this.

6. **Directivity**: As the frequency increases, dispersive angle decreases; hence, directivity increases and beam width angle decreases. This property leads to further less requirement of microwave power in the directions where we want to send signal.

Beam width ($\theta_B$) for parabolic reflector is given by,

$$\theta_B = 140^\circ \times (\lambda / D) \quad (1.3)$$

Therefore,

$$D = 140^\circ \times (\lambda / \theta_B) \quad (1.4)$$

where $\theta_B \rightarrow$ Beam width (degrees), $\lambda \rightarrow$ Wavelength (cm), $D \rightarrow$ Diameter of antenna (cm).

For example, for the same beam width requirement of 1°, smaller antenna is required at microwave frequency, for example:

**At 30 GHz (Microwave):**

$$\lambda = 1.0 \text{ cm and } \theta_B = 1^\circ$$

So, $D = 140^\circ \times 1.0/1^\circ \rightarrow 140$ cm (which is practical)

**At 100 MHz:**

$$\lambda = 300 \text{ cm and } \theta_B = 1^\circ$$

So,

$$D = 140^\circ \times 300/1^\circ \rightarrow 42,000 \text{ cm}$$
$$= 420 \text{ m (which is not easy to make or use)}$$

Hence, it is clear that antenna size is much smaller and easier to handle at microwave frequency.

7. **Interaction with metal attenuation, penetration, and reflection**: Microwave incident on the metal walls of the oven behaves similar to visible light hitting a silver mirror. The microwaves are absorbed very effectively, since the electric fields of the waves interact very strongly with the nearly free electrons of the metal. In a simple model, the electron undergoes damped forced oscillation and absorbs energy partly. These accelerated electrons re-radiate electromagnetic waves at the same frequency and in phase, hence a major part of the microwave is perfectly reflected. Microscopically, this behaviour is described by the complex dielectric constant $\varepsilon(\omega)$, which is the square of the complex refractive index $(\mu), \varepsilon_d = \varepsilon_r + i\varepsilon_i = (\mu_r + i\mu_i)^2$.

The refractive index ($\mu$) of many metals gives reflectivities close to 100% at low frequencies. The penetration depth of electromagnetic waves of wavelength A is given by

$$\delta = \lambda / 4\pi\mu_i.$$

For example, for microwave with $\lambda$ = 12.2 cm incident on aluminium, $\delta = 1.2$ µm. These are similar to skin depths, i.e. the attenuation depths of alternating currents of frequency $\omega$ in metals (see Fig. 1.4). **This explains why microwaves do not cross metals, e.g. a cell phone kept in a metal enclosure/almirah does not receive signal.**

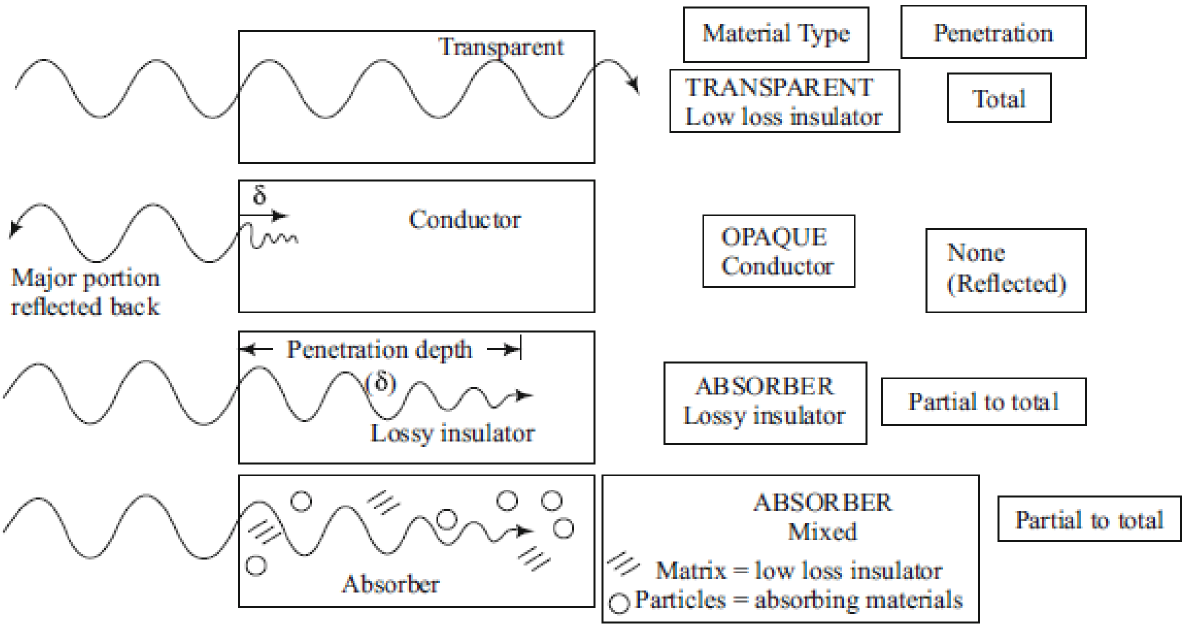



**Fig. 1.4** Interaction of microwaves with different materials

8. **Passive lumped components at microwave frequencies**

(a) **Wire and Resistor**

From conventional ac circuit analysis, we know that resistance $R$ is independent of frequency. Also that a low value of capacitor ($C$ = 1 pt) and inductor ($L$ = 1 pH) have very large reactance $(X_C = 1/\omega c = 3.18 \times 10^9\ \Omega \approx \infty)$ and very low reactance $(\omega_L = 3.14 \times 10^{-7}\ \Omega \approx 0)$ at 50 Hz (Fig 1.5).

As is well known that in a conductor, ac current density is highest at the surface and falls as we go close to the core. This current density falls to $1/\sqrt{2}$ value of the surface current density at a depth called skin depth ($\delta$), which is a function of frequency, conductivity, and permeability as:

$$\delta = 1\Big/\sqrt{\pi f \mu \sigma}$$

With ac charge flowing in the wire establishes an ac magnetic field around, which induces ac

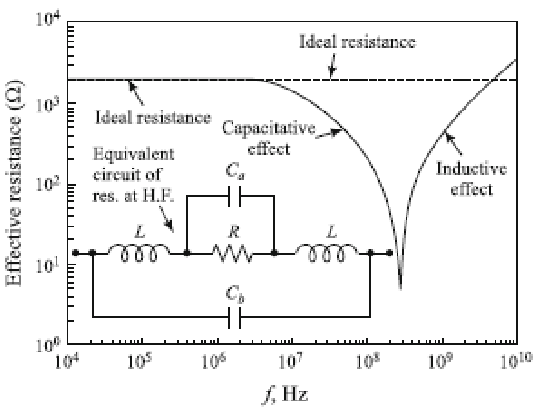



**Fig. 1.5** Equivalent circuit of a 2000 Ω resistor and its effective impedance as a function of frequency. At μw frequencies, it behaves like an inductance

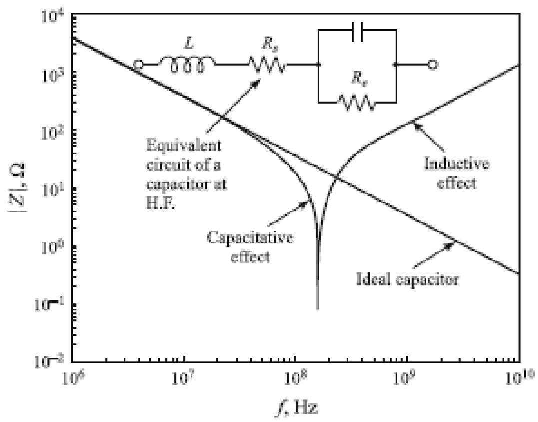
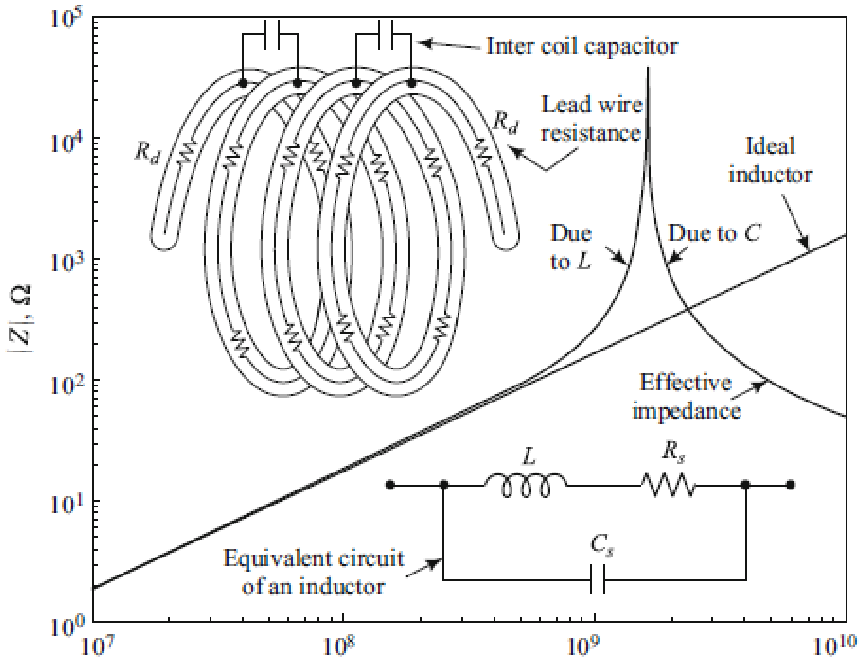



**Fig. 1.6** Equivalent circuit of a capacitor and its effective impedance as a function of frequency. At μw frequencies it also behaves more like an impedance

Fig. 1.7 Equivalent circuit of an inductor and its effective impedance as a function of frequency. At μw frequency, it behaves more like a capacitor




9. **Microwave heating mechanism:** Any dielectric (including water or food having water) get heated due to

   (i) Dipole relaxation loss/orientation loss
   (ii) Conduction loss.

Out of these two, the first one is most dominant in bipolar molecule, which is there in most of the dielectric and therefore they orient/oscillate like dumble as microwave propagates through it (see Fig. 1.8). The dielectric constant can be written as:

$$\varepsilon_d = \varepsilon_r + \varepsilon_i$$

conducting plasma (spark) along with formation of ozone plus nitrogen oxide, and both are unhealthy.

3. Direct exposure to human body is injurious and therefore should be avoided.

## Applications

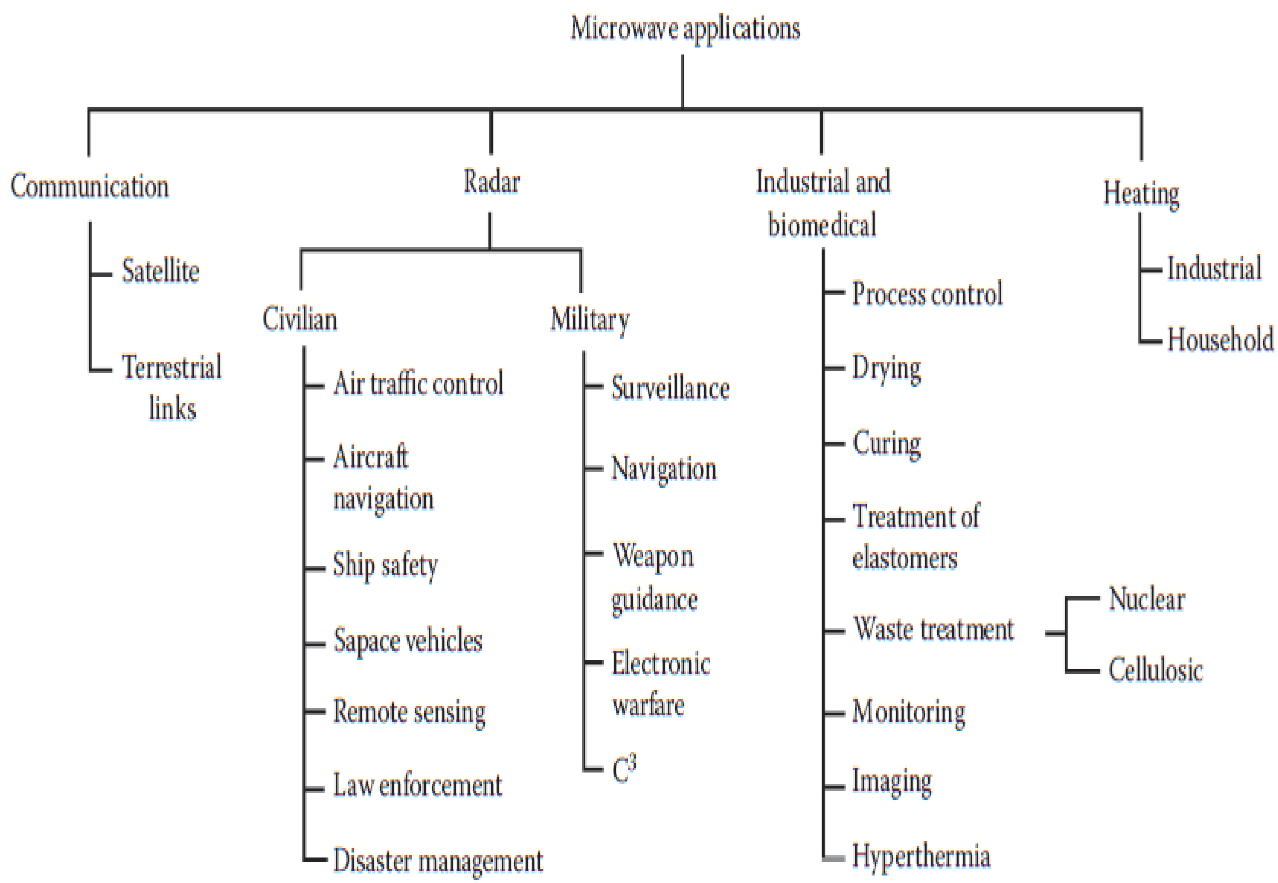



**FIGURE 1.2**
Applications of microwaves.

As illustrated in Figure 1.2, microwaves have a wide range of applications that encompass areas of communications, radars and navigation, home, industry, scientific research and the medical field. The frequencies allocated to industrial, scientific research and medical applications are 0.915, 2.45, 5.8, 10.525 and 20.125 GHz. The industrial control and measurement applications include (i) thickness measurement of metal sheets in rolling mills, (ii) continuous measurement of wire diameters, (iii) monitoring and measurement of moisture contents, (iv) motion sensors based on 'Doppler effect' and (v) applications based on thermal effects of microwaves. At microwave frequencies, skin depth in metals is very small, and a metal surface causes total reflection. Most of the measurements for industrial applications involve the determination of complex reflection and transmission coefficients. As the wavelength is small, the phase variations are quite rapid. Consequently, a small change in position or dimension gives rise to a significant phase change that can be detected and measured. Some of the applications noted above are further elaborated below.

### 1.5.1 Communication

Before the advent of optical systems, most of the long-distance communication systems were based on networks of microwave radio relay links including those of LOS, tropospheres and satellites. Wireless local area network (LAN) protocols, such as Bluetooth, IEEE 802.11 and IEEE 802.11a specifications use 2.4 and 5 GHz Industrial, Scientific and Medical (ISM) bands. Long-range wireless Internet access services (up to about 25 km) use 3.5–4.0 GHz range. The worldwide interoperability for microwave access (WIMAX) services operate at the 3.65 GHz band. Metropolitan area network protocols, such as WIMAX are based on standards such as IEEE802.16, designed to operate between 2 and 11 GHz. Commercial implementations are in the 2.3, 2.5, 3.5 and 5.8 GHz ranges. Mobile broadband wireless access protocols operate between 1.6 and 2.3 GHz to provide mobility and in-building penetration characteristics similar to mobile phones but with vastly greater spectral efficiency. Some mobile phone networks, such as Global System for Mobile (GSM), use the low-microwave/high-UHF frequencies around 1.8 and 1.9 GHz. Digital Video Broadcasting–Satellite services to Handhelds (DVB-SH) and Satellite-Digital Multimedia Broadcasting (S-DMB) use 1.452–1.492 GHz, while proprietary/incompatible satellite radio uses around 2.3 GHz for Digital Audio Radio Service (DARS).

Microwaves are used in telecommunication transmissions because of their short wavelengths. This aspect results in smaller but highly directional antennas and in larger bandwidths. Most satellite systems operate in the C, X, $K_a$ or $K_u$ bands of the microwave spectrum. These frequencies not only allow larger bandwidths but also avoid crowding of UHF frequencies and are still staying below the atmospheric absorption of EHF frequencies. Satellite TV either operates in the C band for the traditional large-dish fixed satellite service or $K_u$ band for direct broadcast satellite. Military communications primarily run over X or $K_u$-band links, with $K_a$ band being used for Minstar.

### 1.5.2 Radars

Microwave radiations are used to detect the range, speed and other characteristics of remote objects. Radars are also used for applications such as air traffic control, weather forecasting, navigation of ships and speed limit enforcement. Microwave techniques involving Gunndiode oscillator and waveguides are used in motion detectors for automatic door openers.

Table 1.3 summarises microwave applications in the areas of communication and radars. The corresponding band and frequency ranges (in gigahertz) are also given for most of these services. In view of this table, one can easily appreciate the importance of microwaves.

### 1.5.3 Radio Astronomy

Microwaves are used in most of the radio astronomy systems. In general, these systems observe the naturally occurring microwave radiations. Some active radar experiments have also been conducted with objects in the solar system to determine distances or mapping invisible objects.

### 1.5.4 Navigation

Microwaves are used in global navigation satellite systems including Chinese Beidou, American global positioning satellite (GPS) and Russian GLONASS in various frequency bands between 1.2 and 1.6 GHz.

### 1.5.5 Home Appliances

Microwave ovens using cavity magnetrons are the common kitchen appliances. A microwave oven passes (non-ionising) microwave radiations, at a frequency of about 2.45 GHz, through food. These result in dielectric heating by absorption of energy in water, fats and sugar contained in the food item. Water in the liquid state possesses many molecular interactions that broaden the absorption peak. In the vapour phase, isolated water molecules absorb at around 22 GHz, almost 10 times the frequency of the microwave oven.

### 1.5.6 Industrial Heating

Microwave heating is widely used in industrial processes for drying and curing the products.

### 1.5.7 Plasma Generation

Many semiconductor processing uses microwaves to generate plasma for purposes such as reactive ion etching and plasma-enhanced chemical vapour deposition. Microwave frequencies ranging from 110 to 140 GHz are used in stellarators and tokamak experimental fusion reactors to heat the fuel into a plasma state. The upcoming International Thermonuclear Experimental Reactor (ITER) is expected to range from 110 to 170 GHz and will employ electron cyclotron resonance heating.

### 1.5.8 Weaponry System

Less-than-lethal weaponry exists that uses millimetre waves to heat a thin layer of human skin to an intolerable temperature so as to make the targeted person move away. A 2-s burst of the 95 GHz focussed beam heats the skin to a temperature of 130°F (54°C) at a depth of 0.4 mm. The United States Air Force and Marines currently use this type of active denial system.

### 1.5.9 Spectroscopy

Microwave radiation is used in electron paramagnetic resonance spectroscopy, in X-band region (~9 GHz) in conjunction with magnetic fields of 0.3 T. This technique provides information on unpaired electrons in chemical systems, such as free radicals or transition metal ions. The microwave radiation can also be combined with electrochemistry as in microwave-enhanced electrochemistry.

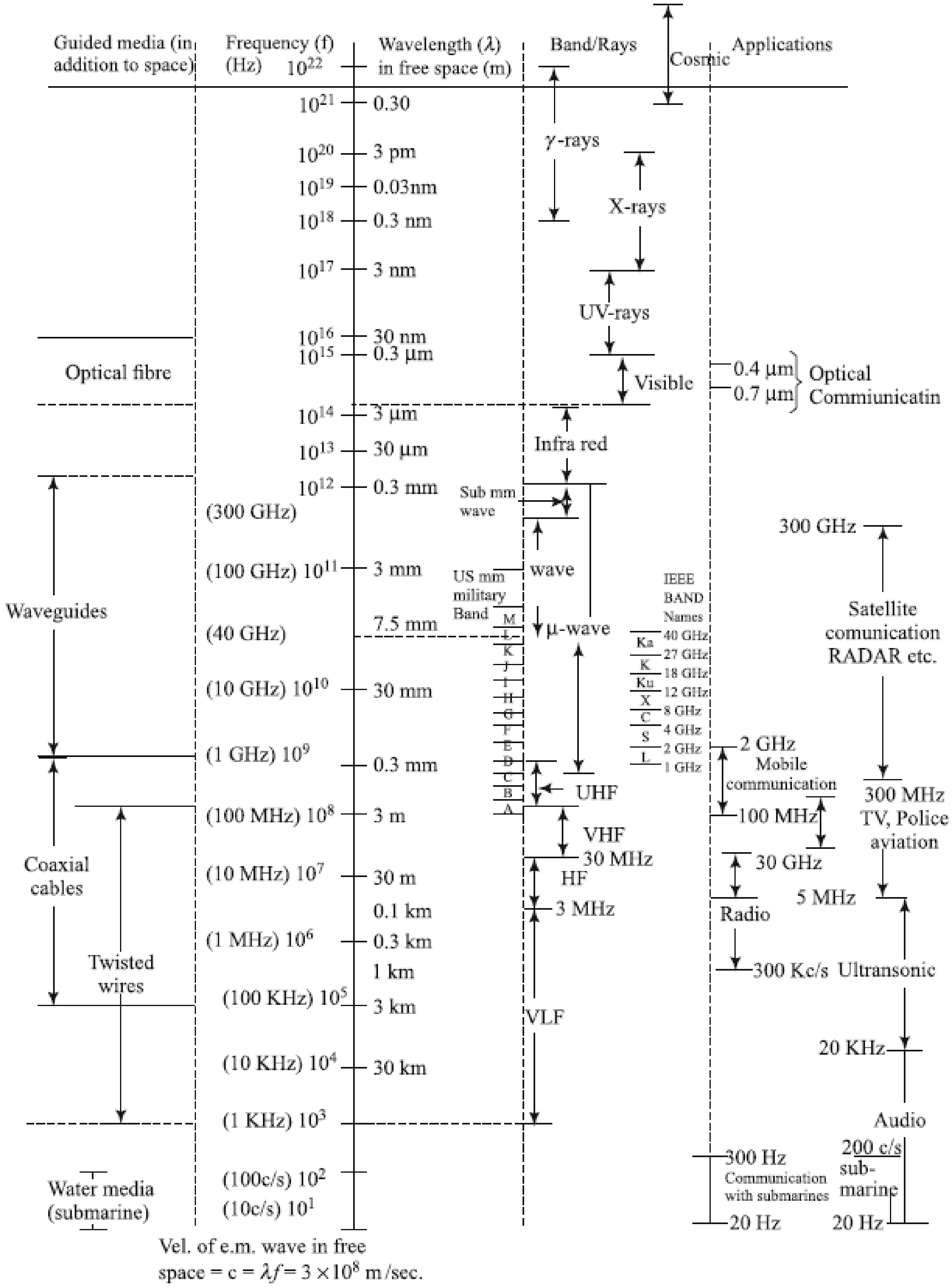



**Fig. 1.2** Frequency spectrum: audio and EM waves: frequency, bands, guided media, and applications