1

Introduction to Microwaves

1.1 Microwaves and Electromagnetic Radiation

Electromagnetic (EM) *radiation* is a form of energy radiated in the form of a wave traveling at the speed of light, comprising both electric and magnetic fields that oscillate at right angles to each other and in the direction of propagation. The propagation of an electromagnetic wave is illustrated in Figure 1.1.

The electromagnetic theory was first presented by James Clerk Maxwell (see Figure 1.2) on 8th December 1864 to the Royal Society of London, and in the following year his key paper entitled 'A Dynamical Theory of the Electromagnetic Field' was published in the *Philosophical Transactions of the Royal Society of London.* In his original paper, Maxwell presented 20 equations involving 20 variables which were later simplified into the four equations for electromagnetic theory (Maxwell's equations). In the paper, he wrote [1]:

> 'The theory I propose may therefore be called a theory of the *Electromagnetic Field*, because it has to do with the space in the neighbourhood of the electric or magnetic bodies, and it may be called *Dynamical* Theory, because it assumes that in that space there is matter in motion, by which the observed electromagnetic phenomena are produced.
>
> The electromagnetic field is that part of space which contains and surrounds bodies in electric or magnetic conditions.
>
> . . ..
>
> The velocity is so nearly that of light, that it seems we have strong reason to conclude that light itself (including radiant heat, and other radiations if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws.'
>
> *Maxwell, 'A Dynamical Theory of the Electromagnetic Field,' 1864*

Generally, EM radiation is classified by the wavelength (in order of decreasing wavelength and increasing frequency) into radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays, as shown in Figure 1.3.

Microwaves and Metals Manoj Gupta and Wong Wai Leong Eugene

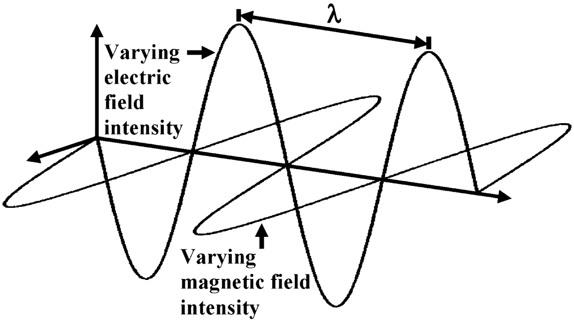


Figure 1.1 Schematic representation of an electromagnetic wave

Microwaves form part of the EM spectrum with frequencies ranging from 300 MHz to 300 GHz and wavelengths of 1 m to 1 mm respectively. The term *micro-wave* was first coined by A.G. Clavier in a paper published in 1931 by the International Telephone and Telegraph to describe the propagation of an 18 cm wavelength radio link from Dover, UK to Calais, France [2]. In another paper by Clavier in 1933, the term *microwave* was used to refer to wavelengths of about 0.5 m.

Microwaves can be further classified into three bands: the Ultra High Frequency (UHF) band with frequencies ranging from 300 MHz to 3 GHz, the Super High Frequency (SHF) band with frequencies ranging from 3 to 30 GHz and the Extremely High Frequency (EHF) band with frequencies ranging from 30 to 300 GHz.

1.2 Development of Microwaves

In 1831, Faraday discovered electromagnetic induction. Maxwell began working on Faraday's concept on the lines of force in his mid-20s, and in 1864, he proposed the theory of electromagnetics [2]. The electromagnetic field theory proposed by Maxwell predicted the presence of invisible electromagnetic waves, and in the late 1880s, the German scientist Heinrich Hertz first demonstrated the presence of the invisible electromagnetic waves with a

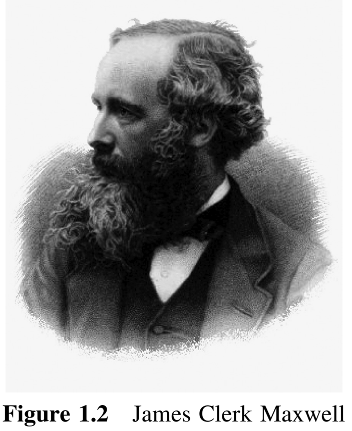


Figure 1.2 James Clerk Maxwell

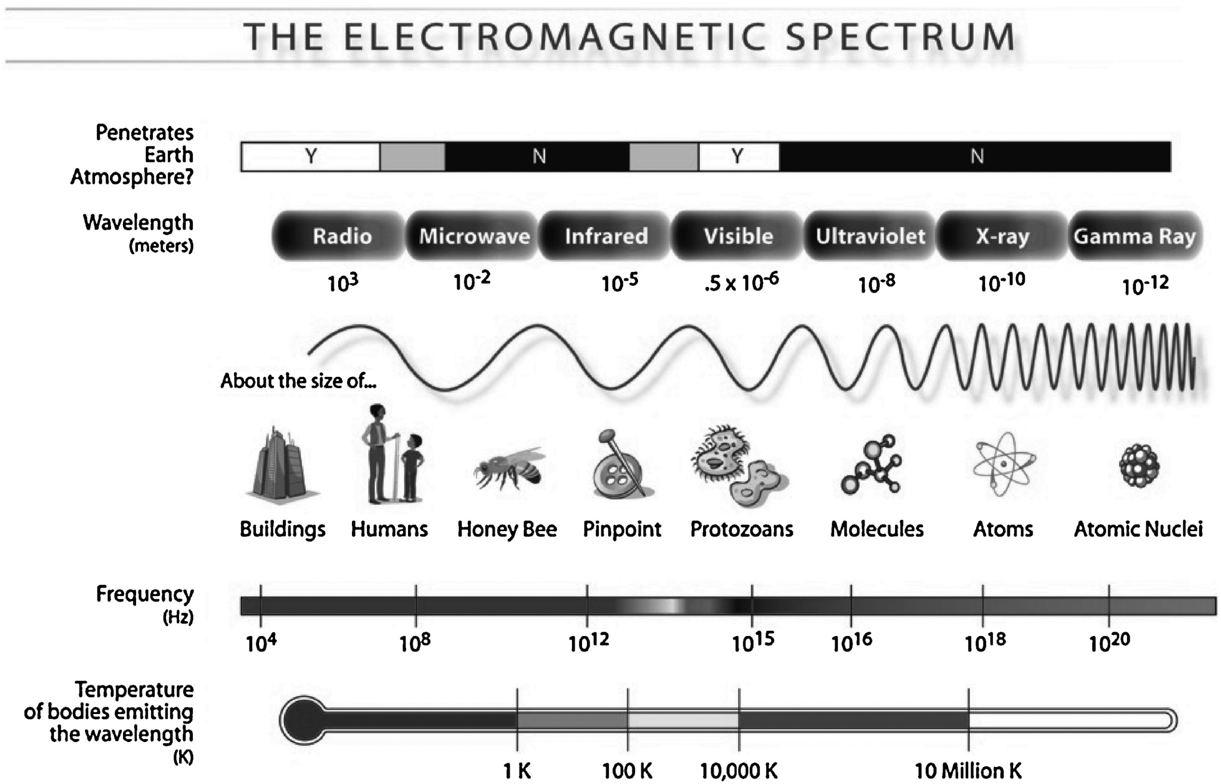


Figure 1.3 The electromagnetic spectrum (image courtesy of NASA)

wavelength longer than that of light. He demonstrated the reflection of radio waves from objects using apparatus that consisted of a spark-gap generator that excited a dipole and a parabolic cylinder antenna operating at a microwave frequency of approximately 450 MHz [3].

In the 1890s, the Indian physicist Jagadish Chandra Bose extended Hertz's experiment using an improved apparatus at higher frequencies ranging from 60 to 120 GHz.

From 1900 to the 1930s, investigations into microwaves led to the development of basic radar concepts. However, the rapid development of microwave technology came during World War II with the urgent need to improve radar detection of enemy aircraft and submarines and the invention of the high-power cavity magnetron. Rapid advances made in the research and development of microwave radar and associated technologies that emerged during the war are well documented in the M.I.T Radiation Laboratory Series [4]. Additionally, the important milestones in the development of microwave technology from the 19th century to 1980 are summarized in an article by Sobol and Tomiyasu published in *IEEE Transactions of Microwave Theory and Techniques* [2].

1.3 Applications of Microwaves

Since their rapid development during World War II, microwaves have been expanded to numerous applications in addition to radar and communication. Existing applications of microwaves are summarized in Table 1.1.

1.3.1 Microwave Heating/Processing of Materials

Microwaves are being used for their ability to heat materials. The most common application of microwave heating is the domestic microwave oven illustrated in Figure 1.4, where it is used to heat and cook food. In industry, microwave heating has been applied to bacon cooking, tempering of frozen meats, processing of potato chips and vulcanization of rubber [5–8].

The use of microwaves for the processing of organic materials and inorganic materials such as polymers, ceramics and minerals has been widely reported [5–8].

Microwave processing systems usually consist of a microwave source for the generation of microwaves, an applicator to deliver the power to the material and a control system for the monitoring and regulation of power to the material. The most common type of microwave generator used is the magnetron, which is explained in Section 1.5. Microwave applicators include multimode, where multiple modes are sustained simultaneously inside the cavity, and single mode, where only a single mode is sustained. The heating of materials is controlled by variations in the power and duration of microwave radiation on the materials.

Table 1.1 Summary of microwave applications

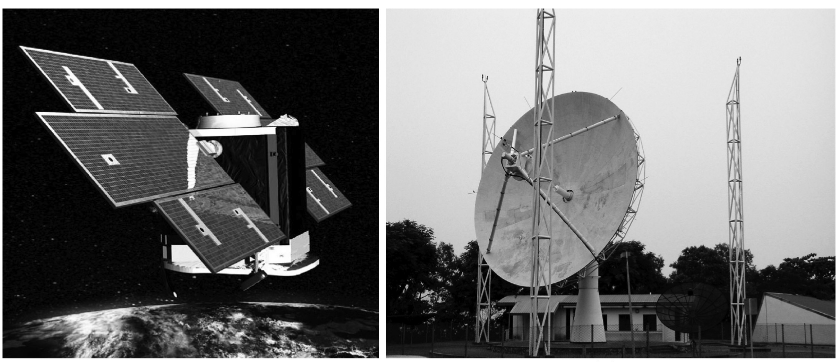
• Microwave heating	• Communication
• Radar detection	• Navigation
• Electronic warfare	• Medical
• Scientific	• Industrial
• Power transmission	• Weather control

Figure 1.4 A typical domestic microwave oven

Further details on microwave heating/processing of materials will be covered in the subsequent chapters of this book.

1.3.2 Communications

Microwaves are used extensively in satellite communication for the transmission of signals and information because of their ability to penetrate Earth's atmosphere with minimum losses, high frequency and short wavelength [9, 10]. The high frequency of microwaves provides a greater bandwidth capability so that more information can be transmitted within the bandwidth. For example, when using an AM radio signal with a carrier frequency of 1000 kHz to transmit audio information contained over a bandwidth of 40 kHz, it will take up 4 % of the carrier, while the use of a 10 GHz microwave signal with a 10 % bandwidth system can provide a bandwidth of 1 GHz that will allow transfer of more information such as AM and FM radio signals, shortwave radio, broadcast television, telephone calls and computer digital data simultaneously [9, 10]. The short wavelength of microwaves allows high-gain antennas with narrow beamwidth to be constructed for use in radar applications, since antenna gain is proportional to the square of the operating frequency. Information from spacecraft is transmitted at microwave frequencies and received by huge antennae on Earth, as shown in Figure 1.5.



(a) **(b)**

Figure 1.5 A satellite communication system consisting of (a) a space satellite (image courtesy of NASA/JPL-Caltech) and (b) a ground (or earth) station for transmitting or receiving signals

Microwave technologies have revolutionized the communication and transfer of information in the modern world. Examples include:

- ‘*Live*’ ***telecasts of television news and events around the world.*** We can now enjoy the luxury of watching real-time news coverage as it unfolds, the performance of athletes in the Olympic Games and winners of the Oscar Academy Awards instantaneously, regardless of our geographical location. All these are made possible with the direct transmission of television broadcast signals in the microwave frequency using satellites.
- ***Cable TV***, ***Internet and telephone calls using coaxial cables.*** In traditional television broadcasting using radio waves, a television antenna is required and separate telephone lines are required for Internet and telephone calls. Since cable television signals use only a portion of the bandwidth available over coaxial lines, other digital services such as broadband Internet and cable telephony can also be used simultaneously.
- ***Telecommunication.*** The Global System for Mobile Communications (GSM) mobile phone networks and cordless telephones operate in the microwave frequency. Most GSM networks operate at 900 MHz or 1800 MHz and in parts of the USA and Canada, 850 MHz and 1900 MHz are also used. According to the GSM association, the GSM network is used by 2 billion users across more than 210 countries as of June 2006, with China being the largest single GSM market in the world with more than 370 million users [11]. Cordless telephones used at home also operate at the common microwave frequencies of 2.4 GHz and 5.8 GHz.
- ***Audio and video conferencing.*** Multi-party communication spanning different continents is possible with the use of modern satellite communication. Companies are able to hold meetings and discussions using video conferencing. People are able to see and talk to their loved ones or friends, watch TV and video and access the Internet using a mobile phone with the latest 3GSM technology.
- ***Wireless local area networks*** (***LANs***). LAN transmits information using the 2.4 GHz and 5 GHz frequency bands. Currently, the major wireless LAN standard is the IEEE 802.11 (or Wi-Fi). Wireless base stations (access points) are wired to an Ethernet network and are capable of transmitting over an area of several hundred feet through walls and other nonmetal barriers, allowing a user with a wireless Wi-Fi adapter to connect to the Internet. An illustration of a wireless LAN is shown in Figure 1.6. Wi-Fi connectivity is incorporated into many modern electronic products to wirelessly connect different

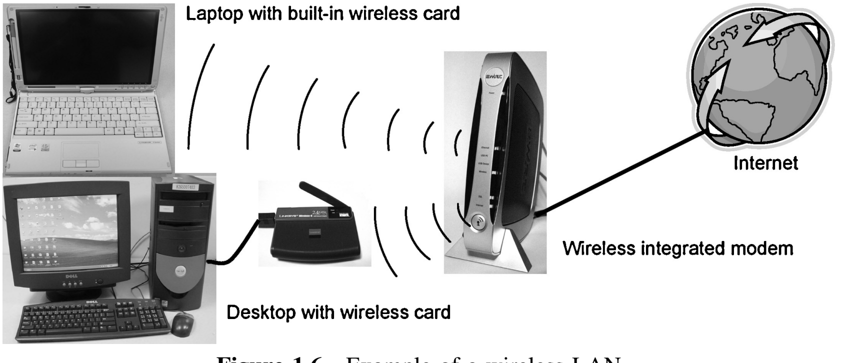


Figure 1.6 Example of a wireless LAN

Figure 1.7 Examples of Bluetooth-enabled devices such as mobile phones, hands-free kits and laptops

electronic gadgets such as computers, printers, mobile phones and digital cameras without the need for cables or wires.

- ***Bluetooth technology.*** This also makes use of the 2.4 GHz microwave frequency for the transmission of information over short distances between devices, gradually replacing traditional infrared transmission (IrDA), which is used for very short distances just between two devices but requires line of sight. Current Bluetooth applications include computer peripherals such as printers, keyboards and mice, mobile phones and hands-free devices and also the latest Sony Playstation 3, where Bluetooth technology is used as an interface for its wireless controllers. Examples of Bluetooth devices are shown in Figure 1.7.
- ***Space exploration.*** The ability of microwaves to penetrate Earth's ionosphere and travel in space makes them the natural choice for space exploration communications. Pictures, video and information of distant planets and stars captured by satellites and space shuttles are sent using microwaves back to Earth. Currently, the most distant man-made object in the universe is the Voyager 1 spacecraft (illustrated in Figure 1.8), which was launched more than 25 years ago on 5th September 1977. As of 13th January 2006, the spacecraft

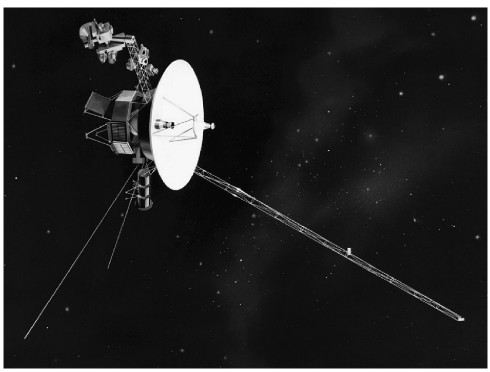


Figure 1.8 Voyager spacecraft (image courtesy of NASA/JPL-Caltech)

was 9.1 billion miles from the Sun (about 98 AU) and traveling at a speed of 3.6 AU per year [12]. One 'AU' equals the distance between the Sun and Earth, or 93 million miles. At that distance, a microwave signal sent from one of NASA's deep space network antennae on Earth, traveling at the speed of light towards Voyager 1 will require about 13 hours and 39 minutes to reach Voyager 1's receiver and vice versa.

1.3.3 Radio Detection and Ranging (Radar)

Radar is a method of determining the presence, location, velocity and other characteristics of a target through the use of equipment that operates at microwave frequencies. A microwave signal is transmitted by radar and is reflected from the target/object back to the radar. The reflected signal is compared with the transmitted signal to determine the velocity, range, azimuth, elevation and shape of the target/object. Originally developed for military applications, the Global Positioning System (GPS) is a well-known example of the use of radar in navigation. Table 1.2 lists the different applications of radar and its function [3, 8–10] and Figures 1.9–1.14 illustrate some of the applications of radar.

Table 1.2 Applications of radar

Radar application	Usage
Search and rescue	Emergency beacon to aid in locating and rescuing aircraft, vessels and people in distress.
Air traffic control	Provide location, speed, identification and guidance of planes in and out of an airport.
Radar altimeter	Measures an aircraft's true height above ground.
Air and missile defense	Surveillance and identification of enemy aircraft or missiles and deployment of weapons against them.
Missile guidance	Control the flight of a ballistic missile to the target.
Land warfare	Battlefield surveillance, detection and location of mortar and artillery and mine detection.
Naval surface warfare	Surface surveillance, antisurface and antisubmarine warfare and navigation.
Marine	For collision avoidance, navigation and tracking purposes.
Navigation and tracking	Provide information on directions and locations and tracking of people, vehicles, ships and aircraft.
Automotive	Electronic parking payment and tolls, sensors for vehicular collision avoidance, blind-spot detection and cruise control.
Police and Sports	Speed detection.
Security	Detection of intruders and protection of buildings and homes.
Remote sensing and mapping	Provide terrain and geographical maps of the ground, information on fire outbreak, pollution, ice mapping and the ozone layer.
Weather	Monitor and provide information on precipitation, wind speed and cloud formation.
Environmental studies	Tracking of endangered species and migratory patterns of animals, fish and birds.
Space exploration	Study of distant stars and planets.

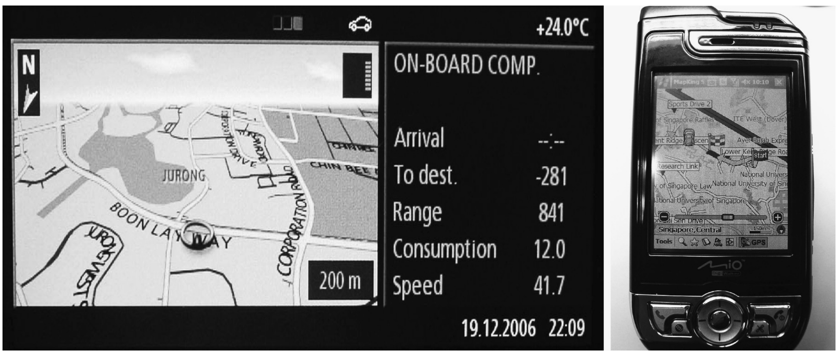
Figure 1.9 Schematic representation of the Search And Rescue Satellite Aided Tracking (SARSAT) System operating at a frequency of 406 MHz to detect and locate aircraft, shipping vessels and people in distress (image courtesy of NOAA-SARSAT)

1.3.4 Electronic Warfare

Electronic warfare involves the use of techniques to reduce the effectiveness of an enemy's radar and electronic equipment and to enhance the survivability of one's own forces through control and manipulation of electromagnetic energy. It can be classified into electronic attack, electronic protection and electronic support.

Figure 1.10 Electronic Road Pricing (ERP) gantry in Singapore

Figure 1.11 PATRIOT surface-to-air guided missile (SAM) system (image courtesy of White Sands Missile Range Historical Foundation)



(a) (b)

Figure 1.12 (a) In-built vehicular and (b) handheld GPS navigational aid

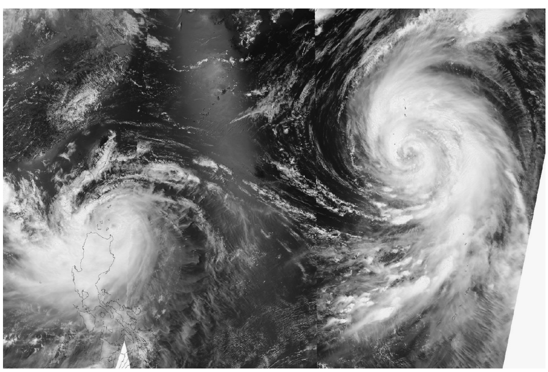


Figure 1.13 Typhoon formation over the Pacific Ocean in June 2004 (image courtesy of NASA)

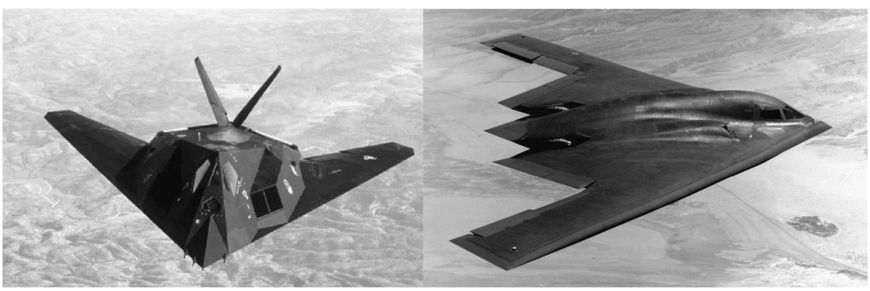
Figure 1.14 Satellite image of Singapore, Batam island and parts of Malaysia (image courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center)

Electronic support makes use of radar to gather information and provide surveillance, detection, identification and warning for accurate assessment.

Electronic attack involves the use or manipulation of electromagnetic energy to reduce the effectiveness of the enemy's radar and devices that use electromagnetic energy to destroy or incapacitate enemy forces.

Electronic protection aims to protect against enemy electronic attack and support. Examples include [10]:

- ***Stealth technology.*** Aircraft, ships, missiles and vehicles are specially designed to reduce the amount of microwave power they reflect, or to absorb it totally. Examples of stealth aircraft are shown in Figure 1.15.
- ***Noise and deceptive jamming.*** The intentional emission of microwave signals to attempt to camouflage the presence of targets or to mislead the enemy by the transmission of false information by altering the original signal.
- ***Chaff.*** Countermeasure used by aircraft, ships or vehicles by spreading large numbers of thin metal foils over an area to create false secondary targets by reflecting the microwave signal back to the radar in order to distract radar-guided missiles.



(a) **(b)**

Figure 1.15 (a) F-117 Nighthawk attack aircraft and (b) B-2 Spirit bomber (images courtesy of United States Air Force)

Figure 1.16 ADS system (images courtesy of Joint Non-Lethal Weapons Directorate)

- ***Decoys.*** Countermeasure used to distract radar-guided missiles by amplifying and transmitting the signal back to the radar.
- ***Anti-radiation missiles.*** A radar-guided missile which homes in on the microwave signal transmitted by radar.
- ***Nonlethal weaponry.*** Microwave bombs create a short and intense electromagnetic pulse (EMP) which generates a transient surge of thousands of volts capable of disabling all electronic devices within range. The latest development in microwave weaponry is the Active Denial System (ADS) shown in Figure 1.16 [13] developed by the US military, which operates at a frequency of 95 GHz and uses a directional planar array antenna to emit a nonionizing electromagnetic beam of energy that penetrates approximately 0.5 mm into human skin tissue, where nerve receptors are concentrated. Within seconds, the beam will heat the exposed skin tissue to a level where intolerable pain is experienced, which will immediately cease once the target moves out of the beam or when the beam is turned off.

1.3.5 Medical Applications

Microwaves are used in medical applications for their ability to create intense heat and as a power source in medical equipment for radiology treatment. In radiation therapy, microwaves are used as a power source to accelerate electrons to high energy in a medical linear accelerator and the electrons are then directed to collide with a metal target [10]. Upon impact, electrons are displaced from the atomic shells of the target metal and X-rays are emitted. The high-energy X-rays are used in cancer treatment to destroy the cancer cells. Figure 1.17 shows a schematic diagram of a typical medical accelerator used in cancer treatment.

Microwaves can also be used in the hyperthermia treatment of cancer by raising the temperature of the cancerous tissue to kill it [8, 14]. This treatment exposes the body tissue to high temperatures up to 44 °C, with minimal injury to the surrounding healthy tissue. Cancerous regions are usually characterized by regions of low oxygen content in tissues and low pH due to insufficient blood flow, which makes the cancer cells particularly sensitive to temperatures between 40 and 44 °C. During hyperthermia treatment, the reduced blood flow in tumor tissue causes it to heat more easily than normal tissue. The effect of the heat causes damage and death to the cancer cells, probably due to protein denaturation observed at temperatures $> 40\,^{\circ}C$ leading to alterations in the cell molecular structure and enzyme

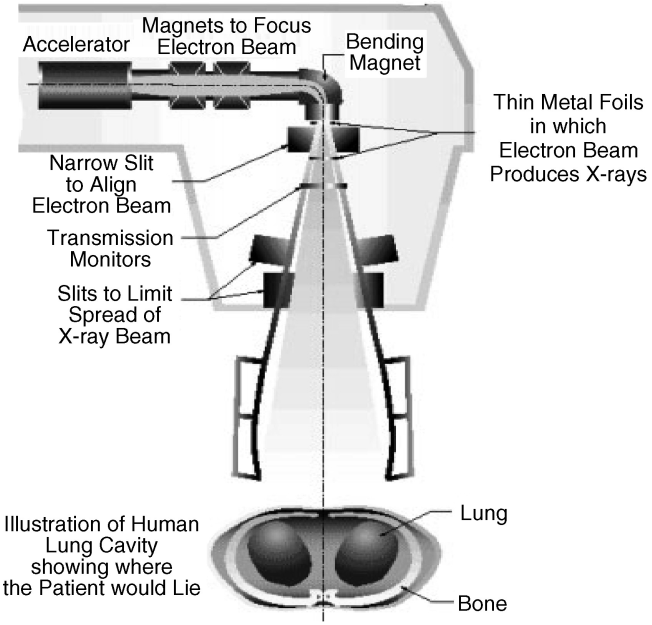


Figure 1.17 Schematic of a typical medical linear accelerator used for cancer treatment (reproduced by permission of Stanford Linear Accelerator Center)

complexes. Hyperthermia treatment is frequently used in combination with either radiotherapy or chemotherapy.

Microwaves are also used to treat atrial fibrillation [15], a cardiac condition caused by the irregular and rapid beating of the upper two chambers of the heart. By placing a special microwave ablation catheter on the heart, a surgeon can heat the irregularly beating muscle to create lesions to block the conduction of abnormal electrical beats and restore the normal heartbeat. Microwave ablation is a much faster and safer method of surgery for treating atrial fibrillation which involves making small incisions on the patient's chest, and the entire surgery can be completed in a few hours.

Microwaves used in magnetic resonance imaging (MRI) show promising application in the detection and location of tumors, for example, in the detection of breast cancer, due to the difference in dielectric properties of cancer tissues and normal breast tissue at microwave frequencies [8, 16]. Microwaves provide several advantages over traditional X-ray mammography such as the use of nonionizing radiation: they are able to detect smaller tumors and no breast compression is required.

Active research is on-going to enhance the capability of detection of cancer using microwaves.

1.3.6 Scientific Applications

Scientific applications include the measurement of microwave radiation from objects in astronomy, chemistry and biological studies, linear accelerators and nuclear research.

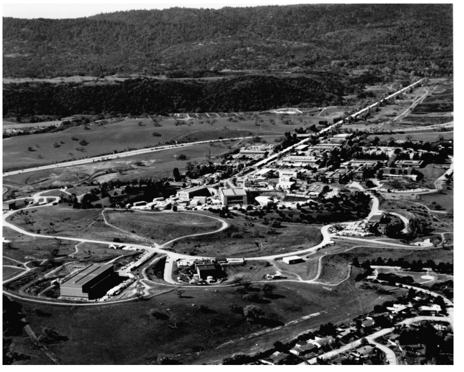


Figure 1.18 Aerial view of Stanford Linear Accelerator Center (reproduced by permission of Stanford Linear Accelerator Center)

In radioastronomy, astronomers measure the microwave radiation from stars and galaxies in outer space in order to understand their formation and their composition. Astronomers use antennae to capture electromagnetic radiation emissions from astronomical objects and convert these to pictures.

Microwaves have been used to significantly accelerate and enhance chemical synthesis and reactions. Microwave-accelerated organic synthesis is receiving widespread adoption in pharmaceutical, life science and chemical research. Other chemical applications of microwaves include microwave absorption spectroscopy, nuclear magnetic resonance spectroscopy and electron spin resonance spectroscopy [8].

Linear accelerators use microwave power generated by a klystron for high energy physics research. At the Stanford Linear Accelerator Center (see Figure 1.18), microwaves provide energy to accelerate the electrons along the two-mile accelerator structure with one klystron every forty feet.

Microwaves are used in the heating of plasma to extremely high temperatures for nuclear fusion research. Microwave-producing gyrotrons are used worldwide in almost every controlled fusion installation to heat plasma to the immense energies required for nuclear fusion. Nuclear fusion possesses many advantages such as the release of more energy than nuclear fission, easy availability of fuel and environmental friendliness with no hazardous waste or by-products produced. ITER is an international project involving The People's Republic of China, the European Union and Switzerland, India, Japan, the Republic of Korea, the Russian Federation and the United States of America in the development of a nuclear fusion reactor capable of operating at over 100 million degrees Celsius and producing 500 MW of fusion power at Cadarache, France at a cost of over $3500 million over 20 years [17]. Figure 1.19 shows the schematic of the ITER nuclear fusion reactor.

1.3.7 Industrial and Commercial Applications

One of the industrial applications of microwaves can be found in semiconductor processing techniques, where microwaves are used to generate plasma for reactive ion etching and plasma-enhanced chemical vapor deposition (CVD) [6]. Microwave discharge lamps are used for

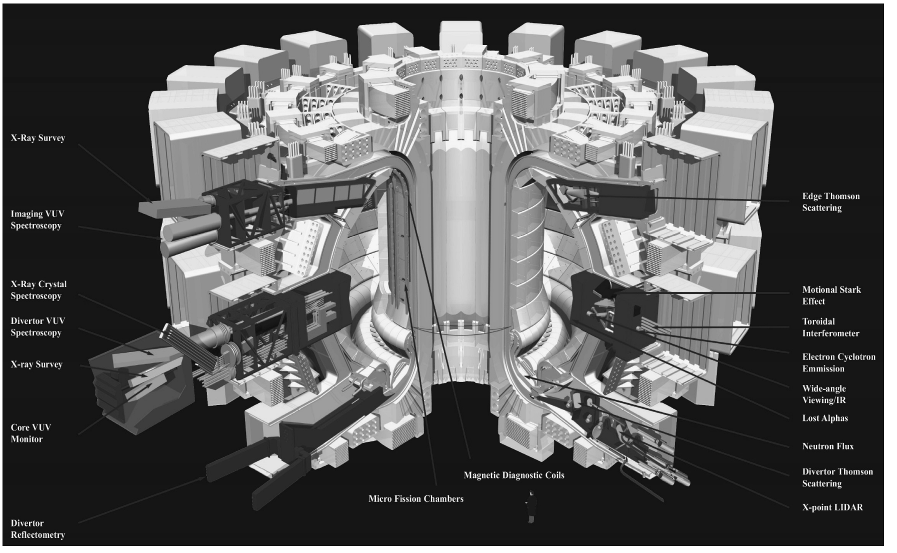


Figure 1.19 ITER nuclear fusion reactor (reproduced by permission of ITER)

curing purposes because of their efficient production of ultraviolet light with less infrared radiation and heating than conventional UV sources [5].

A major commercial application of microwaves is in the security sector. Currently, microwaves are employed in intrusion detection and perimeter protection of key facilities such as nuclear power plants, airports, prisons, military bases and important government and industrial buildings. Increasing concerns and legislation in transportation security due to recent terrorist threats have fueled research in microwaves for security equipment. Conventional metal detectors used to check passengers at airports are limited in that they can only detect metal objects. Other security technologies, such as X-ray imaging used to screen luggage, are unsuitable for checking people because of their use of ionizing radiation. New detection equipment has been developed that uses microwaves to detect and identify suspicious objects (metallic and nonmetallic) hidden under clothing. Figure 1.20 shows the new security imaging system using microwaves developed by Smiths Detection.

Perhaps the most common commercial application lies in the use of microwaves for identification and tracking purposes. Radio frequency identification (RFID) is the combination of radio technology and radar and was first used in the 1960s for the tracking of nuclear and other hazardous materials [18]. An RFID system typically consists of two main components:

1. A transponder or tag to contain the data, which is usually placed on or attached to the object to be identified, as shown in Figure 1.21. The tag may contain an electronic microchip and a microwave antenna.
2. A reader to read the transmitted data from the tag.

Frequencies currently used are typically 125 kHz (low frequency), 13.56 MHz (high frequency), or 800–960 MHz (ultra high frequency). Tags in the microwave (UHF) frequency bands provide a greater range for detection than tags in the lower frequencies.

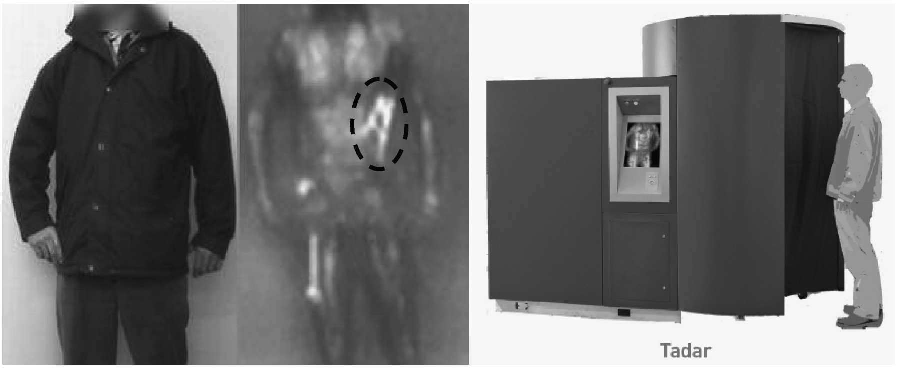


Figure 1.20 New Tadar security imaging system developed by Smiths Detection that can reveal all concealed objects on a person, including nonmetallic objects, by the use of a millimeter-wave camera (reproduced by permission of Smiths Detection)

Recent developments in technology have allowed for the development of low-cost, miniature and intelligent RFID tags. RFID is applied in electronic road tolls and parking, contactless smart cards for fare payment on mass transit systems, security and personal identification cards, car immobilizers, library systems, transport and logistics management and many other applications [18]. RFID serves as a replacement for the current bar code scanners used to track products and shipments because it does not require line-of-sight access to read the tag, it provides a larger detection range than that of a bar code reader, it allows simultaneous communication with multiple RFID tags by readers and has the ability to store more information within the tag. Figure 1.22 illustrates some devices that employ the use of RFID.

Microwaves are also used for the nondestructive testing (NDT) of different materials for inspection purposes and to determine reliability. Crack or void detection within the materials is evaluated by comparison of the differences in reflected wave intensity between materials with cracks/voids and without cracks/voids. The current and potential applications of microwave NDT techniques have been summarized in Table 1.3 [19].

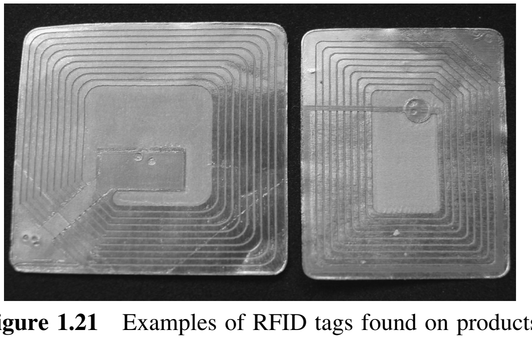


Figure 1.21 Examples of RFID tags found on products

(a) (b) (c)

Figure 1.22 Examples of RFID devices: (a) car keys containing a passive tag, (b) an EZ-link card for payment of fares on public transport in Singapore and (c) an RFID card access system

Table 1.3 Examples of applications of microwave NDT techniques

Composite inspection

- Accurate measurement of thickness for coatings and various dielectric materials.
- Detection and measurement of defects and flaws in composites.
- Identification of rust and corrosion under paint and composite coatings.
- Determination of the orientation of fiber and breakage in reinforced composites during production and in actual service.

Dielectric material characterization

- Accurate characterization of the dielectric material property.
- Determination of porosity in dielectric materials.
- Determination of curing level in chemically reactive materials.
- Correlation of electrical properties of materials to their physical and mechanical properties.

Metal surface inspection

- Detection of stress-related fatigue cracks and process-related flaws on the surface of metals.
- Determination of crack size and crack tip.
- Detection of obscured and sub-surface cracks.
- Evaluation of roughness of metal surface.

Microwave imaging

- Imaging of localized and distributed interior and surface flaws.

Industrial applications

- Moisture and humidity detection in timber, wood, textiles, grains, foods, etc.
- Inspection of concrete.
- Evaluation of water-to-cement ratio for cement, mortar and concrete.
- Detection of buried objects.

Table adapted from [19] with kind permission of Springer Science and Business Media.

1.3.8 Potential Applications

Many potential applications of microwaves are envisioned due to their unique properties. The potential uses of microwaves in waste remediation of hazardous materials, regeneration and recovery have been reported [6, 7]. Another potential application of microwaves is in mineral processing [20]. Due to the selective heating of various minerals by microwaves, microwaves can be applied in selective mineral liberation, leaching/extraction, phase transformation of minerals and enhancement of magnetic and electrical separation. Research has shown the enhancement in extraction of gold, iron, zinc and titanium using microwaves and desulphurization of coal for cleaner combustion.

One possible future use of microwaves that has generated much interest is the use of microwaves for power transmission and solar-powered satellites [5, 21]. It was demonstrated at the JPL Goldstone facility in the Mojave desert, USA that 30 kW of microwave power can be transmitted over 1.6 km and converted to dc power with an efficiency of 84 %. An artist's impression of future microwave power transmission using a solar-powered satellite is illustrated in Figure 1.23. Active research on microwave power transmission has also been carried out in Japan, Russia, France, Canada and Germany.

It is also envisioned that microwaves can be used to control the intensity and alter the path of hurricanes by heating the air around a hurricane using an array of solar-powered satellites [22].

Also, it has been proposed that microwaves could provide energy for future space transportation. Research on nuclear fusion-powered engines and microwave-powered spacecraft is being developed. The Microwave Lightcraft concept (shown in Figure 1.24) developed by NASA is powered by microwaves beamed from an orbiting solar-powered satellite to the lightcraft. The energy received breaks air molecules into a plasma and a magnetohydrodynamic fanjet provides the lifting force.

The applications of microwaves in various sectors are enormous and continue to expand with improvements in technology and a deeper understanding of the different attributes of microwaves. In the modern digital world, microwaves will continue to play a vital role in shaping our way of life.

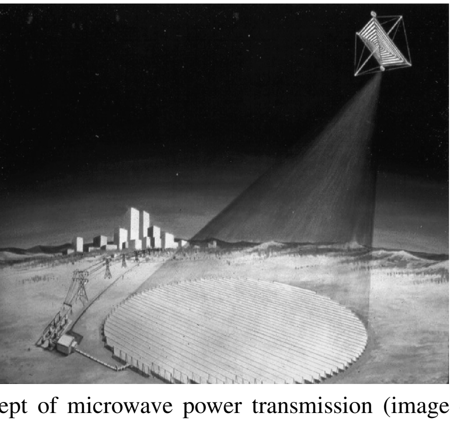


Figure 1.23 Artist's concept of microwave power transmission (image courtesy of Space Studies Institute)

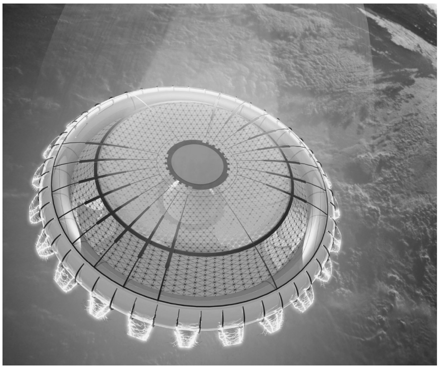


Figure 1.24 Microwave Lightcraft concept (image courtesy of NASA Marshall Space Flight Center)

1.4 Frequency Allocation

Although microwave frequencies range from 300 MHz to 300 GHz, most of the frequencies are restricted to government usage, leaving only a limited range of frequencies available for commercial and domestic usage. The International Telecommunication Union (ITU) operating within the United Nations System provides the basic framework that is relevant for the international radio-regulatory arrangement. Regulatory authorities for different countries utilize the international table of frequency allocations of the ITU as a guideline to release certain bands termed as industrial, scientific and medical (ISM) bands for unregulated usage. The majority of common electronic equipment operates at the unregulated ISM bands of 915 MHz, 2.45 GHz and 5.8 GHz. The permitted ISM bands according to the ITU are listed in Table 1.4.

Table 1.4 Permitted ISM bands in microwave frequencies

ISM frequency	Tolerance	Wavelength (cm)	Region applicable
433.92 MHz	± 0.87 MHz	69.09	Region 1
896 MHz	± 10.0 MHz	33.46	UK only
915 MHz	± 13.0 MHz	32.77	Region 2
2450 MHz	± 50.0 MHz	12.24	Worldwide
5800 MHz	± 75.0 MHz	5.17	Worldwide
24 125 MHz	± 125.0 MHz	1.24	Worldwide
61.25 GHz	± 250.0 MHz	0.49	Worldwide
122.50 GHz	± 500.0 MHz	0.24	Worldwide
245.00 GHz	± 1.0 GHz	0.12	Worldwide

Wavelength computed based on: speed of light ($\approx 3 \times 10^8$ m/s) = frequency $\times$ wavelength.
Region 1 includes Europe and parts of Asia.
Region 2 includes the Western hemisphere.

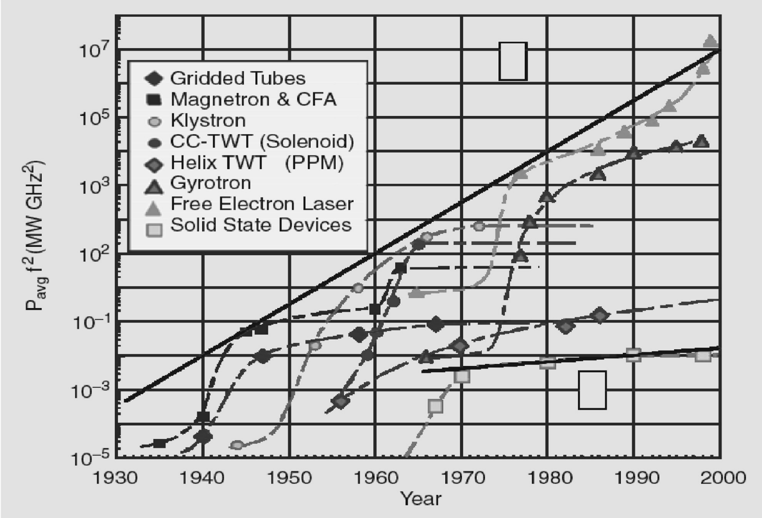
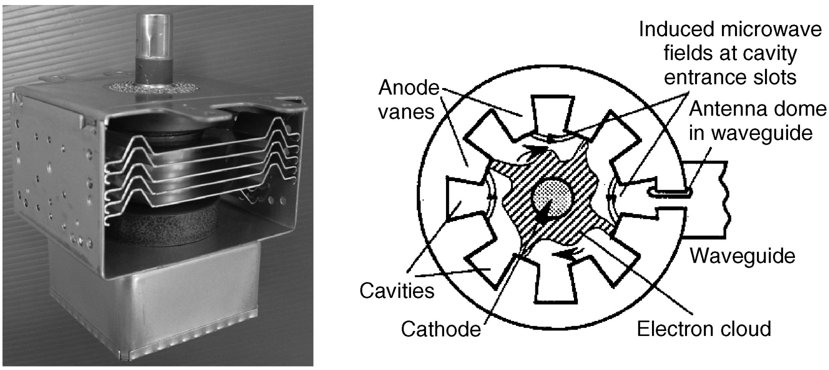


Figure 1.25 Progression of device power density $P_{av}f^2$ for major device types (reproduced from [23] by permission of IEEE, © 2001)

1.5 Microwave Generators

The development and power of various microwave generators are illustrated in Figure 1.25. Microwave generators include the magnetron, power grid tubes, traveling wave tubes (TWTs), crossed-field amplifiers (CFAs), the klystron and gyrotron. The selection of the types of microwave generators for use depends on various factors including power, frequency, efficiency, gain, bandwidth, phase, size, weight and cost.

The *magnetron* (shown in Figure 1.26) is the most commonly used microwave generator because of its high efficiency, compact size and low cost. It is used widely in microwave ovens and radar systems. A magnetron converts electrical energy to microwave radiation and typically operates at a frequency of 2.45 GHz. There are two types of magnetron available. A



(a) (b)

Figure 1.26 (a) A magnetron and (b) schematic cross-sectional view of the magnetron cavity [25] (© 1996 John Wiley & Sons, Ltd. Reproduced with permission) *pulsed magnetron* produces high peak output power from kilowatts to several megawatts for very short durations [8, 24]. A *continuous wave* (*CW*) *magnetron* produces continuous output power in the range of a few watts to kilowatts [8, 24].

In the magnetron (a crossed-field oscillator because both magnetic and electric fields are used and they are perpendicular to each other), electrons emitted from the hot cathode are made to rotate circularly in the coaxial space between the cathode and the anode under the influence of an axial magnetic field [25]. In the presence of an electromagnetic field, alternating positive and negative voltages are generated on the anode vanes and electrons emitted from the cathode can either be accelerated or decelerated [8]. Bunching of electrons occurs due to the presence of regions of accelerating and decelerating fields and the shape of the electron cloud is in the form shown in the shaded region in Figure 1.26(b). The number of 'spokes' in the electron cloud is half that of the number of cavities [8].

The power for a cooker magnetron used in microwave ovens typically ranges from 0.3 to 3 kW and for a high power magnetron at 915 MHz it can range from 25–100 kW [5]. The cooker magnetron has a cost price of approximately US$10 and a yearly production of 30 to 40 million tubes internationally [5].

Power grid tubes are commonly used at lower frequencies and consist of a cathode, grid and anode. The weak microwave signal to be amplified is applied between the grid and the cathode. The signal applied to the grid controls the electron flow drawn from the cathode and results in a larger signal at the anode. The output of power-grid tubes ranges from low-power tubes capable of producing approximately 1 kW at frequencies of 350 MHz to high-power tubes used in fusion research (plasma heating) that are capable of producing more than 2 MW of output at frequencies in the 30 MHz range through the use of special grid structures [6].

The *Klystron* is a high-power microwave generator and is used in applications such as linear accelerators, UHF television transmission, industrial heating and modern radar systems. Klystrons typically operate at frequencies ranging from 300 MHz to 40 GHz with a peak power output of 100 W to 150 MW and average power output between 100 W and 1 MW [8]. The schematic of a medical linear accelerator was shown earlier in Figure 1.17.

The operation of the klystron can be simplified as follows [8, 24]: an electron beam is generated by an electron gun and travels along a circuit consisting of a series of resonant cavities separated from each other by drift tubes. Magnets are frequently used to focus the electron beam as it passes through the circuit. The output of the klystron is obtained by velocity modulation of the electron beam, leading to bunching of electrons. Velocity modulation is obtained by varying the velocities of the electrons, alternately accelerating and decelerating the electrons through the application of a microwave signal as they pass through a pair of closely spaced grids in the input cavity, which is located close to the drift tube entrance. Bunches of accelerated and decelerated electrons are further modulated as they pass through intermediate cavities. At the output cavity, the amplified signal is extracted.

Gyrotrons are high-powered electron tubes which emit a millimeter wave beam by bunching electrons with cyclotron motion in a strong magnetic field. Gyrotrons are capable of producing much higher power levels at millimeter wavelengths than other tubes. Power output can range from kilowatts to several megawatts [26]. Operating frequencies range from about 8 to 800 GHz [27]. Gyrotrons can be designed for pulsed or continuous operation. They are used primarily for the cyclotron resonance heating of fusion plasmas in fusion reactors, for sintering of ceramics and joining of metals [27].

1.6 Summary

- Microwaves form part of the EM spectrum, with frequencies ranging from 300 MHz to 300 GHz.
- Microwave usage is extremely diverse, with applications in heating, radar, communication, industry, science, medicine and power transmission.
- Many common microwave appliances and equipment operate at the unregulated ISM bands of 915 MHz and 2.45 GHz.
- Microwave generators include magnetrons, power grid tubes, traveling wave tubes, crossed-field amplifiers, klystrons and gyrotrons. The most commonly used microwave generator is the magnetron, which is used in the domestic microwave oven.

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