12 Systems using electromagnetic waves

12.1 INTRODUCTION

The purpose of this chapter is to provide a brief survey of the range of systems which depend upon electromagnetic waves for their operation. They fall into two main categories: those which are concerned with the transmission of information and those whose purpose is the transmission of power. The first category includes radio, television, satellite communications and radar. The second embraces industrial and domestic microwave and r.f. heating, medical hyperthermia and schemes for using microwaves to beam power down from satellite power stations. The total range of systems is so diverse that it is only possible in this book to give some idea of the main applications of electromagnetic waves.

12.2 RADIO WAVE PROPAGATION

Electromagnetic waves travel in a straight line in a uniform medium so it might be expected that they could only be used for line-of-sight communications. In fact, as is well known, worldwide communication is possible at some frequencies. The various mechanisms responsible for the propagation of radio waves are illustrated in Fig. 12.1. The layers of the atmosphere which are involved are the troposphere and the ionosphere. The former is the layer lying closest to the surface of the Earth with a typical thickness of 10 km. Most of the weather variations in the atmosphere take place in this layer. The ionosphere is made up of a series of layers between 50 km and 400 km from the Earth's surface which are characterized by the presence of free electrons generated by ionizing radiation.

The assumption that the waves travel in straight lines is only correct if they are moving through a uniform medium. Because the density of the atmosphere decreases with height so, therefore, does its refractive index. Equation (1.91) shows that the effect of this decrease is to cause rays to be

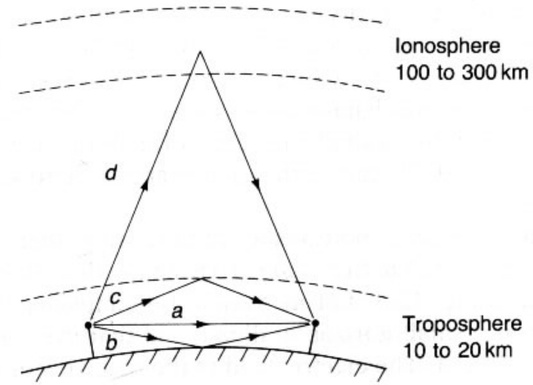

Fig. 12.1 Paths between transmitter and receiver for radio waves: (a) direct wave, (b) reflected wave (known together as the ground wave), (c) tropospheric wave and (d) sky wave.

bent away from the normal as they travel upwards and towards the normal as they travel downwards. The refractive index of the atmosphere, even at sea level, is close to unity (typically 1.0003) so that the effect is very slight. Nevertheless, over long distances the curvature of the path *a* in Fig. 12.1 is appreciable. Figure 12.2 shows the effect of this on communication between two antennas which are elevated above the Earth's surface. If the path between the two antennas is a straight line then the point B is the furthest point from the transmitter at which satisfactory reception is possible. The curvature of the ray actually makes it possible for the signal to be received at B′. Calculations involving curved paths are inconvenient so it is usual to allow for the curvature of the path AB′ by using an effective radius for the Earth which is about 4/3 of the actual radius. It must be remembered that the properties of the atmosphere vary from time to time so that communication over the horizon which relies on tropospheric refraction is not always certain.

Propagation through the atmosphere is affected by several different processes of absorption. At frequencies above 10 GHz absorption by the molecules of the atmosphere is important. Water molecules have a resonance at 22 GHz which produces an attenuation of about 0.16 dB km^{-1}. The oxygen molecule has a group of absorption lines at 60 GHz which

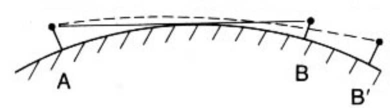

Fig. 12.2 Showing how the range of radio communication is increased by tropospheric refraction.

produce an attenuation of 15 dB km^{-1}. The actual attenuation depends on the atmospheric pressure and humidity. For signals travelling vertically through the atmosphere in a satellite communications system the one-way attenuation from these mechanisms is less than 1 dB for frequencies up to 50 GHz. Attenuation by rainfall increases with frequency and with the amount of rain. At 10 GHz the attenuation is around 1 dB km^{-1} when the rainfall is 25 mm h^{-1}.

Besides the direct wave from transmitter to receiver there will normally also be a reflected wave (*b* in Fig. 12.1). To examine this effect consider the situation shown in Fig. 12.3. Let us assume for simplicity that the transmitting antenna is a small horizontal dipole and that the curvature of the Earth can be neglected. The electric field at the receiving antenna, B, can be expressed as

$$\boldsymbol{E}_{\mathrm{B}} = \boldsymbol{E}_{\mathrm{A}} + \boldsymbol{E}_{\mathrm{A}'} \tag{12.1}$$

where $\boldsymbol{E}_{\mathrm{A}}$ and $\boldsymbol{E}_{\mathrm{A}'}$ are the electric field intensities at B for waves taking the paths AB and ACB respectively. The reflected wave can be regarded as being generated by an image antenna A′ whose amplitude and phase are adjusted to allow for the finite conductivity of the Earth's surface. Then, by a straightforward extension of the theory of Section 5.8 the field at B is

$$\boldsymbol{E}_{\mathrm{B}} = \boldsymbol{E}_{\mathrm{A}} \exp \mathrm{j}\psi/2 + \varrho \boldsymbol{E}_{\mathrm{A}} \exp -\mathrm{j}\psi/2, \tag{12.2}$$

where ϱ is the amplitude of the reflection coefficient of the Earth,

$$\psi = 2k_0h_1 \cos \phi + \alpha \tag{12.3}$$

and α is the phase difference between antenna A and its image A′.

If the Earth is regarded as a perfect conductor then $\varrho = 1$ and $\alpha = 180°$. The field at B is then

$$\begin{aligned} \boldsymbol{E}_{\mathrm{B}} &= 2\boldsymbol{E}_{\mathrm{A}} \cos (k_0h_1 \cos \phi + \pi/2) \\ &= 2\boldsymbol{E}_{\mathrm{A}} \sin (k_0h_1 \cos \phi) \\ &= \boldsymbol{E}_{\mathrm{A}}F, \end{aligned} \tag{12.4}$$

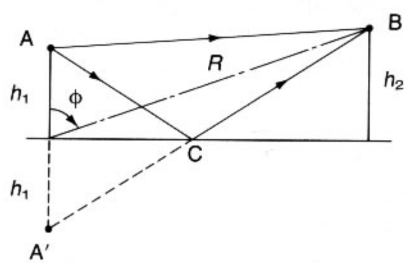

Fig. 12.3 Geometry of ground-wave reception.

where

$$F = 2 \sin \left(\frac{k_0h_1h_2}{R}\right). \tag{12.5}$$

The factor F is known as the path gain factor. It can vary from zero to 2 depending upon the relative positions of the antennas. Rather more complicated expressions for this factor emerge if the finite conductivity and curvature of the Earth are taken into account. The principle remains the same, namely that the field at the receiving antenna varies depending upon whether the interference between the direct and reflected waves is constructive or destructive. Radio sets often include an automatic gain control (AGC) loop so that this effect is not apparent to the user. If, however, the radio is operating at the limit of its sensitivity then the AGC loop can no longer compensate for the variations in the signal received. Thus the reception of a weak station by a car radio varies noticeably as the car moves along the road.

The reflection of waves by the Earth's surface is further complicated by scattering and diffraction of the waves by hills, trees and buildings. These effects become important at frequencies above 10 MHz (30 m wavelength) when the typical size of the obstacles is comparable with the wavelength of the waves. At lower frequencies the effects can be included in the effective reflection coefficient of the ground.

The upper limit of the troposphere is marked by a temperature inversion (warm air above cold air) with an abrupt change in the refractive index. The refractive index is also affected by the humidity of the air. Any abrupt change in refractive index will reflect radio waves so that they follow a path such as *c* in Fig. 12.1. Tropospheric reflection can increase the range of reception to a hundred miles or more beyond the geometrical horizon. Under certain special conditions it is possible for the curvature of the ray to be equal to that of the Earth's surface. This effect, known as ducting, can extend the range of communication to several thousand miles and can intefere with microwave communication links.

The effects described in the previous paragraph are strongly dependent upon the atmospheric conditions which exist in the troposphere at a particular time. They are, therefore, an uncertain means of long-range communication. The reflection of waves by the ionosphere which is more constant (though still variable) is normally used for long-range radio. As ionizing particles and radiation enter the atmosphere they pass freely until the air density is high enough for appreciable ionization to take place. There is then a region of increasing ionization until all the particles and photons have given up their energy. The resulting distribution of charge density with height is shown in Fig. 12.4. The ionosphere has a number of layers with differing properties as shown in Fig. 12.4. Of these the most important for radio communication is the F_2 layer whose ionization varies

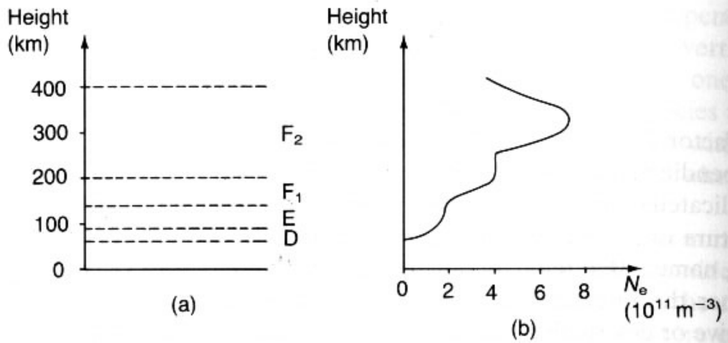

Fig. 12.4 The ionosphere: (a) approximate heights and, (b) approximate electron densities of the layers.

in a complex way linked to the sunspot number. The F_1 layer is the result of daytime solar radiation so it disappears, at night being merged with the F_2 layer. The E region is ionized by solar ultraviolet and X-rays and, to some extent by cosmic rays. The D region has much lower ionization and its main effect is to attenuate waves passing through it.

The propagation of waves through an ionized gas was studied in section 1.6 where it was shown that the permittivity is given by (1.62)

$$\varepsilon = \varepsilon_0\left(1 - \frac{\omega_p^2}{\omega^2}\right). \tag{12.6}$$

Thus the refractive index of the F_2 layer ($n = \sqrt{\varepsilon}$) is less than that of free space and waves are therefore reflected by it. Strictly, the effects of collisions in the electron plasma should be included in the theory. The result is that the permittivity is given by

$$\varepsilon = \varepsilon_0\left[1 - \frac{\omega_p^2}{(\omega^2 + \nu^2)}\right], \tag{12.7}$$

where ν is the mean collision frequency. The energy dissipation by the collisions results in an effective conductivity

$$\sigma = \frac{\omega_p^2 \nu \varepsilon_0}{\omega^2 + \nu^2}. \tag{12.8}$$

The conductivity depends upon both the electron density and the collision frequency. At high altitudes ν is very low whilst ω_p decreases rapidly below the bottom of the E layer. It turns out that the conductive effects are limited to a thin layer at the bottom of the E region. This layer therefore causes high attenuation of signals passing through it.

The reflection of waves by the ionosphere varies with frequency. At frequencies below 150 kHz the change in the electron density within one

wavelength is so great that it can be represented as a step in the refractive index so that the wave is reflected abruptly. The propagation of waves at low frequencies is analysed in terms of waveguide modes propagating between the Earth's surface and the ionosphere. These frequencies are normally used for worldwide communication and for navigation systems such as Loran C.

At higher frequencies it is necessary to regard the wave as passing through a medium whose refractive index varies with position. The result, as with tropospheric propagation, is that the ray becomes curved and may be turned back towards the Earth's surface. Frequencies above 30 MHz are not very well reflected by the ionosphere and cannot be used for long-distance communications. Short-wave radio (3 to 30 MHz) provides useful, medium-power, long-range communications in which the whole of the received signal is reflected from the ionosphere. Because of the variable nature of the ionosphere it is subject to fading, multipath interference and high noise interference.

In the 150 to 1500 kHz band the ground wave is stable and subject only to moderate attenuation and the ionospheric reflection at night is reliable. This band is widely used for marine communications and navigation and medium-wave broadcasting. The signal received is made up of the sum of the ground wave and the sky wave. It is therefore subject to multipath interference and fading. Wave propagation in the ionosphere is subject to Faraday rotation because of the effects of the Earth's magnetic field (see Section 1.8) and careful attention must be paid to the polarization of the antennas if good reception is to be obtained.

It will be evident that this section is a very brief summary of a very complex subject. For fuller information consult Jordan and Balmain (1968) and Kirby (1982).

12.3 RADIO COMMUNICATIONS

The earliest use of electromagnetic waves was in radio communications. From its beginnings as wireless telegraphy this field has expanded to include public broadcasting at frequencies from 'long wave' (150 kHz) to VHF (100 MHz) and mobile and cellular radio. We shall not discuss here the variety of modulation schemes used to maximize the signal-to-noise ratio or to make best use of the available bandwidth. The reader should consult books on telecommunications such as Dunlop and Smith (1984) for further information on this subject. We note in passing that the frequency bandwidth required for a given flow of information is independent of the carrier frequency and that many more communication channels can be fitted into the range 90 to 100 MHz than into the range 150 to 300 kHz.

Figure 12.5 shows a simple short-range radio communication system. The two antennas are assumed to be in each other's far field but close

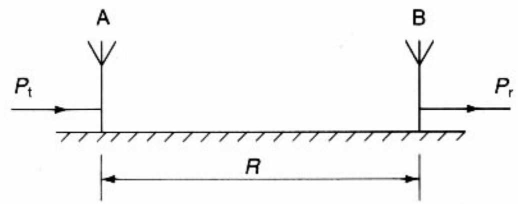

Fig. 12.5 A simple short-range radio communication system.

enough together so that the curvature of the Earth's surface can be neglected. If, for the moment, we ignore the possibility that waves are reflected from the surface of the earth then the relationship between the transmitted power and the received power is given by (5.48)

$$P_r = \frac{A_{e2}g_1}{4\pi R^2} P_t, \tag{12.9}$$

where A_e is the effective area of an antenna and g is its gain. We also saw in Chapter 5 that these two quantities are related to each other by (5.54)

$$A_e = \frac{\lambda^2}{4\pi} g \tag{12.10}$$

so that (12.9) can be rewritten in the form

$$\frac{P_r}{P_t} = \frac{A_{e1}A_{e2}}{R^2\lambda^2}. \tag{12.11}$$

This equation is known as the Friis transmission formula. It can also be written as

$$\frac{P_r}{P_t} = \frac{g_1 g_2 \lambda^2}{(4\pi R)^2}. \tag{12.12}$$

Equation (12.12) reveals some basic facts about radio communications. If we assume that a certain P_r is the minimum which will ensure that the signal received is above the noise level then doubling the range requires the transmitted power to be increased by a factor of 4 if the same antennas are used. Alternatively the gains of the antennas could be increased to compensate for the increased range by increasing either their size or their directivity. It appears from (12.12) that the received power should increase as the wavelength increases. In general this does not happen because the directivities of antennas tend to be lower at longer wavelengths.

It is often convenient to express (12.12) in decibels with the result

$$P_r = P_t + G_1 + G_2 - L_s, \tag{12.13}$$

where the transmitted and received powers (P_t and P_r) and the antenna

gains (G_1 and G_2) are expressed in decibels and the free-space path loss L_s is given by

$$L_s = 20 \log_{10}\left(\frac{4\pi R}{\lambda}\right). \tag{12.14}$$

In any real communication system there must be other losses in the feeder cables and in propagation through the air. These losses, which may be variable to take account of rainfall, can be included as a propagation loss L_p to give

$$P_r = P_t + G_1 + G_2 - L_s - L_p. \tag{12.15}$$

Careful control over the use of the available frequency spectrum is exercised by national regulatory bodies with the aim of minimizing interference between stations. Frequencies are allocated for international, national or local use with prescribed maximum power levels. Even with these precautions it is common experience that there can be interference between stations particularly in the medium wave band at night when the ionospheric reflections are at their best. Transmitted power levels of up to 50 kW are normal for national broadcasting with greater powers being used for international short-wave stations.

Radio communication at frequencies above 30 MHz is virtually limited to line-of-sight paths with the requirement becoming more stringent as the frequency increases and diffraction effects are less helpful in providing a signal in the geometrical shadow of an obstacle. Because waves at these frequencies are not affected by ionospheric reflections it is possible to use horizontal and vertical polarization to provide freedom of interference between neighbouring stations which are transmitting at the same frequency.

12.4 TELEVISION BROADCASTING

Colour television broadcasting requires a bandwidth of 8 MHz for each channel. Channels in the UHF region (470 to 890 MHz) are allocated for TV transmission because there is adequate bandwidth available for a large number of stations whilst the receiver technology is less expensive than at higher, microwave, frequencies. At UHF there must be a line of sight between the transmitting and receiving antennas. Main transmitters employ very tall aerial masts and transmit powers of up to 50 kW. Additional local transmitters are needed to provide coverage in areas shadowed by hills. The polarization of the wave is used to avoid interference between adjacent transmitters.

At UHF it is possible to make receiving antennas with gains greater than 10 dB which are compact enough for domestic use. The transmitting antennas make use of dipole arrays which are usually arranged to give uniform coverage in all directions. The phases of the feeds to dipoles at different heights on the mast are adjusted to tilt the radiation pattern down towards the horizon. In some cases the antenna may also be arranged to give an asymmetrical radiation pattern in the horizontal plane.

12.5 MICROWAVE COMMUNICATIONS

An important use of microwave radio is in point-to-point communication links of the kind typified by the Telecom Tower in London and similar towers elsewhere. There are a number of frequency bands allocated for this purpose of which the most used are those in the region of 4 and 6 GHz, each of which has 500 MHz bandwidth. The route chosen must be strictly line-of-sight with stages typically 40 km in length. The antennas used have high gain (40 to 50 dB) and consequently low side-lobe powers. The result is that such a communications system has a good level of security. The number of channels which can be handled by the system is doubled by making use of both horizontal and vertical polarization. This kind of system provides a good example of the use of equation (12.15).

Example

Find the power received at the end of a 40 km, 6 GHz, microwave link if the antennas have 40 dB gain, the transmitted power is 20 W and the propagation losses are not more than 6 dB.

Solution

The wavelength at 6 GHz is 50 mm so the free space loss is

$$L_s = 20 \log_{10}\left(\frac{4\pi \times 40\,000}{0.05}\right) = 140\,\text{dB} \qquad (12.16)$$

and the transmitted power is

$$P_t = 10 \log_{10}\left(\frac{20}{0.001}\right) = 43\ \text{dBm} \qquad (12.17)$$

so that the minimum power received is

$$\begin{aligned} P_r &= 43 + 40 + 40 - 140 - 6 \\ &= -23\,\text{dBm} \end{aligned} \qquad (12.18)$$

that is 5 μW. This signal level is comfortably within the range of sensitivity of microwave receivers.

If the strength of the signal received is plotted against the distance between the transmitter and receiver the result is as shown in Fig. 12.6. As would be expected the signal level falls off steadily with periodic variations caused by interference between the direct and reflected waves. Once the transmitter is over the horizon as perceived by the receiver the signal level falls off very rapidly. The signal does not fall abruptly to zero because of the effects of diffraction. This can be understood by considering Fig. 12.7 which shows a receiver whose line of sight to the transmitter is blocked by a hill. The radiation from the transmitter illuminates the plane A–A containing the hill. The radiation at any point beyond this plane can be calculated by using Huygens' method of secondary wavelets (see Section 5.9). The result is that the intensity of the radiation at points on the plane B–B varies as shown in Fig. 12.8 (Longhurst, 1973). Within the geometrical shadow there is still some detectable signal because the effects of the individual wavelets do not quite cancel out.

The existence of the diffraction field can be used for over-the-horizon communications. It is sometimes possible to make use of diffraction by a mountain to extend the range of a microwave link. The penalty to be paid

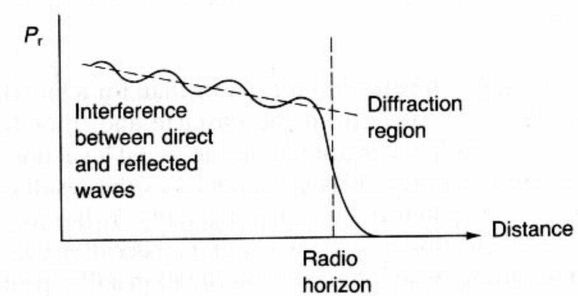

Fig. 12.6 Variation of received power with distance from the transmitter.

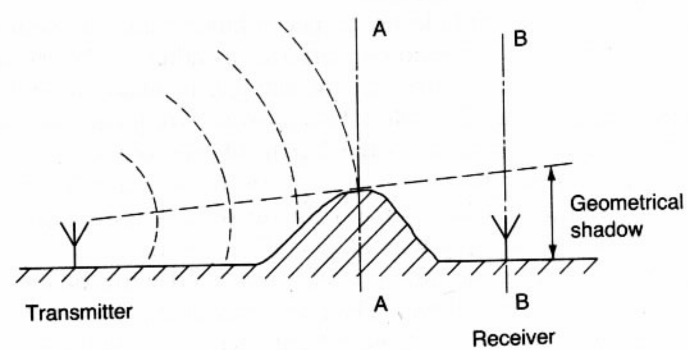

Fig. 12.7 Geometry of reception beyond an obstacle.

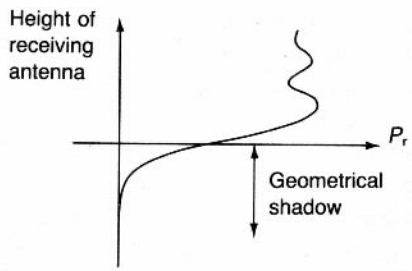

Fig. 12.8 Variation of received power caused by diffraction by an obstacle.

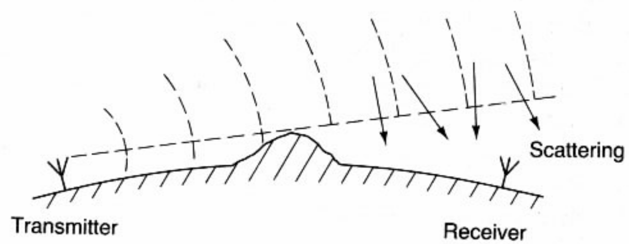

Fig. 12.9 Increased signal level at an over-the horizon receiver as a result of tropospheric scattering.

is the need for much greater transmitter power than for a line-of-sight link. As the receiver moves further from the obstacle and, therefore, further into the geometrical shadow it is found that the signal level does not fall off as fast as predicted by theory. This is explained as the result of scattering of the radiation by turbulence and inhomogeneity in the troposphere as shown in Fig. 12.9. The effect is put to use in troposcatter communication systems which are useful when it is not possible to install repeater stations. An example is the system used to communicate with oil rigs in the North Sea. A transmitter power of the order of 1 kW is needed to provide a strong enough signal at the receiver.

Satellite communication links are a special kind of microwave link. The satellite is normally in geostationary orbit at a radius of 35 800 km. This arrangement has the advantage that the satellite is always in view of the Earth station and that no Doppler shifting of the frequency is caused by motion of the satellite relative to the Earth. On the other hand it places greater demands upon the microwave system than a satellite in a lower orbit (because of the very large range) and introduces a propagation delay of about 0.5 s into a two-way telephone conversation.

Many current systems use frequencies around 6 GHz for the uplinks and around 4 GHz for the downlinks. The free-space path loss is 200 dB for a satellite in geostationary orbit at these frequencies so it is necessary to use high-power transmitters and high-gain antennas. Earth stations typically

have transmitter powers of the order of a few kilowatts and antennas up to 30 m in diameter with 60 dB gain. The satellite has much more limited power supplies and cannot carry such a large antenna. The satellite transmitter typically has a power output of a few watts and an antenna gain of 20 dB. The ground station must therefore have a very high-gain, low-noise, receiver to enable it to receive signals of the order of a picowatt successfully. Newer satellite systems make use of uplink and downlink channels at 14 and 12 GHz respectively making it possible for higher gain antennas to be used.

Direct broadcasting of television by satellite (DBS) has different requirements depending upon whether the transmissions are received at the central station of a cable TV network or directly by the consumers. The former systems have the same general characteristics as the general-purpose systems described above because it is economically viable for the cable TV operators to make use of an expensive high-gain antenna and low-noise microwave preamplifier. For direct reception in the home the satellite transmitter must have an output power of about 200 W to allow smaller antennas and cheaper preamplifiers to be used. The systems have 12 GHz downlink and 17 GHz uplink frequencies.

12.6 RADAR

Radar (RAdio Detection And Ranging) was the first use to which microwave power sources were put. The first systems operated by transmitting pulses of microwave power from a rotating antenna. Some of the signal was reflected from targets such as aircraft and the time delay of the reflected pulse measured the distance from the transmitter to the target. The direction in which the antenna was pointing supplied information about the direction of the target. From these early beginnings a whole radar family has grown up which includes both pulsed and continuous wave (c.w.) systems. Examples are radars for: threat warning, target location, air traffic control, missile guidance, speed measurement and automatic landing. The information which can be extracted from the returned signal includes: range, velocity, acceleration, angular direction (horizontal and vertical) and target size, shape and identification.

A pulsed radar emits short pulses (a few microseconds) of microwave energy at a fixed pulse repetition frequency (p.r.f.) as shown in Fig. 12.10(a). The returned pulses (of much lower amplitude) resulting from reflection of the first transmitted pulse might be as shown in Fig. 12.10(b). Pulse A has an unambiguous time delay from the transmitted pulse so the range of the target is known. Pulse B has returned during the next transmitted pulse. Unless precautions are taken, the leakage of the transmitted pulse into the receiver would destroy it. For this reason a pulsed radar always incorporates a device to protect the receiver during the transmitter

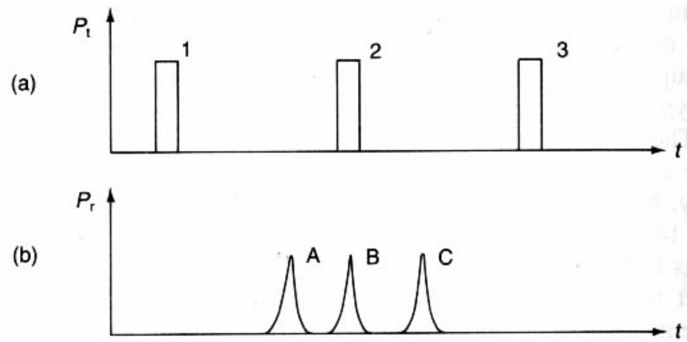

Fig. 12.10 Radar pulses: (a) transmitted pulses and, (b) received pulses. A gives unambigous range information, B is blanked by a transmitter pulse and C gives ambiguous range information.

pulse. This device, which is either a gas discharge 'TR cell' or a semiconductor switch, short circuits the receiver input. Thus pulse B remains undetected. Pulse C has returned after the next transmitted pulse and there is therefore uncertainty about whether it is a reflection of pulse 1 or pulse 2. If unambiguous range information is required it is necessary to use a low p.r.f. so that all possible returns occur before the next pulse.

The ability of a radar to discriminate between two closely spaced targets depends upon the pulse length as illustrated in Fig. 12.11. The long transmitted pulse in Fig. 12.11(a) produces a single long returned pulse. When the pulse length is shortened (Fig. 12.11(b)) it is revealed that there are two targets close together whose returns overlapped when the transmitter pulse was longer. Getting high resolution by shortening the pulse length has the disadvantage that a higher transmitter power may be needed to provide sufficient energy in the returned pulses. An alternative is to use pulse-compression techniques. A pulse-compression radar transmits a long

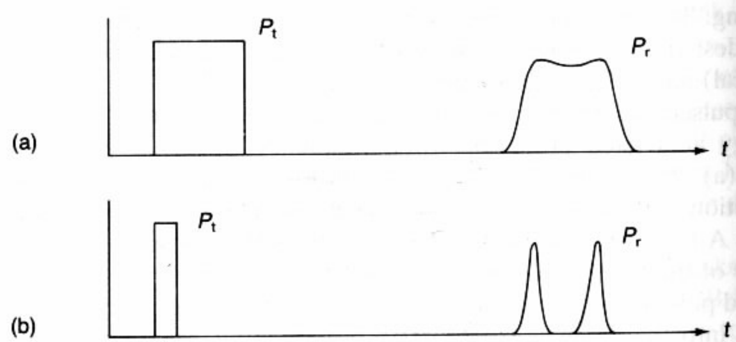

Fig. 12.11 Resolution of a radar: (a) with a long pulse and, (b) with a short pulse.

pulse during which the frequency is swept over a range of a few hundred megahertz as shown in Figs. 12.12(a) and (b). The returned pulse is passed through a dispersive filter which delays the lower frequencies more than the higher ones. The output from this filter is then a much shorter pulse with greater amplitude as shown in Fig. 12.12(c). A pulse-compression radar requires a power amplifier (klystron, TWT or CFA) in place of the magnetron oscillators used in fixed-frequency radar.

The power density at the target is given by (5.46)

$$S_1 = \frac{P_t G}{4\pi R^2}, \tag{12.19}$$

where P_t is the power and G the antenna gain of the transmitter, and R is the range. The power reflected by the target depends upon its size and shape and the material from which it is made. These are grouped together as an effective area known as the target cross-section (σ). The power density of the reflected signal at the transmitter is therefore

$$S_2 = \frac{P_t G \sigma}{(4\pi R)^2}. \tag{12.20}$$

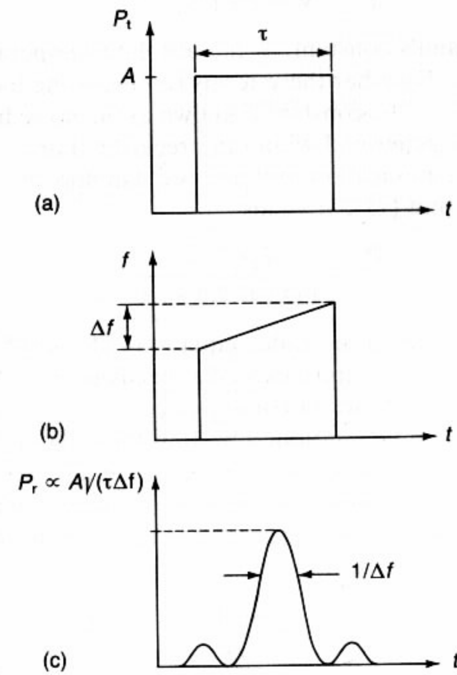

Fig. 12.12 Pulses for pulse-compression radar: (a) transmitted power, (b) transmitted frequency, and (c) compressed received pulse.

If the effective area of the radar antenna is A_e then the power received is

$$P_r = \frac{P_t G \sigma A_e}{(4\pi R)^2}. \tag{12.21}$$

Normally the same antenna is used for transmission and reception so that we can make use of the relationship between the effective area and the gain of an antenna (5.54)

$$A_e = \frac{G\lambda^2}{4\pi} \tag{12.22}$$

to produce an expression for the power received. If the system and propagation losses are represented by L then the result is

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L}. \tag{12.23}$$

If this signal is to be detected reliably then it must exceed the noise power in the receiver. Noise is a manifestation of random thermal events which is spread uniformly over all frequencies. Thus the noise power in the receiver can be written

$$N = FkTB, \tag{12.24}$$

where k is Boltzmann's constant, T the absolute temperature and B the receiver bandwidth. Together these terms represent the background noise radiated from the sky. The constant F known as the noise figure represents the additional noise generated within the receiver. For a fuller discussion of noise in telecommunication systems see Dunlop and Smith (1984). Combining (12.22) and (12.23) yields

$$\frac{P_r}{N} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L FkTB}. \tag{12.25}$$

This equation is known as the radar equation. The left-hand side is the signal-to-noise ratio and this must exceed a specified level if the system is to function correctly. An important consequence of this equation is that the transmitter power must be multiplied by 16 if the range is to be doubled.

The effective target cross-section decreases rapidly when the target is smaller than one wavelength. For a sphere of radius a where $a \gg \lambda$ the cross-section is πa^2. A flat plate of area A normal to the incident wave has a cross-section

$$\sigma = \frac{4\pi A^2}{\lambda^2}. \tag{12.26}$$

Radars employing short pulses or pulse compression can sometimes discriminate between the cross-sections of different parts of the target. The reflected pulse then has a characteristic shape, known as the *signature* of the target, which can be used to identify it.

One interesting radar cross-section is that of an antenna whose input has been short circuited. The power received is

$$P_r = SA_e \tag{12.27}$$

so that the power reflected back towards the transmitter is

$$P = SA_e G \tag{12.28}$$

thus the radar cross-section of the antenna is

$$\sigma = A_e G = \frac{G^2\lambda^2}{4\pi}. \tag{12.28}$$

This means that the gain and radiation pattern of an antenna can be measured by measuring the signal reflected from it when it is short circuited.

If the target is moving relative to the transmitter then the returned frequency is Doppler shifted. The frequency shift can then be used to measure the relative velocity. This has found an everyday application in the radar speed meters used by the police. Other uses include vehicle detectors for portable traffic lights, aircraft landing systems and docking systems for oil tankers and spacecraft. Doppler systems can use either pulsed or c.w. sources. In pulsed Doppler systems the frequency shift is detected by a set of filters which discriminate between adjacent narrow bands of frequencies. The p.r.f. and its harmonics produce signals which may fall in the range of the filters and there are therefore certain velocities which cannot be measured by a pulsed Doppler system.

Much effort and ingenuity has gone into the processing of radar signals to maximize the ability of systems to detect targets in the presence of reflections from trees, hills, buildings and the like (known collectively as 'clutter') and of signals from other systems. Deliberate attempts to produce misleading responses in a radar system, commonplace in the military environment, are known as electronic countermeasures (ECM) (see Section 12.7). For a fuller discussion of radar systems see the book by Skolnik (1967).

12.7 ELECTRONIC COUNTERMEASURES

The development of ever more advanced military radar systems has been parallelled by the development of electronic countermeasures (ECM) systems. These have the purpose of providing some defence against hostile radars. The threat may be from a surveillance radar or from the radar guidance system of a missile. Simple techniques are the deployment of decoys or of 'chaff' (thin aluminium strips designed to have a large radar cross-section). Efforts are also made to minimize the radar cross-sections of potential targets to make them harder to detect.

More sophisticated ECM systems employ transmitters to produce signals designed to confuse the hostile radar. These signals may be from high-power noise sources or oscillators and designed to swamp the radar reflection with a much bigger jamming signal. If, as often, the frequency of the hostile radar is not known in advance an alternative technique is to use a wide-band receiver and transmitter. This equipment receives the hostile signal and then retransmits it at a higher power level in a way which confuses the hostile radar.

The development of ECM has led to electronic counter countermeasures (ECCM). These techniques are designed to make a radar harder to jam. One common method is to use rapid and random changes in the operating frequency (frequency agility).

12.8 INDUSTRIAL AND DOMESTIC APPLICATIONS

The main industrial application of microwaves is for heating. The applications include cooking, drying, curing and hardening, melting and sterilization. The first of these is familiar in the form of the domestic microwave cooker. The different ways of applying the microwave power fall into two main categories: resonant and non-resonant. In a resonant cavity the field patterns are known and fixed. The material to be processed is usually a lossy dielectric so it must be placed in a region of maximum electric field. Figure 12.13 shows how a cylindrical cavity resonating in the TM_{010} mode can be used for heating a dielectric liquid.

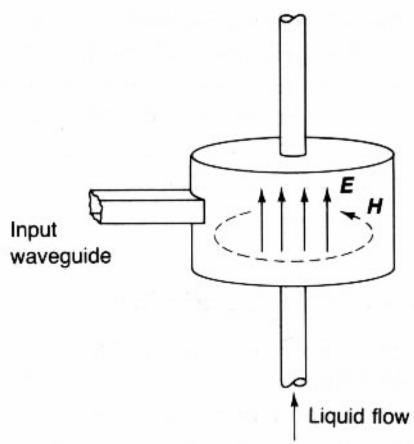

Fig. 12.13 Single-mode microwave cavity for heating liquids.

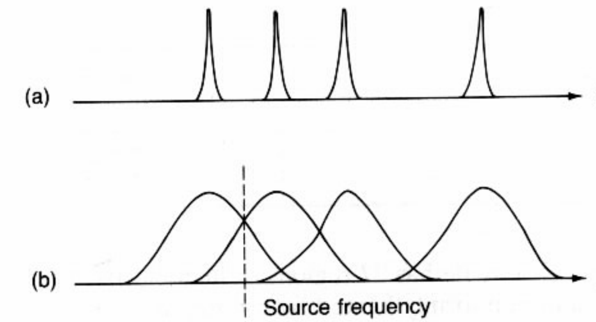

Fig. 12.14 Spectrum of resonances in a multi-mode microwave oven: (a) with the oven empty, and (b) with the widths of the resonances increased by loading.

Single-mode cavities are not suitable for batch heating processes because of the very non-uniform distribution of power within the cavity. The solution is to use a larger cavity so that there are several higher-order modes close to the source frequency. The presence of the dielectric load in the cavity lowers the Q of the resonances causing their resonance curves to overlap as shown in Fig. 12.14. There is then appreciable coupling of the input power into two or more modes each of which has several regions of high electric field within the cavity. To obtain more uniform heating still it is usual either to mount the load on a turntable so that it moves through the field pattern, or else a rotating metal paddle (a 'mode stirrer') is arranged to alter the coupling of the source to the different modes of the cavity. Multi-mode cavities are used in domestic ovens and for a wide range of industrial processes.

Example

A domestic microwave oven which operates at 2.45 GHz has internal dimensions: width 330 mm, depth 338 mm, height 268 mm. Investigate the mode spectrum in the region of the operating frequency.

Solution

The resonant frequencies of a rectangular cavity are given by equation (7.41). Substitution of values of m, n and l gives the range of possible resonances. Finding the complete mode spectrum is time consuming and is best programmed on a computer. Examples of modes close to the source frequency are given in Table 12.1.

The presence of the dielectric load moves the resonances downwards and broadens them. Thus the (3,3,3) resonance could well be excited in a

Table 12.1

m	n	l	f (GHz)
1	4	3	2.483
4	1	3	2.512
3	3	3	2.538

particular case. This mode has 27 regions of high electric field so that the load could be quite uniformly heated by rotating it.

A third way of coupling microwave power into a load is to use some kind of travelling-wave applicator. It may be sufficient to use the fields in a rectangular waveguide as shown in Fig. 12.15. The items to be heated pass through the guide on a conveyor belt or in a pipe like the water calorimeter shown in Fig. 11.3. This arrangement suffers from the disadvantage that the size of the items to be heated is limited by the size of the waveguide. Alternative designs which can heat larger objects employ meander lines and other slow-wave structures.

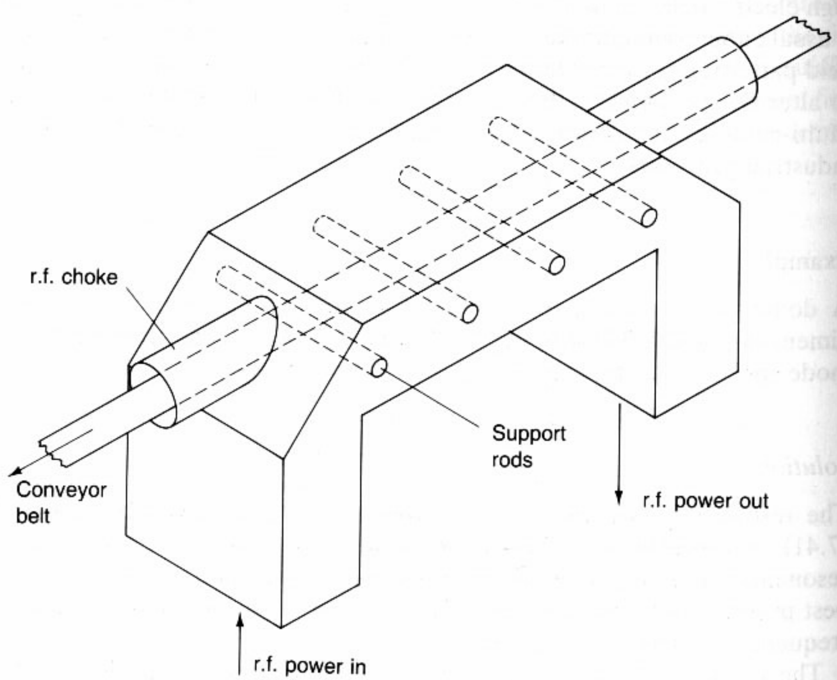

Fig. 12.15 Arrangement of a waveguide applicator for microwave heating.

A full review of microwave heating and drying techniques and their applications is given by Metaxas and Meredith (1983).

12.9 MEDICAL APPLICATIONS

The ability of microwave power to heat biological tissue, exploited in the microwave oven, has a number of consequences in the medical field. It is clearly dangerous for human tissue to be exposed to too much microwave power and anyone working with microwave power systems needs to be aware of the hazards and the precautions which must be taken to ensure safe working. The microwave power heats the body tissue and permanent damage may occur if the heat generated cannot be removed quickly enough by the blood stream. Some parts of the body, especially the eyes are particularly sensitive to microwave radiation. Care must be taken never to look into an open waveguide or antenna even at low power levels. In the USA and Western Europe a figure of $10\,\mathrm{mW\,cm^{-2}}$ was adopted as the maximum safe exposure on the basis of heating effects. In the Soviet Union and Eastern Europe the level was set at $10\,\mu\mathrm{W\,cm^{-2}}$ on the basis of non-heating effects which have been observed in laboratory experiments.

In medicine it is common to use heat applied externally to assist healing and to reduce pain. Microwave heating has the advantage that the power can penetrate to the region inside the body where it is needed. Power levels from $100\,\mathrm{mW\,cm^{-2}}$ to a few watts per square centimetre are used. This technique is known as microwave hyperthemia. The possibility of using it as a way of selectively heating malignant growths is being investigated.

Microwave power is also used in radiotherapy for the treatment of cancer. Electrons accelerated in a linear accelerator (see Section 10.8) are used to produce high-energy X-rays either by collision with a target or by direct bombardment of the human body.

12.10 COMPUTER-AIDED DESIGN OF MICROWAVE SYSTEMS

The complicated interactions between the components of a microwave system make it difficult to design. In particular the possibility of resonances and of effects due to the loading of one component by another need to be carefully investigated. Computer-aided design (CAD) methods are now commonly used in the microwave industry to simulate the performance of systems before they are built. These packages contain routines for carrying out transmission-line manipulations and mathematical models of many of the different kinds of transmission line and component which may be used. The results of calculations can be displayed graphically as frequency response curves or Smith charts. CAD packages of this kind are a powerful way of investigating and optimizing system performance. The effects of possible design changes can be studied and steps taken to get rid of any unwanted characteristics.

12.11 CONCLUSION

This chapter has reviewed briefly some of the systems which make use of electromagnetic radiation, especially those which work at microwave frequencies. The aim has been to emphasize the importance of the material covered earlier in the book by showing how it is applied in major engineering systems. In each case it has only been possible to provide a very brief introduction to give some idea of the scope of the subject and the way in which it is related to electromagnetic theory. The reader is encouraged to consult the books and papers listed in the bibliography to find out more about these subjects.

The author is convinced that familiarity with the material covered in this book is still a vital part of the professional competence of any electronic engineer.

EXERCISES

12.1 A microwave communication link is to be designed to operate over a 20 km range at 14 GHz. The antennas available have 32 dB gain, the anticipated propagation losses are 6 dB and the path gain factor varies between 0.7 and 1.6. If the signal level at the receiver is to be not less than 1 μW what must the transmitter power be?

12.2 Calculate the signal level at the receiver of a direct-broadcasting satellite system if the satellite is in geostationary orbit, the frequency is 12.1 GHz, the transmitter power is 200 W and the antennas have 26 dB and 34 dB gain.

12.3 What is the range of the radio horizon for a radar set in a small boat whose antenna is 5 m above the sea surface?

12.4 Calculate the signal level at the receiver of a radar set operating at 1.12 GHz whose transmitted power is 1 MW if the antenna gain is 38 dB, the target is at a distance of 97 km and the target cross-section is $10\,m^2$.

12.5 A radar set is operated with 1 μs pulses and a pulse-repetition frequency of $680\,s^{-1}$. What are the minimum detection range and the range resolution?

References

Akhtarzad, S. and Johns, P.B. (1975) Solution of Maxwell's equations in three space dimensions and time by the TLM method of numerical analysis, *Proc. IEE*, **122**, 1349.

Baden-Fuller, A.J. (1987) *Ferrites at Microwave Frequencies*. Peter Peregrinus, London.

Bailey, M.C. and Crosswell, W.F. (1982) Antennas. In *Electronic Engineers' Handbook* (D.J. Fink and D. Christiansen, eds.). McGraw Hill, New York.

Balston, D.M. (1989) Pan-European Cellular Radio, *Electronics and Communication Engineering Journal*, **1**, 7–13.

Bar-Lev, A. (1979) *Semiconductors and Electronic Devices*. Prentice-Hall International, London.

Barton, D.K. (1982) Radar Principles. In *Electronic Engineers' Handbook* (D.G. Fink and D. Christiansen, eds.). McGraw-Hill, New York.

Bleaney, B.I. and Bleaney, B. (1976) *Electricity and Magnetism*, 3rd edn. Oxford University Press, Oxford.

Bryant, G.H. (1988) *Principles of Microwave Measurement*. Peter Peregrinus, London.

Carter, G.W. (1967) *The Electromagnetic Field in its Engineering Aspects*, 2nd edn. Longmans, London.

Carter, R.G. (1986). *Electromagnetism for Electronic Engineers*. Van Nostrand Reinhold, Wokingham.

Carter, G.W. and Richardson, A. (1972) *Techniques of Circuit Analysis*. Cambridge University Press, Cambridge.

Collin, R.E. (1966) *Foundations for Microwave Engineering*. McGraw-Hill, New York.

Connolly, D.J. (1976) Determination of the interaction impedance of coupled-cavity slow-wave structures, *IEEE Trans. on Electron Devices*, **ED-23**, 491–3.

Dekker, A.J. (1959) *Electrical Engineering Materials*. Prentice Hall, Englewood Cliffs, NJ.

Di Giacomo, J.J. *et al.* (1958) *Design and Fabrication of Nanosecond Digital Equipment*. RCA, Princeton, NJ.

Dunlop, J. and Smith, D.G. (1984) *Telecommunications Engineering*. Van Nostrand Reinhold (UK), Wokingham.

Edwards, T.C. (1981) *Foundations for Microstrip Circuit Design*. Wiley-Interscience, Chichester.

Field, J.C.G. (1983) An introduction to electromagnetic screening theory, *IEE Colloquium Digest No. 1983/88*.

Forrer, M.P. and Jaynes, E.T. (1960) Resonant modes in waveguide windows, *IRE Trans. on Microwave Theory and Techniques*, **MTT-8**, 147–50.
Fox, A.G. (1947) An adjustable waveguide phase changer, *Proc. IRE*, **35**, 1489–98.
Fujisawa, K. (1958) General treatment of klystron resonant cavities, *IRE Trans. on Microwave Theory and Techniques*, **MTT-6**, 344–58.
Gardiol, F.E. (1984) *Introduction to Microwaves*. Artech House, Dedham, Mass.
Getsinger, W.J. (1973) Microstrip dispersion model, *IEEE Trans. on Microwave Theory and Techniques*, **MTT-22**, 34–9.
Gilmour, A.S.Jr (1986) *Microwave Tubes*. Artech House, Dedham, Mass.
Granatstein, V.L. and Alexeff, I. (eds.) (1987) *High Power Microwave Sources*. Artech House, Dedham, Mass.
Green, R.J. (1989) Optical communications; past, present and future, *Electronics and Communication Engineering Journal*, **1**, 105–14.
Halbach, K. and Holsinger, R.F. (1976) SUPERFISH a computer program for the evaluation of RF cavities with cylindrical symmetries, *Particle Accelerators*, **7**, 213–22.
Harvey, A.F. (1963) *Microwave Engineering*. Academic Press, New York.
Jackson, G.A. (1989) Survey of EMC measurement techniques, *Electronics and Communication Engineering Journal*, **1** (2), 61–70.
Jones, E.C.Jr and Hale, H.W. (1982) Filters and attennuators. In *Electronic Engineers' Handbook* (D.G. Fink and D. Christiansen, eds.). McGraw-Hill, New York.
Jordan, E.C. and Balmain, K.G. (1968) *Electromagnetic Waves and Radiating Systems*, 2nd edn. Prentice Hall, Engelwood Cliffs, NJ.
Kajfez, D. and Guillon, P. (eds.). (1986) *Dielectric Resonators*. Artech House, Dedham, Mass.
Keiser, B.E. (1983) *Principles of Electromagnetic Compatibility*. Artech House, Dedham, Mass.
Kirby, R.C. (1982) Radio-wave Propagation. In *Electronic Engineers' Handbook* (D.G. Fink and D. Christiansen, eds.). McGraw-Hill, New York.
Laverghetta, T.S. (1976) *Microwave Measurements and Techniques*. Artech House, Dedham, Mass.
Levy, R. (1959) A guide to the practical application of Chebyshev functions to the design of microwave components, *Proc. IEE*, **106c**, 193–9.
Liao, S.Y. (1980) *Microwave Devices and Circuits*. Prentice-Hall, Engelwood Cliffs, NJ.
Longhurst, R.S. (1973). *Geometrical and Physical Optics*, 3rd edn. Longmans, London.
Louisell, W.H. (1960) *Coupled Mode and Parametric Electronics*. Wiley, New York.
McLachlan, N.W. (1955) *Bessel Functions for Engineers*, 2nd edn. Oxford University Press, Oxford.
Marcuvitz, N. (1986) *Waveguide Handbook*. Peter Peregrinus, London.
Matthaei, G.L., Young, L. and Jones, E.M.T. (1964) *Microwave Filters, Impedance Matching Networks and Coupling Structures*. McGraw-Hill, New York.
Metaxas, A.C. and Meredith, R.J. (1983) *Industrial Microwave Heating*. Peter Peregrinus, London.
O'Reilly, J.J. (1984) *Telecommunication Principles*. Van Nostrand Reinhold, (UK), Wokingham.
Pengelly, R.S. (1986) *Microwave Field Effect Transistors*, 2nd edn. Research Studies Press, Letchworth.

Pierce, J.R. (1954) Coupling of modes of propagation, *Journal of Applied Physics*, **25**, 179.
Ramo, S., Whinnery, J.R. and van Duzer, T. (1965) *Fields and Waves in Communication Electronics*. Wiley, New York.
Rosser, W.G.V. (1964) *An Introduction to the Theory of Relativity*. Butterworths, London.
Rudge, A.W., Milne, K., Olver, A.D. and Knight, P. (eds.) (1982–3). *The Handbook of Antenna Design* (2 vols.). Peter Peregrinus, London.
Saad, T.S. (ed.) (1971) *Microwave Engineers' Handbook*. Artech House, Dedham, Mass.
Schelkunoff, S.A. (1943) *Electromagnetic Waves*, Van Nostrand, New York.
Seely, S. (1972) *An Introduction to Engineering Systems*. Pergamon, New York.
Skolnik, M.J. (1967) *Introduction to Radar Systems*. McGraw-Hill, New York.
Topping, J. (1962). *Errors of Observation and their Treatment*, 3rd edn. Chapman and Hall, London.
Waldron, R.A. (1967) *The Theory of Waveguides and Cavities*. Applied Science Publisher, Baukung.
Watson, J. (1988) *Opto-electronics*. Van Nostrand Reinhold International, London.
Webb, R.T. (1985) Ten years of TWT progress, *Electronics and Power*, **31**, 120.
Weiland, T. (1983) TBCI and URMEL. New computer codes for wake field and cavity mode calculations, *IEEE Trans. on Nuclear Science*, **NS-30**, 2489–91.
Weiland, T. (1985) Computer modelling of two- and three-dimensional cavities, *IEEE Trans. on Nuclear Science*, **NS-32**, 2738.