CHAPTER 20

Radio

Chapter summary

Maxwell first suggested the existence of electromagnetic waves in 1864. Later, Heinrich Rudolf Hertz used an arrangement of rudimentary resonators to demonstrate the existence of electromagnetic waves. Hertz's apparatus was extremely simple and comprised two resonant loops, one for transmitting and the other for receiving. Each loop acted both as a tuned circuit and as a resonant aerial. The transmitting loop was excited by means of an induction coil and battery. Some of the energy radiated by the transmitting loop was intercepted by the receiving loop and the received energy was conveyed to a spark gap where it could be released as an arc. The energy radiated by the transmitting loop was in the form of an **electromagnetic wave** – a wave that has both electric and magnetic field components and that travels at the speed of light.

In 1894, Marconi demonstrated the commercial potential of the phenomenon that Maxwell predicted and Hertz actually used in his apparatus. It was also Marconi that made radio a reality by pioneering the development of telegraphy without wires (i.e. wireless). Marconi was able to demonstrate very effectively that information could be exchanged between distant locations without the need for a 'land-line'.

Marconi's system of **wireless telegraphy** proved to be invaluable for maritime communications (ship to ship and ship to shore) and was to be instrumental in saving many lives. The military applications of radio were first exploited during the First World War (1914 to 1918) and, during that period, radio was first used in aircraft.

The radio frequency spectrum

Radio frequency signals are generally understood to occupy a frequency range that extends from a few tens of kilohertz (kHz) to several hundred gigahertz (GHz). The lowest part of the radio frequency range that is of practical use (below 30 kHz) is only suitable for narrow-band communication. At this frequency, signals propagate as ground waves (following the curvature of the Earth) over very long distances. At the other extreme, the highest frequency range that is of practical importance extends above 30 GHz. At these microwave frequencies, considerable bandwidths are available (sufficient to transmit many television channels using point-to-point links or to permit very high definition radar systems) and signals tend to propagate strictly along line-of-sight paths.

At other frequencies signals may propagate by various means, including reflection from ionized layers in the ionosphere. At frequencies between 3 MHz and 30 MHz ionospheric propagation regularly permits intercontinental broadcasting and communications.

For convenience, the radio frequency spectrum is divided into a number of bands, each spanning a decade of frequency. The use to which each frequency range is put depends upon a number of factors, paramount amongst which is the propagation characteristics within the band concerned. Other factors that need to be taken into account include the efficiency of practical aerial systems in the range concerned and the bandwidth available. It is also worth noting that, although it may appear from Fig. 13.1 that a great deal of the radio frequency spectrum is not used, it should be stressed that competition for frequency space is fierce. Frequency allocations are, therefore, ratified by international agreement and the various user services carefully safeguard their own areas of the spectrum.

Electromagnetic waves

As with light, radio waves propagate outwards from a source of energy (transmitter) and comprise electric (**E**) and magnetic (**H**) fields at right angles to one another. These two components, the **E-field** and the **H-field**, are inseparable. The resulting wave travels away from the source with the E and H lines mutually at right angles to the direction of **propagation**, as shown in Fig. 20.2.

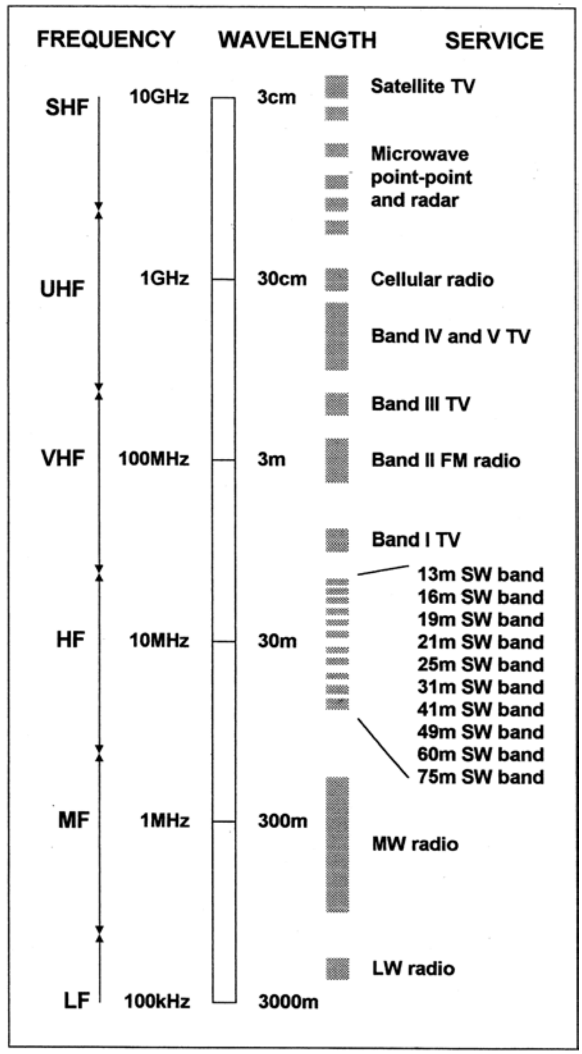

Figure 20.1 The radio frequency spectrum

Radio waves are said to be **polarized** in the plane of the electric (E) field. Thus, if the E-field is vertical, the signal is said to be vertically polarized whereas, if the E-field is horizontal, the signal is said to be horizontally polarized.

Fig. 20.3 shows the electric E-field lines in the space between a transmitter and a receiver. The transmitter aerial (a simple dipole – see page 000) is supplied with a high-frequency alternating

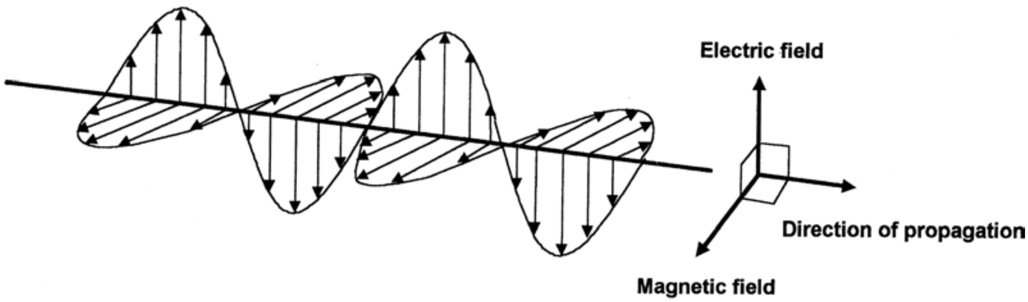

Figure 20.2 An electromagnetic wave

current. This gives rise to an alternating electric field between the ends of the aerial and an alternating magnetic field around (and at right angles to) it.

The direction of the E-field lines is reversed on each cycle of the signal as the **wavefront** moves outwards from the source. The receiving aerial intercepts the moving field and voltage and current is induced in it as a consequence. This voltage and current is similar (but of smaller amplitude) to that produced by the transmitter.

Frequency and wavelength

Radio waves propagate in air (or space) at the **speed of light** (300 million metres per second). The velocity of propagation, v, wavelength, λ, and frequency, f, of a radio wave are related by the equation:

$$v = f\lambda = 3 \times 10^8$$

This equation can be arranged to make f or λ the subject, as follows:

$$f = \frac{3\times10^8}{\lambda} \text{ Hz}$$

and

$$\lambda = \frac{3\times10^8}{f} \text{ m}$$

As an example, a signal at a frequency of 1 MHz will have a wavelength of 300 m whereas a signal at a frequency of 10 MHz will have a wavelength of 30 m.

When a radio wave travels in a cable (rather than in air or 'free space') it usually travels at a speed that is between 60% and 80% of that of the speed of light.

Example 20.1

Determine the frequency of a radio signal that has a wavelength of 15 m.

Solution

Using the formula:

$$f = \frac{3\times10^8}{\lambda} \text{ Hz}$$

where λ = 15 m gives:

$$f = \frac{3\times10^8}{15} = \frac{300\times10^6}{15} = 20\times10^6 \text{ Hz or 20 MHz}$$

Example 20.2

Determine the wavelength of a radio signal that has a frequency of 150 MHz.

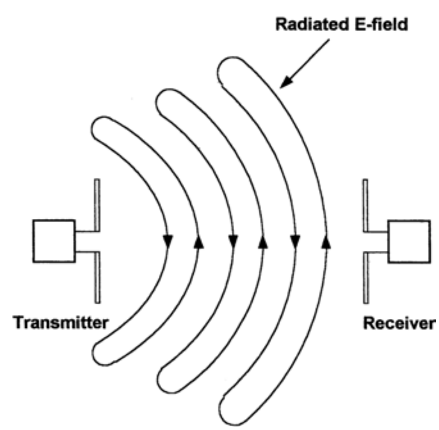

Figure 20.3 E-field lines between a transmitter and a receiver

Solution

Using the formula:

$$\lambda = \frac{3 \times 10^8}{f} \text{ m}$$

where f = 150 MHz gives:

$$\lambda = \frac{3 \times 10^8}{f} = \frac{3 \times 10^8}{150 \text{ MHz}} = \frac{300 \times 10^6}{150 \times 10^6} = \frac{300}{150} = 2 \text{ m}$$

Example 20.3

If the wavelength of a 30 MHz signal in a cable is 8 m, determine the velocity of propagation of the wave in the cable.

Solution

Using the formula:

$$v = f\lambda = 3 \times 10^8$$

where v is the velocity of propagation in the cable, gives:

$$= f \quad = 30 \text{ MHz} \times 8 \text{ m} = 2.4 \times 10^8 \text{ m/s}$$

A simple CW transmitter and receiver

Fig. 20.4 shows a simple radio communication system comprising a **transmitter** and **receiver** for use with **continuous wave** (CW) signals. Communication is achieved by simply switching (or 'keying') the radio frequency signal on and off. Keying can be achieved by interrupting the supply to the power amplifier stage or even the oscillator stage; however, it is normally applied within the driver stage that operates at a more modest power level. Keying the oscillator stage usually results in impaired frequency stability. On the other hand, attempting to interrupt the appreciable currents and/or voltages that appear in the power amplifier stage can also prove to be somewhat problematic.

The simplest form of CW receiver need consist of nothing more than a radio frequency amplifier (which provides gain and selectivity) followed by a detector and an audio amplifier. The **detector** stage mixes a locally generated radio frequency signal produced by the **beat frequency oscillator** (BFO) with the incoming signal to produce a signal within the audio frequency range.

As an example, assume that the incoming signal is at a frequency of 100 kHz and that the BFO is producing a signal at 99 kHz. A signal at the difference between these two frequencies (1 kHz) will appear at the output of the detector stage. This will then be amplified within the audio stage before being fed to the loudspeaker.

Example 20.4

A radio wave has a frequency of 162.5 kHz. If a beat frequency of 1.25 kHz is to be obtained, determine the two possible BFO frequencies.

Solution

The BFO can be above or below the incoming signal frequency by an amount that is equal to the beat frequency (i.e. the audible signal that

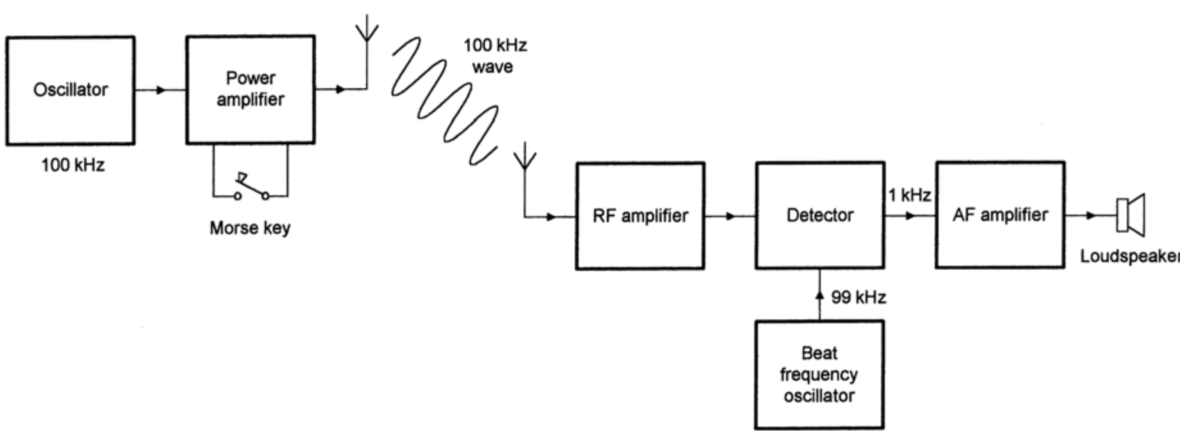

Figure 20.4 Simplified block schematic of a radio communication system comprising a continuous wave (CW) transmitter and a simple receiver with a beat frequency oscillator (BFO)

results from the 'beating' of the two frequencies and which appears at the output of the detector stage).

Hence, $f_{BFO} = f_{RF} \pm f_{AF}$

from which:

$$f_{BFO} = 162.5 \text{ kHz} \pm 1.25 \text{ kHz}$$
$$= 160.75 \text{ kHz or } 163.25 \text{ kHz}$$

Morse code

Transmitters and receivers for CW operation are extremely simple but nevertheless they can be extremely efficient. This makes them particularly useful for disaster and emergency communications or for any situation that requires optimum use of low-power equipment. Signals are transmitted using the code invented by Samuel Morse (see Fig. 20.5).

The Morse code uses a combination of dots (short periods of transmission) and dashes (slightly longer periods of transmission) to represent characters. As an example, Fig. 20.6 shows how the radio frequency carrier is repeatedly switched on and off to transmit the character 'C'.

Modulation

In order to convey information using a radio frequency carrier, the signal information must be

A	• –	N	– •
B	– • • •	O	– – –
C	– • – •	P	• – – •
D	– • •	Q	– – • –
E	•	R	• – •
F	• • – •	S	• • •
G	– – •	T	–
H	• • • •	U	• • –
I	• •	V	• • • –
J	• – – –	W	• – –
K	– • –	X	– • • –
L	• – • •	Y	– • – –
M	– –	Z	– – • •
1	• – – – –	6	– • • • •
2	• • – – –	7	– – • • •
3	• • • – –	8	– – – • •
4	• • • • –	9	– – – – •
5	• • • • •	0	– – – – –

Figure 20.5 Morse code

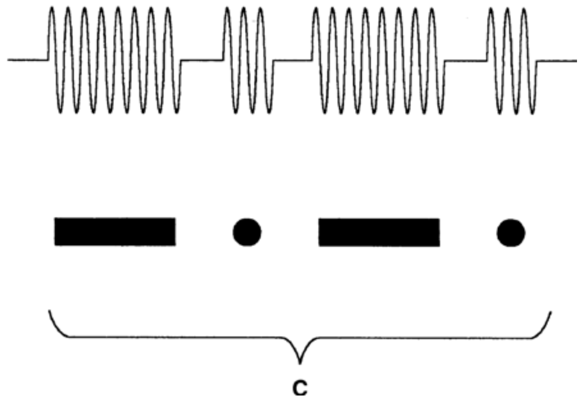

Figure 20.6 RF signal for the Morse letter 'C'

superimposed or 'modulated' onto the carrier. **Modulation** is the name given to the process of changing a particular property of the carrier wave in sympathy with the instantaneous voltage (or current) a signal.

The most commonly used methods of modulation are **amplitude modulation** (AM) and **frequency modulation** (FM). In the former case, the carrier amplitude (its peak voltage) varies according to the voltage, at any instant, of the modulating signal. In the latter case, the carrier frequency is varied in accordance with the voltage, at any instant, of the modulating signal.

Fig. 20.7 shows the effect of amplitude and frequency modulating a sinusoidal carrier (note that the modulating signal is, in this case, also sinusoidal). In practice, many more cycles of the RF carrier would occur in the time-span of one cycle of the modulating signal.

Demodulation

Demodulation is the reverse of modulation and is the means by which the signal information is recovered from the modulated carrier. Demodulation is achieved by means of a **demodulator** (sometimes called a **detector**). The output of a demodulator consists of a reconstructed version of the original signal information present at the input of the modulator stage within the transmitter. We shall see how this works a little later.

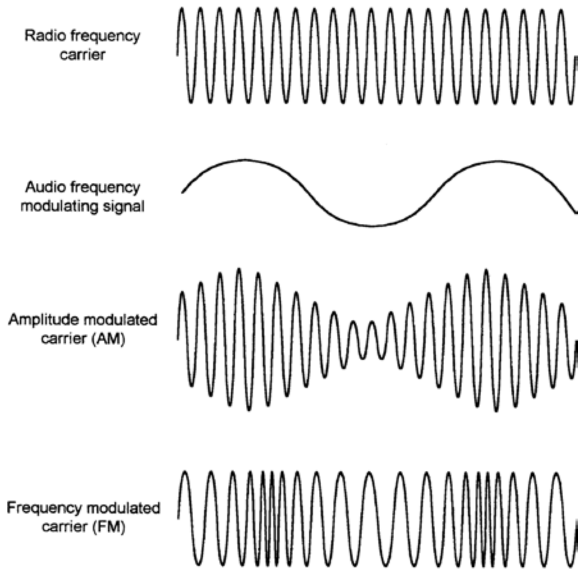

Figure 20.7 Amplitude modulation (AM) and frequency modulation (FM)

An AM transmitter

Fig. 20.8 shows the block schematic of a simple AM transmitter. An accurate and stable RF oscillator generates the radio frequency **carrier** signal. The output of this stage is then amplified and passed to a modulated RF power amplifier stage. The inclusion of an amplifier between the RF oscillator and the modulated stage also helps to improve frequency stability.

The low-level signal from the microphone is amplified using an AF amplifier before it is passed to an AF power amplifier. The output of the power amplifier is then fed as the supply to the modulated RF power amplifier stage. Increasing and reducing the supply to this stage is instrumental in increasing and reducing the amplitude of its RF output signal.

The modulated RF signal is then passed through an aerial tuning unit. This matches the aerial to the RF power amplifier and also reduces the level of unwanted harmonic components that may be present.

An FM transmitter

Fig. 20.9 shows the block schematic of a simple FM transmitter. Once again, an accurate and stable RF oscillator generates the radio frequency carrier signal. As with the AM transmitter, the output of this stage is amplified and passed to an RF power amplifier stage. Here again, the inclusion of an amplifier between the RF oscillator and the RF power stage helps to improve frequency stability.

The low-level signal from the microphone is amplified using an AF amplifier before it is passed to a **variable reactance** element (e.g. a variable capacitance diode – see page 000) within the RF oscillator tuned circuit. The application of the AF signal to the variable reactance element causes the frequency of the RF oscillator to increase and decrease in sympathy with the AF signal.

The final RF signal from the power amplifier is passed through an aerial tuning unit that matches the aerial to the RF power amplifier and also helps to reduce the level of any unwanted harmonic components that may be present. As with the final stages of an AM transmitter, the RF power amplifier usually operates at an appreciable power level and this uses Class C to increase efficiency.

A tuned radio frequency (TRF) receiver

Tuned radio frequency (TRF) receivers provide a means of receiving local signals using fairly minimal circuitry. The simplified block schematic of a TRF receiver is shown in Fig. 20.10.

The signal from the aerial is applied to an RF amplifier stage. This stage provides a moderate amount of gain at the signal frequency. It also provides **selectivity** by incorporating one or more tuned circuits at the signal frequency. This helps the receiver to reject signals that may be present on adjacent channels.

The output of the RF amplifier stage is applied to the demodulator. This stage recovers the audio frequency signal from the modulated RF signal. The demodulator stage may also incorporate a tuned circuit to further improve the selectivity of the receiver.

The output of the demodulator stage is fed to the input of the AF amplifier stage. This stage increases the level of the audio signal from the

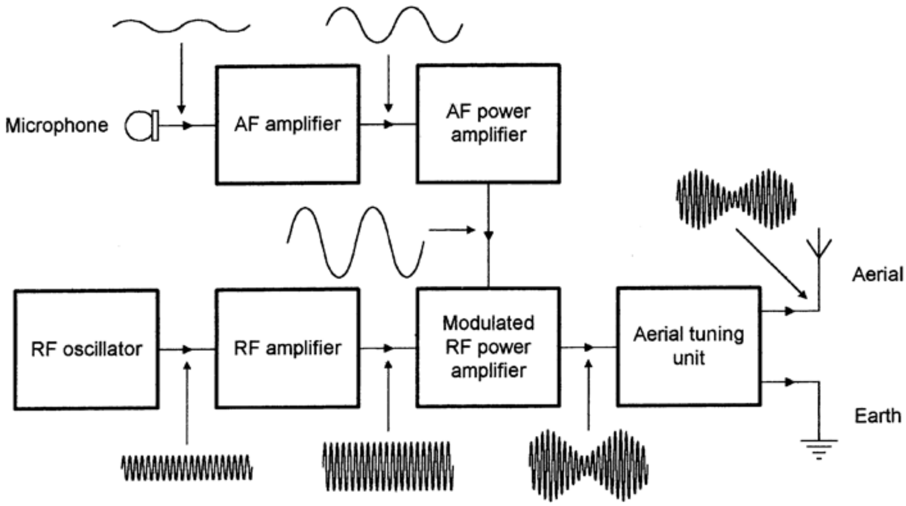

Figure 20.8 An AM transmitter

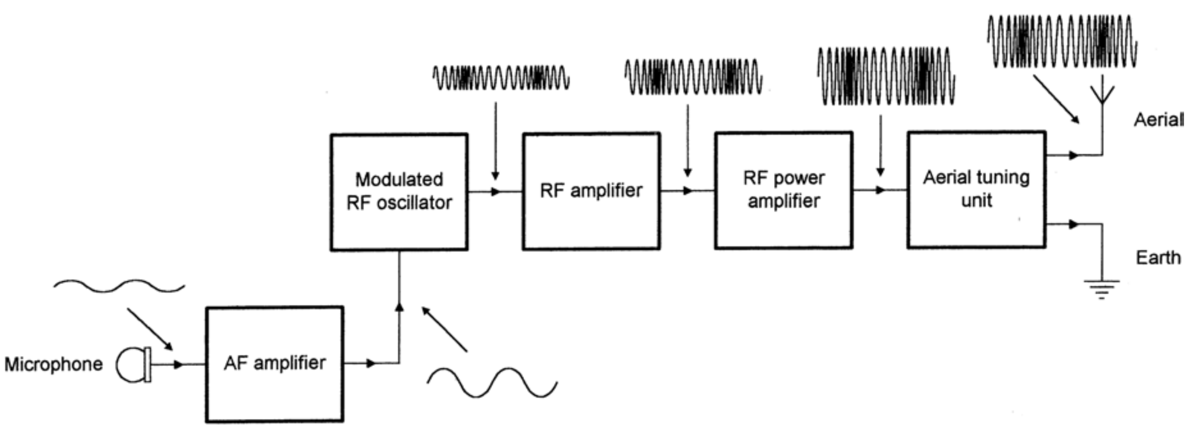

Figure 20.9 An FM transmitter

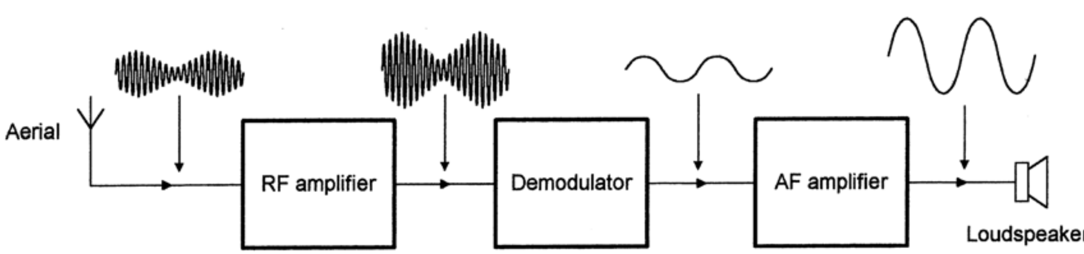

Figure 20.10 A TRF receiver

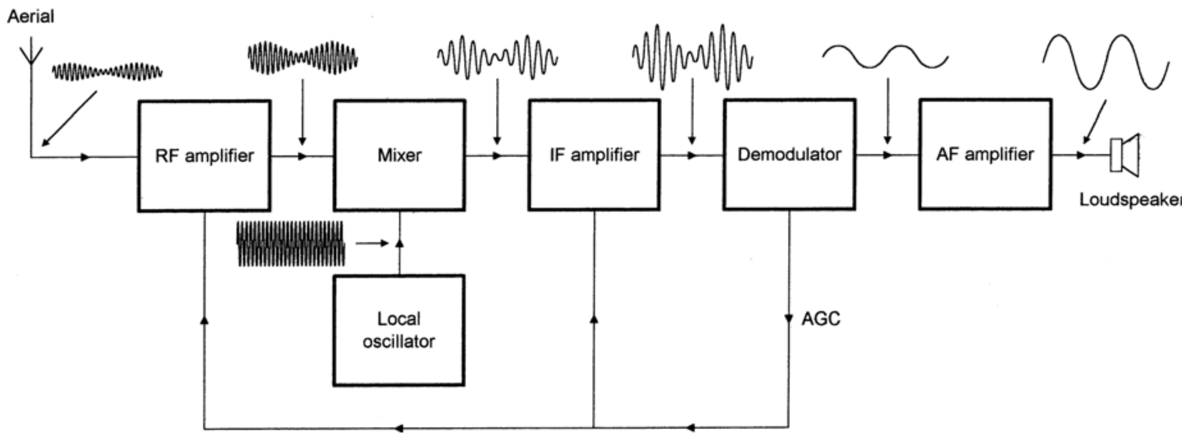

Figure 20.11 A superhet receiver

demodulator so that it is sufficient to drive a loudspeaker.

TRF receivers have a number of limitations with regard to sensitivity and selectivity and this makes them generally unsuitable for use in commercial radio equipment.

A superhet receiver

Superhet receivers provide both improved **sensitivity** (the ability to receive weak signals) and improved **selectivity** (the ability to discriminate signals on adjacent channels) when compared with TRF receivers. Superhet receivers are based on the **supersonic-heterodyne** principle where the wanted input signal is converted to a fixed **intermediate frequency** (IF) at which the majority of the gain and selectivity is applied. The intermediate frequency chosen is generally 455 kHz or 470 kHz for AM receivers and 10.7 MHz for communications and FM receivers. The simplified block schematic of a simple superhet receiver is shown in Fig. 20.11.

The signal from the aerial is applied to an **RF amplifier** stage. As with the TRF receiver, this stage provides a moderate amount of gain at the signal frequency. The stage also provides selectivity by incorporating one or more tuned circuits at the signal frequency.

The output of the RF amplifier stage is applied to the **mixer** stage. This stage combines the RF signal with the signal derived from the **local oscillator** stage in order to produce a signal at the **intermediate frequency** (IF). It is worth noting that the output signal produced by the mixer actually contains a number of signal components, including the sum and difference of the signal and local oscillator frequencies as well as the original signals plus harmonic components. The wanted signal (i.e. that which corresponds to the IF) is passed (usually by some form of filter) to the IF amplifier stage. This stage provides amplification as well as a high degree of selectivity.

The output of the IF amplifier stage is fed to the demodulator stage. As with the TRF receiver, this stage is used to recover the audio frequency signal from the modulated RF signal.

Finally, the AF signal from the demodulator stage is fed to the AF amplifier. As before, this stage increases the level of the audio signal from the demodulator so that it is sufficient to drive a loudspeaker.

In order to cope with a wide variation in signal amplitude, superhet receivers invariably incorporate some form of **automatic gain control** (AGC). In most circuits the d.c. level from the AM demodulator (see page 000) is used to control the gain of the IF and RF amplifier stages. As the signal level increases, the d.c. level from the demodulator stage increases and this is used to reduce the gain of both the RF and IF amplifiers.

The superhet receiver's intermediate frequency f_{IF}, is the difference between the signal frequency,

f_{RF}, and the local oscillator frequency, f_{LO}. The desired local oscillator frequency can be calculated from the relationship:

$$f_{LO} = f_{RF} \pm f_{IF}$$

Note that in most cases (and in order to simplify tuning arrangements) the local oscillator operates above the signal frequency, i.e. $f_{LO} = f_{RF} + f_{IF}$

Example 20.5

A VHF Band II FM receiver with a 10.7 MHz IF covers the signal frequency range, 88 MHz to 108 MHz. Over what frequency range should the local oscillator be tuned?

Solution

Using $f_{LO} = f_{RF} + f_{IF}$ when f_{RF} = 88 MHz gives f_{LO} = 88 MHz + 10.7 MHz = 98.7 MHz

Using $f_{LO} = f_{RF} + f_{IF}$ when f_{RF} = 108 MHz gives f_{LO} = 108 MHz + 10.7 MHz = 118.7 MHz

The local oscillator tuning range should therefore be from 98.7 MHz to 118.7 MHz.

RF amplifiers

Fig. 20.12 shows the circuit of a typical RF amplifier stage (this circuit can also be used as an IF amplifier in a superhet receiver). You might like to contrast this circuit with Fig. 7.34 shown on page 148. The amplifier operates in class A and uses a small-signal NPN transistor connected in common-emitter mode. The essential difference

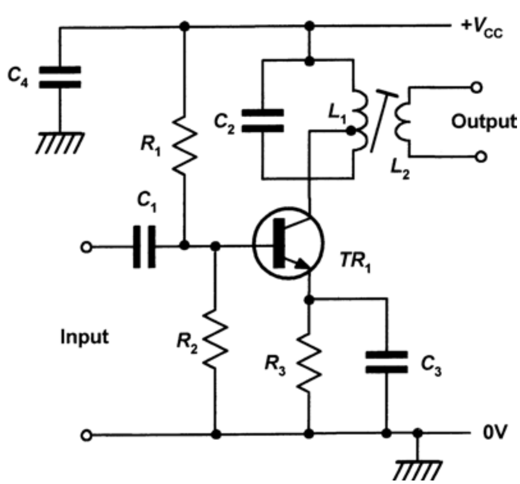

Figure 20.12 An RF amplifier

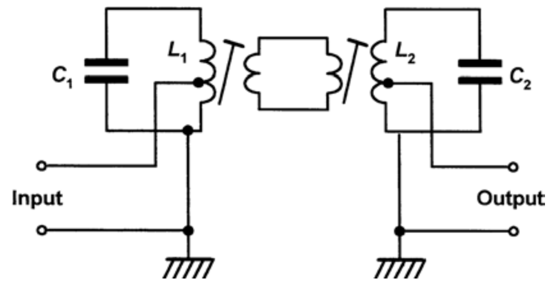

Figure 20.13 A tuned band-pass filter

between the circuit shown in Fig. 20.12 and that shown in Fig. 7.34 is that the RF amplifier uses a parallel tuned circuit as a collector load.

To improve matching and prevent damping of the tuned circuit (which results in a reduction in Q-factor and selectivity) the collector of TR_1 is **tapped** into the tuned circuit rather than connected straight across it. Since the tuned circuit has maximum impedance at resonance (see page 000), maximum gain will occur at the resonant frequency. By using a tuned circuit with high Q-factor it is possible to limit the response of the amplifier to a fairly narrow range of frequencies. The output (to the next stage) is taken from a secondary winding, L_2, on the main inductor, L_1.

In order to further improve **selectivity** (i.e. the ability to discriminate between signals on adjacent channels) several tuned circuits can be used together in order to form a more effective **band-pass filter**. Fig. 20.13 shows one possible arrangement. When constructing an RF filter using several tuned circuits it is necessary to use the optimum coupling between the two tuned circuits. Fig. 20.14 illustrates this point.

If the two tuned circuits are too 'loosely' coupled (they are said to be **under-coupled**) the frequency response characteristic becomes flat and insufficient output is obtained. On the other hand, if they are too 'tightly' coupled (they are said to be **over-coupled**) the response becomes broad and 'double-humped'. The optimum value of coupling (when the two tuned circuits are said to be **critically coupled**) corresponds to a frequency response that has a relatively flat top and steep sides.

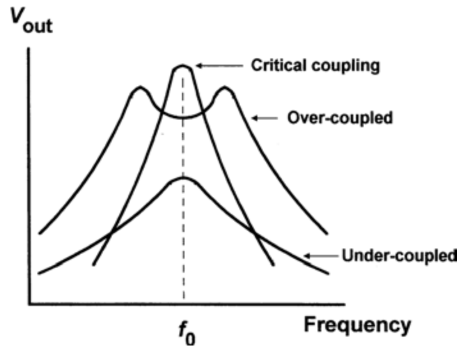

Figure 20.14 Frequency response for two coupled tuned circuits showing different amounts of coupling between the tuned circuits

AM demodulators

Fig. 20.15 shows the circuit of a typical AM demodulator stage. The RF input is applied to a parallel tuned circuit (L_1 and C_1) which exhibits a very high impedance at the signal frequency. A secondary coupling winding, L_2, is used to match the relatively low impedance of the **diode demodulator** circuit to the high impedance of the input tuned circuit. Diode, D_1, acts as a half-wave rectifier conducting only on positive-going half-cycles of the radio frequency signal. Capacitor, C_1, charges to the peak value of each positive-going half-cycle that appears at the cathode of D_1.

The voltage that appears across C_1 roughly follows the peak of the half-cycles of rectified voltage. R_1 and C_2 form a simple filter circuit to remove unwanted RF signal components (this circuit works in just the same way as the smoothing filter that we met in Chapter 6 – see page 000). The final result is a voltage waveform appearing across C_2 that resembles the original modulating signal. As well as providing current path for D_1, R_2 forms a discharge path for C_1 and C_2. Coupling capacitor, C_3, is used to remove any d.c. component from the signal that appears at the output of the demodulator. Waveforms for the demodulator circuit are shown in Fig. 20.16. Fig. 20.17 shows a complete IF amplifier together with an AM demodulator stage. Circuits of this type are used in simple superhet receivers.

Aerials

We shall start by describing one of the most fundamental types of aerial, the **half-wave dipole**. The basic half-wave dipole aerial (Fig. 20.18) consists of a single conductor having a length equal to one-half of the length of the wave being transmitted or received. The conductor is then split in the centre to enable connection to the feeder. In practice, because of the capacitance effects between the ends of the aerial and ground, the aerial is invariably cut a little shorter than a half wavelength.

The length of the aerial (from end to end) is equal to one half wavelength, hence:

$$l = \frac{\lambda}{2}$$

Now since $v = f\lambda$ we can conclude that, for a half-wave dipole,

$$l = \frac{v}{2f}$$

Note that l is the **electrical length** of the aerial rather than its actual **physical length**. End effects, or capacitance effects at the ends of the aerial, require that we reduce the actual length of the aerial and a 5% reduction in length is typically required for an aerial to be resonant at the centre of its designed tuning range.

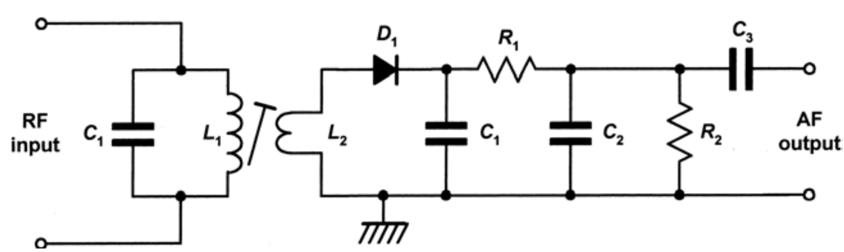

Figure 20.15 A diode AM demodulator

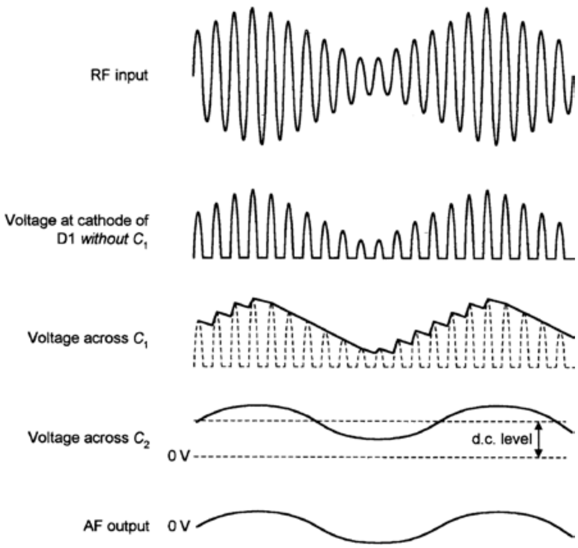

Figure 20.16 Waveforms for the AM demodulator shown in Fig. 20.15

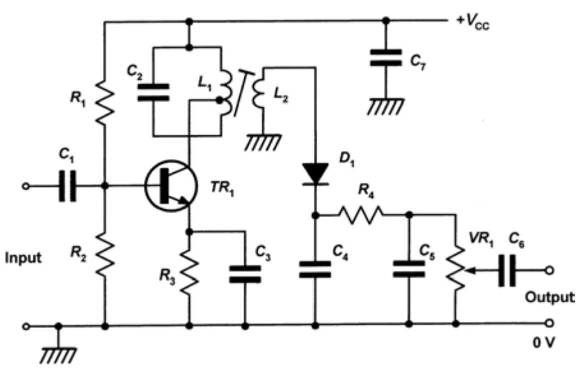

Figure 20.17 A complete RF/IF amplifier and AM demodulator

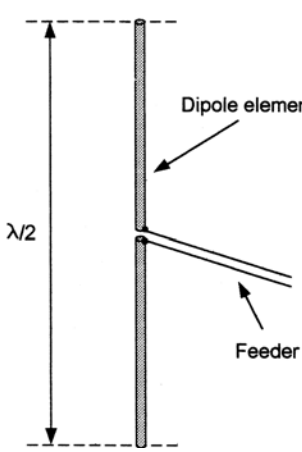

Figure 20.18 A half-wave dipole aerial

Fig. 20.19 shows the distribution of current and voltage along the length of a half-wave dipole aerial. The current is maximum at the centre and zero at the ends. The voltage is zero at the centre and maximum at the ends. This implies that the impedance is not constant along the length of the aerial but varies from a maximum at the ends (maximum voltage, minimum current) to a minimum at the centre.

The dipole aerial has directional properties as illustrated in Fig. 20.20. Fig. 20.20(a) shows the radiation pattern of the aerial in the plane of the antenna's electric field while Fig. 20.20(b) shows the radiation pattern in the plane of the aerial's magnetic field. Things to note from these two diagrams are that:

(a) in the case of Fig. 20.20(a) minimum radiation occurs along the axis of the aerial while the two zones of maximum radiation are at 90° (i.e. are 'normal to') the dipole elements.

(b) in the case of Fig. 20.20(b) the aerial radiates uniformly in all directions.

Hence, a vertical dipole will have an **omni-directional** radiation pattern while a horizontal dipole will have a **bi-directional** radiation pattern. This is an important point as we shall see later. The combined effect of these two patterns in three-dimensional space will be a doughnut shape.

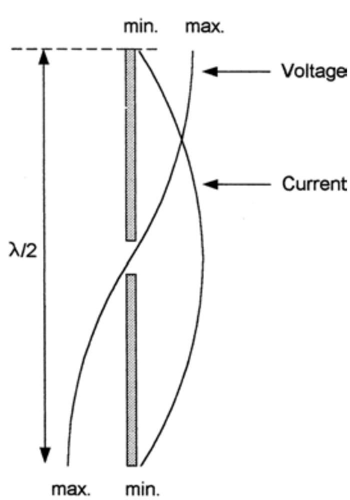

Figure 20.19 Voltage and current distribution in a half-wave dipole aerial

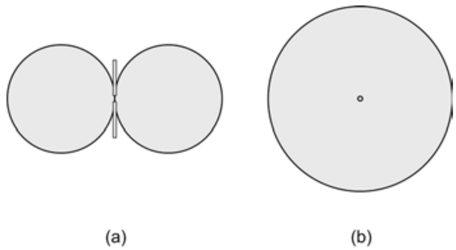

Figure 20.20 Radiation patterns for a half-wave dipole: (a) radiation in the electric field plane (b) radiation in the magnetic field plane

Example 20.6

Determine the length of a half-wave dipole aerial for use at a frequency of 150 MHz.

Solution

The length of a half-wave dipole for 150 MHz can be determined from:

$$l = \frac{v}{2f}$$

where $v = 3 \times 10^8$ m/s and $f = 150 \times 10^6$ Hz.

Hence:

$$l = \frac{v}{2f} = \frac{3 \times 10^8}{2 \times 150 \times 10^6} = \frac{3 \times 10^6}{3 \times 10^6} = 1\ \text{m}$$

Impedance and radiation resistance

Because voltage and current appear in an aerial (a minute voltage and current in the case of a receiving antenna and a much larger voltage and current in the case of a transmitting antenna) an aerial is said to have **impedance**. Here it's worth remembering that impedance is a mixture of resistance, R, and reactance, X, both measured in ohms (Ω). Of these two quantities, X varies with frequency while R remains constant. This is an important concept because it explains why aerials are often designed for operation over a restricted range of frequencies.

The impedance, Z, of an aerial is the ratio of the voltage, E, across its terminals to the current, I, flowing in it. Hence:

$$Z = \frac{E}{I}$$

You might infer from Fig. 20.19 that the impedance at the centre of the half-wave dipole should be zero. In practice the impedance is usually between 70 Ω and 75 Ω. Furthermore, at resonance the impedance is purely resistive and contains no reactive component (i.e. inductance and capacitance). In this case X is negligible compared with R. It is also worth noting that the d.c. resistance (or **ohmic resistance**) of an aerial is usually very small in comparison with its impedance and so it may be ignored. Ignoring the d.c. resistance of the aerial, the impedance of an antenna may be regarded as its **radiation resistance**, R_r (see Fig. 20.21).

Radiation resistance is important because it is through this resistance that electrical power is transformed into radiated electromagnetic energy (in the case of a transmitting aerial) and incident electromagnetic energy is transformed into electrical power (in the case of a receiving aerial).

The equivalent circuit of an aerial is shown in Fig. 20.22. The three series-connected components that make up the aerial impedance are:

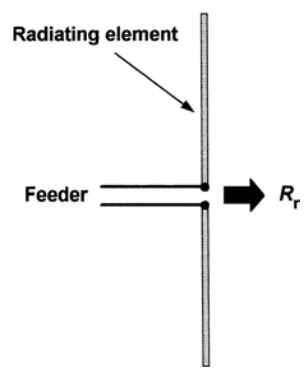

Figure 20.21 Radiation resistance

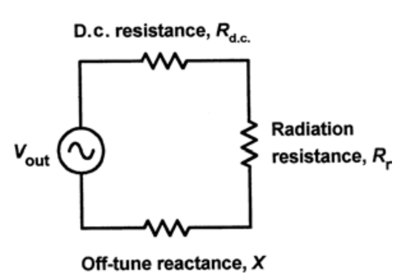

Figure 20.22 Equivalent circuit of an aerial

(a) the d.c. resistance, $R_{d.c.}$
(b) the radiation d.c. resistance, $R_{d.c.}$
(c) the 'off-tune' reactance, X

Note that when the antenna is operated at a frequency that lies in the centre of its pass-band (i.e. when it is *on-tune*) the off-tune reactance is zero. It is also worth bearing in mind that the radiation resistance of a half-wave dipole varies according to its height above ground. The 70 Ω to 75 Ω impedance normally associated with a half-wave dipole is only realized when the aerial is mounted at an elevation of 0.2 wavelengths or more.

Radiated power and efficiency

In the case of a transmitting aerial, the radiated power, P_r, produced by the antenna is given by:

$$P_r = I_a^2 \times R_r$$

where I_a is the aerial current, in amperes, and R_r is the radiation resistance in ohms. In most practical applications it is important to ensure that P_r is maximized and this is achieved by ensuring that R_r is much larger than the d.c. resistance of the antenna elements.

The efficiency of an antenna is given by the relationship:

$$\text{Radiation efficiency} = \frac{P_r}{P_r + P_{loss}} \times 100\%$$

where P_{loss} is the power dissipated in the d.c. resistance present. At this point it is worth stating that, while efficiency is vitally important in the case of a transmitting aerial it is generally unimportant in the case of a receiving aerial. This explains why a random length of wire can make a good receiving aerial but may not be very good as a transmitting antenna!

Example 20.7

An HF transmitting aerial has a radiation resistance of 12 Ω. If a current of 0.5 A is supplied to the aerial, determine the radiated power.

Solution

In this case, $I_a = 0.5$ A and $R_r = 12$ Ω

Now $P_r = I_a^2 \times R_r$ hence:

$$P_r = (0.5)^2 \times 12 = 0.25 \times 12 = 4 \text{ W}$$

Example 20.8

If the aerial in Example 20.7 has a d.c. resistance of 2 Ω, determine the power loss and the radiation efficiency of the aerial.

Solution

From the equivalent circuit shown in Fig. 20.22, the current that flows in the d.c. resistance of the aerial, $R_{d.c.}$, is the same as that which flows in its radiation resistance, R_r. Thus $I_a = 0.5$ A and $R_{d.c.} = 2$ Ω

Now $P_{loss} = I_a^2 \times R_{d.c.}$ hence:

$$P_{loss} = (0.5)^2 \times 2 = 0.25 \times 2 = 0.5 \text{ W}$$

The radiation efficiency of the aerial is given by:

$$\text{Radiation efficiency} = \frac{P_r}{P_r + P_{loss}} \times 100\%$$

$$= \frac{4}{4 + 0.5} \times 100\% = 89\%$$

In this example, more than 10% of the power output is actually wasted!

Aerial gain

The field strength produced by an aerial is proportional to the amount of current flowing in it. However, since different types of aerial produce different values of field strength for the same applied RF power level, we attribute a power gain to the aerial. This power gain is specified in relation to a **reference aerial** and it is usually specified in decibels (dB) – see Appendix 7.

Two types of reference aerial are used, an **isotropic radiator** and a **standard half-wave dipole**. The former type of reference aerial is only a theoretical structure (it is assumed to produce a truly spherical radiation pattern and thus could only be realized in three-dimensional space well away from the Earth). The latter type of aerial is a more practical reference since it is reasonably easy to produce a half-wave dipole for comparison purposes.

In order to distinguish between the two types of reference aerial we use subscripts **i** and **d** to denote isotropic and half-wave dipole reference aerials, respectively. As an example, an aerial having a gain of 10 dB_i produces ten times power gain when compared with a theoretical isotropic radiator. Similarly, an aerial having a gain of 13 dB_d produces 20 times power gain when compared with a half-wave dipole. Putting this another way, to maintain the same field strength at a given point, you would have to apply 20 W to a half-wave dipole or just 1 W to the aerial in question! Some representative values of aerial gain are given in Table 20.1.

Fig. 20.23 shows typical half-wave dipole aerials for domestic VHF Band II FM broadcast reception. The half-wave dipole in Fig. 20.23(a) is horizontally polarized (and therefore has a bi-directional characteristic) while the half-wave dipole in Fig. 20.23(b) is vertically polarized (and therefore has an omni-directional characteristic).

Table 20.1 Some typical values of aerial gain

Application	Gain (dBd)
Half-wave wire dipole for VHF Band II FM broadcast reception	0
Dipole and reflector for Band III digital radio reception	3
Car roof mounted aerial for UHF private mobile radio (PMR)	4
Four-element Yagi for high-quality FM broadcast reception	6
Multi-element Yagi aerial for fringe area Band V terrestrial broadcast TV reception	12
Parabolic reflector antenna for satellite TV reception	24
3 m steerable parabolic dish reflector for tracking space vehciles at UHF	40

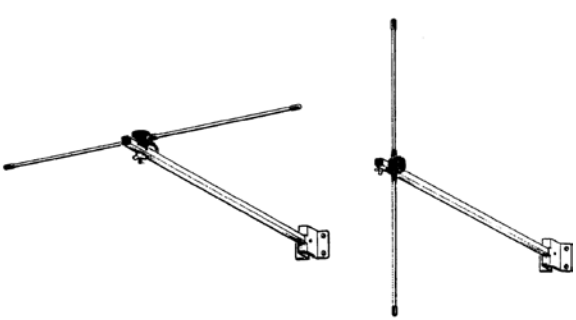

Figure 20.23 Typical dipole aerials for local VHF Band II FM reception: (a) horizontally polarized (b) vertically polarized. Note that (a) is bi-directional and (b) is omni-directional in the horizontal plane

The Yagi beam aerial

Originally invented by two Japanese engineers, Yagi and Uda, the Yagi aerial has remained extremely popular in a wide variety of applications and, in particular, for fixed domestic FM radio and TV receiving aerials. In order to explain, in simple terms, how the Yagi aerial works we shall use a simple light analogy.

An ordinary filament lamp radiates light in all directions. Just like an aerial, the lamp converts electrical energy into electromagnetic energy. The only real difference is that we can *see* the energy that it produces!

The action of the filament lamp is comparable with our fundamental dipole aerial. In the case of the dipole, electromagnetic radiation will occur all around the dipole elements (in three dimensions the radiation pattern will take on a doughnut shape). In the plane that we have shown in Fig. 20.20(a), the directional pattern will be a figure-of-eight that has two lobes of equal size. In order to concentrate the radiation into just one of the radiation lobes we could simply place a reflecting mirror on one side of the filament lamp. The radiation will be reflected (during which the reflected light will undergo a 180° phase change) and this will reinforce the light on one side of the filament lamp. In order to achieve the same effect in our aerial system we need to place a conducting element about one-quarter of a wavelength behind the dipole element. This element is referred to as a **reflector** and it is said to be ‘parasitic’ (i.e. it is not actually connected to the feeder). The reflector needs to be cut slightly longer than the driven dipole element. The resulting directional pattern will now only have one **major lobe** because the energy radiated will be concentrated into just one half of the figure-of-eight pattern that we started with.

Continuing with our optical analogy, in order to further concentrate the light energy into a narrow beam we can add a lens in front of the lamp. This will have the effect of bending the light emerging from the lamp towards the normal line. In order to achieve the same effect in our aerial system we need to place a conducting element, known as a **director**, on the other side of the dipole and about one-quarter of a wavelength from it. Once again, this element is parasitic but in this case it needs to be cut slightly shorter than the driven dipole element. The resulting directional pattern will now have a narrower major lobe as the energy becomes concentrated in the normal direction (i.e. at right angles to the dipole elements).

The resulting aerial is known as a three-element Yagi aerial (see Fig. 20.24). If desired, additional directors can be added to further increase the gain of the aerial and reduce the **beamwidth** of the major lobe. A typical three-element horizontally polarized Yagi suitable for VHF Band II broadcast reception is shown in Fig. 20.25.

Further director elements can be added to increase the gain and reduce the **beamwidth** (i.e. the angle between the half-power or –3dB power points on the polar characteristic) of Yagi aerials. Some typical gain and beamwidth figures for Yagi aerials are given in Table 20.2. From these data it is worth noting that aerial gain increases by an approximate 3 dB every time the antenna doubles in size. It is also worth noting the diminishing return as the Yagi becomes large (e.g. an increase of only 1 dB in gain as the aerial increases in size from 22 to 32 elements!).

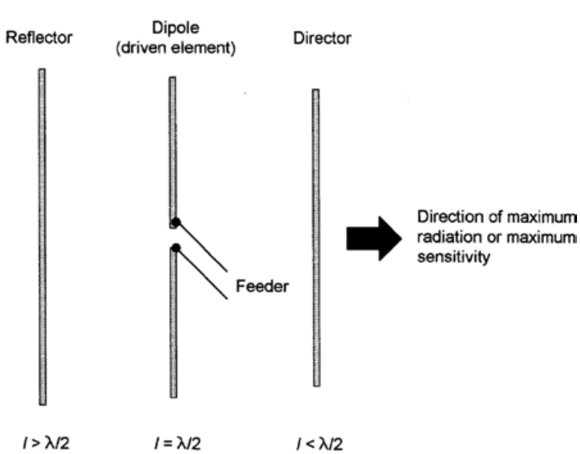

Figure 20.24 A three-element Yagi

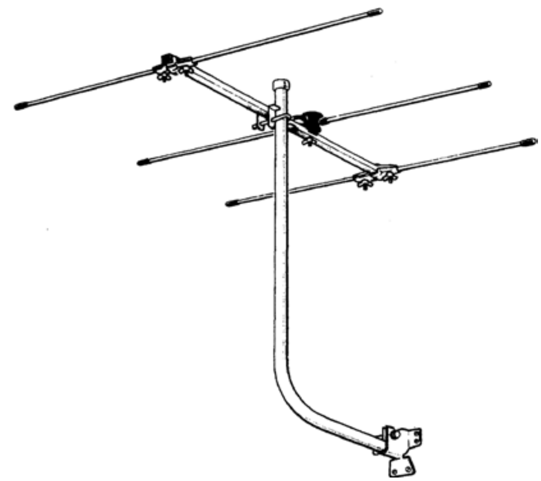

Figure 20.25 A typical three-element Yagi aerial for VHF Band II FM reception

Table 20.2 Typical gain and bandwidth figures for Yagi aerials

Number of elements	Gain (dBd)	Beamwidth (degrees)
3	4	70
4	6	60
8	9	40
16	11.5	20
22	12	13
32	13	10

Practical investigation

Objective

To investigate the operation of a 455 kHz RF/IF amplifier and demodulator stage.

Components and test equipment

Breadboard, 9 V d.c. power supply (or 9 V battery), BC548 (or similar NPN transistor), resistors of 1 kΩ, 4.7 kΩ, 10 kΩ, 22 kΩ 5% 0.25 W, capacitors of 100 pF, 470 pF, 10 nF (two required), 100 nF (two required), ferrite cored high-Q inductor of 220 μH (with series loss resistance of 2 Ω or less), oscilloscope, digital multimeter (for checking bias voltages), RF signal generator with amplitude modulated output, output attenuator and frequency adjustable over the range 200 kHz to 700 kHz, test leads and probes.

Procedure

Connect the circuit as shown in Fig. 20.26. With the signal generator disconnected, connect the d.c. supply and use the digital multimeter on the 20 V d.c. range to measure the collector, base and emitter voltages on TR_1. These should be approximately 9 V, 2.8 V and 2.1 V, respectively. If these voltages are substantially different you should carefully check the wiring and connections to TR_1.

Switch the signal generator on and set the output to 2 mV peak-to-peak (707 μV r.m.s.) at 455 kHz, unmodulated. Connect the oscilloscope (using matched probes) to display the RF output on Channel 1 (or Y1) and the demodulated output on Channel 2 (or Y2). The oscilloscope timebase should be set to 1 μs/cm while the Channel 1 and 2 gain settings should both be set to 100 mV/cm. The Channel 1 input should be set to a.c. while the Channel 2 input should be set to d.c.

Display the waveforms produced and sketch two or three cycles of both waveforms using the layout shown in Fig. 20.28. Now select modulated RF output on the signal generator and set the **modulation depth** to 30%. Change the oscilloscope timebase setting to 1 ms/cm and display the output waveforms produced. Sketch two or three cycles of the waveforms using the layout shown in Fig. 20.29.

Switch the modulation off and check that the output of the signal generator is still set to 455 kHz. Accurately measure the peak–peak RF output (Channel 1). This should be approximately 500 mV peak–peak. Record the output voltage in a table similar to that shown in Table 20.3.

Vary the signal generator output frequency over the range 200 kHz to 700 kHz in suitable steps and record the peak–peak output voltage at each step in your table.

Calculations and graphs

Record your results a table (see Table 20.3). Plot a graph showing the frequency response of the RF/IF amplifier using the graph layout shown in Fig. 20.27. Determine the frequency at which maximum voltage gain is achieved and calculate the stage gain at this frequency. Also determine the bandwidth of the amplifier stage.

Table 20.3 Table of results

Frequency (kHz)	200	300	400	455	500	600	700	800
Voltage (mV pk–pk)								

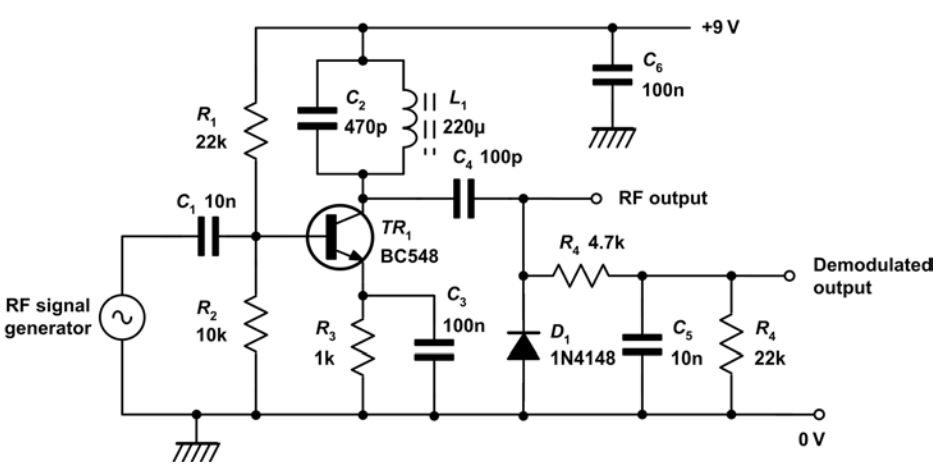

Figure 20.26 RF amplifier/demodulator circuit used in the Practical investigation

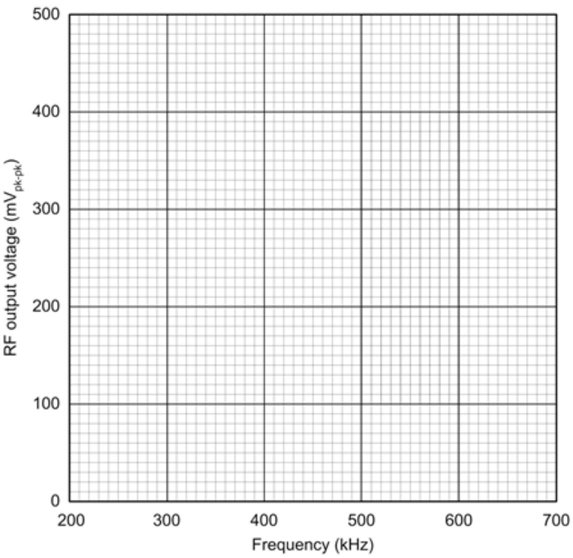

Figure 20.27 Graph layout for plotting the results

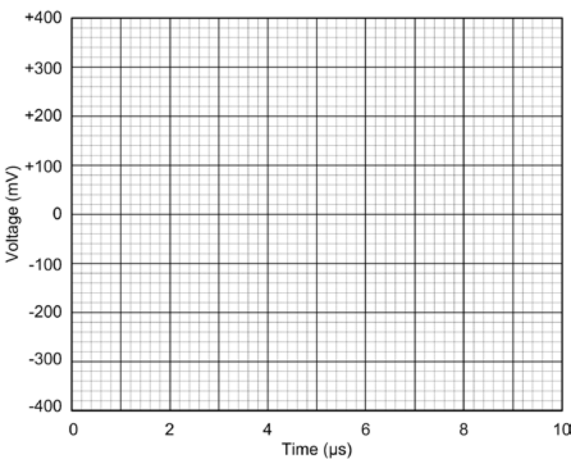

Figure 20.28 Layout for sketching the unmodulated RF output waveform

Conclusions

Comment on the shape of the frequency response and the waveform sketches. Were these what you would expect? Suggest a typical application for the circuit.

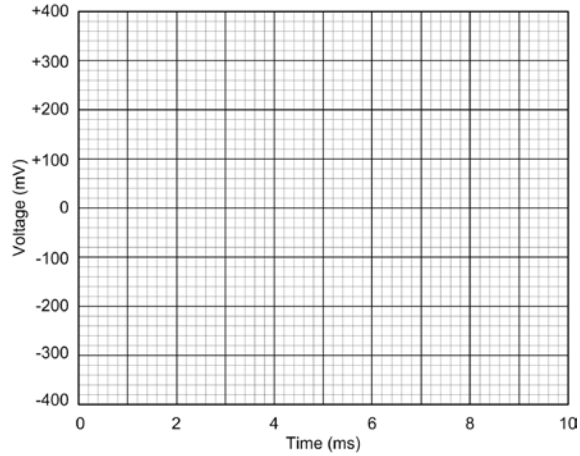

Figure 20.29 Layout for sketching the demodulated waveform

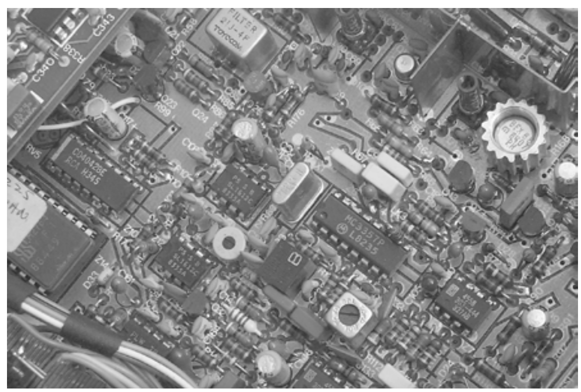

Figure 20.30 10.7 MHz and 455 kHz IF amplifier stages in a typical mobile transceiver

Formulae introduced in this chapter

Frequency and wavelength:
(page 3)

$$v = f\lambda \qquad f = \frac{v}{\lambda} \qquad \lambda = \frac{v}{f}$$

Velocity of propagation:
(page 4)

$v = 3 \times 10^8$ m/s for waves in air or space.

BFO frequency:
(page 5)

$$f_{BFO} = f_{RF} \pm f_{AF}$$

Local oscillator frequency:
(page 9)

$$f_{LO} = f_{RF} \pm f_{IF}$$

Half-wave dipole aerial:
(page 10)

$$l = \frac{\lambda}{2}$$

Aerial impedance:
(page 12)

$$Z = \frac{E}{I}$$

Radiated power:
(page 13)

$$P_r = I_a^2 \times R_r$$

Radiation efficiency:
(page 13)

$$\text{Efficiency} = \frac{P_r}{P_r + P_{loss}} \times 100\%$$

Problems

20.1 A broadcast transmitter produces a signal at 190 kHz. What will be the wavelength of the radiated signal?

Table 20.4 See Question 20.5

Frequency (MHz)	10.4	10.5	10.6	10.7	10.8	10.9	11.0
Voltage (V)	0.42	0.52	0.69	1.0	0.67	0.51	0.41

20.2 What frequency corresponds to the 13 m short wave band?

20.3 A signal in a cable propagates at two-thirds of the speed of light. If an RF signal at 50 MHz is fed to the cable, determine the wavelength in the cable.

20.4 An AM broadcast receiver has an IF of 470 kHz. If the receiver is to be tuned over the medium wave broadcast band from 550 kHz to 1.6 MHz, determine the required local oscillator tuning range.

20.5 The data shown in Table 20.4 were obtained during an experiment on an IF band-pass filter. Plot the frequency response characteristic and use it to determine the IF frequency, bandwidth and Q-factor of the filter.

20.6 Refer to the IF amplifier/AM demodulator circuit shown in Fig. 20.17. Identify the component(s) that provide:

(a) a tuned collector load for TR_1
(b) base bias for TR_1
(c) coupling of the signal from the IF amplifier stage to the demodulator stage
(d) a low-pass filter to remove RF signal components at the output of the demodulator
(e) a volume control
(f) removal of the d.c. level on the signal at the output of the demodulator
(g) a bypass to the common rail for RF signals that may be present on the supply
(h) input coupling to the IF amplifier stage.

20.7 A half-wave dipole is to be constructed for a frequency of 50 MHz. Determine the approximate length of the aerial.

20.8 A power of 150 W is applied to a dipole aerial in order to produce a given signal strength at a remote location. What power, applied to a Yagi aerial with a gain of 8 dB_d, would be required to produce the same signal strength?