No. 214

The Institution of Post Office Electrical Engineers

An Introduction to Waveguides and Microwave Radio Systems

C. F. FLOYD, M.A., A.M.I.E.E.

A Paper read before the London Centre of the Institution on
7th May, 1956, and at other Centres during the Session.

No. 214

The Institution of Post Office Electrical Engineers

An Introduction to Waveguides and Microwave Radio Systems

C. F. FLOYD, M.A., A.M.I.E.E.

A Paper read before the London Centre of the Institution on
7th May, 1956, and at other Centres during the Session.

CONTENTS

An Introduction to Waveguides and Microwave Radio Systems

1. INTRODUCTION

Microwave radio systems operating over line-of-sight paths are now accepted as normal links in this country's trunk network. Most of the broadband channels so far installed are used for television distribution because microwave radio links suitable for this type of traffic can be installed relatively quickly and economically. The application of microwave radio to multi-channel telephony is proceeding rather more slowly, but the main development problems are now solved and the first multi-channel telephony link[1] in the trunk network was opened to traffic in September, 1957. Although the science of microwave radio is still relatively new to the Post Office, it is likely to be of more than passing interest to many who are not at present engaged in radio engineering. Perhaps this paper will help to stimulate such interest ; it is intended for those engaged in other aspects of telecommunications than radio and for students who are seeking a general non-mathematical introduction to some of the microwave techniques that apply to broadband transmission.

The possibility of radio communication using centimetre waves has been visualised for many years : some of the earliest experiments in radio were made, over very short distances, by this means.

However, when long distance communication was found to be possible with lower frequencies, it was logical that the h.f. band as we now know it should be first exploited, the highest frequency used being only a few megacycles per second. As thermionic valves developed the frequency ceiling was raised and short-wave radio was introduced. These systems were narrow band, in that only a very few telephony circuits, sometimes only one, could be carried over them.

The increasing demands for inland trunk circuit expansion led, in the mid-thirties, to the growth of interest in the development of broadband transmission ; the coaxial cable multi-channel system using negative feedback repeaters became practicable with the higher performance valves then being designed, and this was the first type of successful broadband telephony transmission system. The corresponding development in radio transmission came some years later, when new principles were introduced in thermionic valves, that favoured operation at much higher frequencies than hitherto : the magnetron and the klystron were invented, followed later by the travelling-wave valve. These new valves, by making use of the transit time of the electrons, operate most happily at frequencies of several thousands of Mc/s. The first two types of valve, the magnetron and klystron, contain resonant cavities in their make-up, and so have to be tuned to the frequency of operation. The travelling-wave amplifier does not depend on resonance however ; it can therefore operate over a wide frequency range, with the result that it can be made to amplify a bandwidth of several hundreds of megacycles if necessary.

Telecommunication engineers were not slow to realise the possibilities[2] of such a wideband amplifier ; but other new techniques had also to be developed such as filters, attenuators and mixers constructed in waveguide, before broadband radio systems could be designed to exploit the microwave frequencies[3]. Radio is the only practicable transmission medium for frequencies of a few thousand megacycles per second, and path lengths of the order of 30 miles between transmitter and receiver are quite possible. The attenuation of coaxial cable, or waveguide, is too high for either to be a serious competitor with radio at centimetric wavelengths.

The use of still higher frequencies, known as millimetric waves of the order of 50,000 Mc/s, which can be propagated in circular waveguide with remarkably low attenuation, is a still later development that is not within the scope of this paper.

2. MICROWAVES IN WAVEGUIDE

2.1. Why Waveguides are necessary

Since the purpose of this paper is to provide an introduction to microwave engineering, it is desirable to link-up the new techniques with those that are already familiar.

Fundamentally, of course, all alternating currents, whatever their frequency, follow the same physical laws ; but as the frequency of alternation rises, the apparent behaviour of the current in a circuit changes because the relations between various properties of the conducting path and its surroundings are frequency dependent.

For example, a capacitance of 1 picafarad (1 micro-microfarad) gives a reactance of 16 megohms at 10 kc/s, but only 40 ohms at 4000 Mc/s. A short piece of wire with a self inductance of 1 microhenry has a reactance at 10 kc/s of about 0.06 ohms : at 4000 Mc/s it is 24,000 ohms. If a piece of microwave equipment contained such an unscreened piece of wire, the impedance discontinuity at this point could cause the wire to act as a radiator and much of the electrical energy in the circuit would be dissipated as radio waves from the short wire.

Then, too, "skin" effect, whereby a high frequency current is forced by its own field to travel near the surface of a conductor, is very important at microwave frequencies. The current depth in the conductor is probably only a few thousandths of an inch and consequently the nature of the surface has great effect on the high frequency resistance. Roughening of the

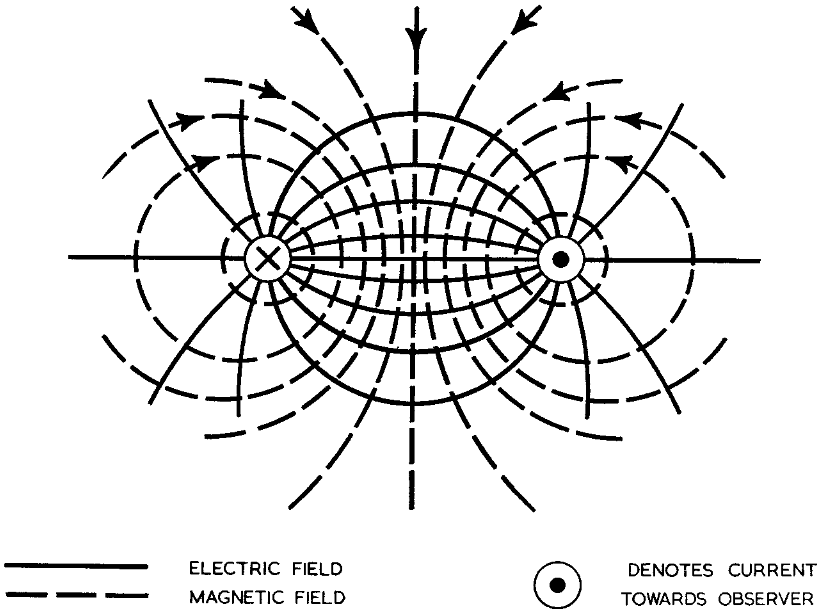


FIG. 1.—FIELD PATTERN ROUND AN OPEN WIRE TRANSMISSION LINE.

surface by scratches or corrosion can greatly increase the transmission loss.

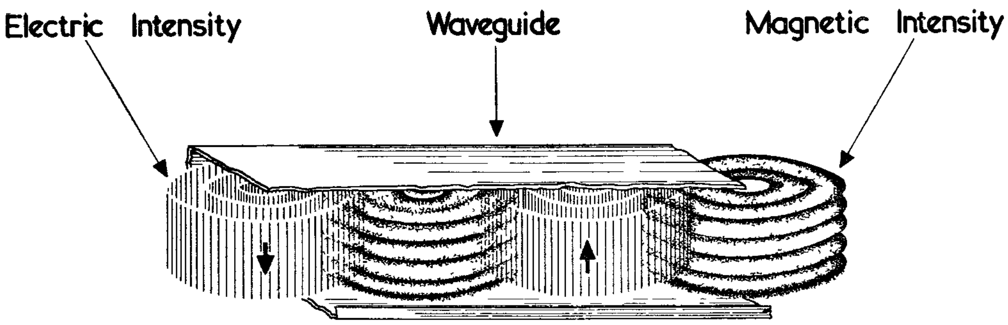
It is, of course, well known that a parallel wire transmission line carrying an alternating current has an attendant electromagnetic field as shown in cross section in Fig. **1.** This field contains two components, loops of magnetic intensity that surround each wire without cutting them, and lines of electric force that stretch between the wires, cutting the magnetic loops everywhere orthogonally. If the alternating current is sinusoidal, these fields are sinusoidal along the transmission line, and at any given cross section they are sinusoidal with time. This electromagnetic field is the means whereby energy is transmitted along the circuit.

A coaxial cable provides a more convenient transmission line for radio frequencies than an open wire line because the electromagnetic field can be enclosed in the space between the two concentric conductors, giving in effect a completely screened pair. Transmission losses in a coaxial cable increase with frequency because both the dielectric losses in the insulating material separating the coaxial conductors and the r.f. resistance of the conducting surfaces are frequency dependent; the first is proportional to frequency and the second to the square of the frequency. Microwaves can be transmitted along coaxial cables of suitable design as can frequencies of a few megacycles per second, but even in specially designed coaxial cables, the losses are high; for example the attenuation of a good coaxial cable aerial feeder may be of the order of 1.5 db per 100 feet at 1000 Mc/s and 3.5 db at 4000 Mc/s.

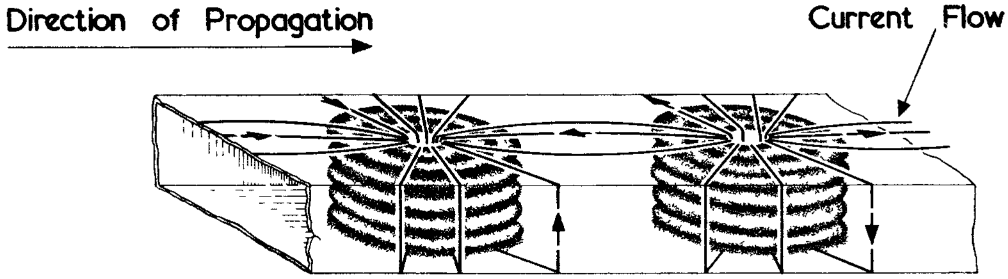
Short transmission lines are often made of waveguide which has lower attenuation than coaxial cable and can therefore be used at much higher frequencies. Waveguide [3], [4], [5], [6] is a form of transmission line in which the inner conductor is entirely dispensed with, the electromagnetic wave being launched down a hollow metal tube as a radio wave. The tube, which is commonly of brass or copper, is usually rectangular and made to accurate internal dimensions. Electromagnetic waves are launched at the sending end, and picked up at the receiving end, by small antennae inside the waveguide. At 4000 Mc/s, copper waveguide has an attenuation of the order of 1 db per 100 foot length, and this type of conductor gives about the lowest attenuation obtainable at such a frequency; but even so the loss is much too high for waveguides to be used for long distance transmission at 4000 Mc/s. They are however used for internal connexions within a radio station and for connecting aerials at mast tops to the equipment at ground level.

At even higher frequencies, e.g. 40,000 Mc/s, some astonishingly low values of attenuation can be obtained in circular waveguide because of a unique characteristic of a mode of transmission in this type of guide which results in decreasing attenuation as the frequency increases. Development work is in its infancy on the application of this millimetric wave transmission and the techniques will not be discussed in this paper. There is little doubt however that this mode of transmission for long distances in circular waveguide will revolutionise broadband trunk circuit provision in the future.

Rectangular waveguide is usually manufactured in drawn lengths of about 10 feet, which are later fitted with robust end flanges that can be bolted together accurately. There is much emphasis on mechanical accuracy in all waveguide construction work, not only because most of the apparatus is heavy and inflexible, so that waveguide runs must be precisely the right size and shape, but also because the electrical performance can be marred by such imperfections as



(a) FIELD DISTRIBUTION



(b) CURRENT FLOW

FIG. 2.—TRANSMISSION IN MATCHED WAVEGUIDE.

ill-fitting joints, rough corners, or burrs on flanges. The inner surface of waveguide must be kept clean and smooth and free from moisture, or tarnish and corrosion will occur. Experiments have shown that for long lengths of brass or copper waveguide the smooth inner surface left by the tube-drawing process can give better transmission than an electro-plated finish, because plating often lacks homogeneity. Corrosive gases must be excluded from the waveguide, and one method[7] of ensuring this is to fill long waveguide runs such as aerial feeders with dry air or nitrogen at a slight pressure above the atmosphere. The ends of the guide are closed by mica windows: these provide a seal against gas leakage without introducing any serious disturbance in the transmission properties of the waveguide feeder.

2.2. Field Patterns in Waveguide

Even the simplest form of electromagnetic field pattern that can exist in a rectangular waveguide is relatively complex and the full analysis is highly mathematical; but the general shape and directions of the magnetic and electric components of the field at any instant can be illustrated fairly readily. The most important case is when the waveguide is working as an infinitely long line, i.e. correctly matched at each end. Fig. **2(a)** illustrates this condition for the fundamental mode of transmission, the waveguide being shown cut away so that the electromagnetic field can be "seen" as it passes along inside the guide.

The electric and magnetic fields are in time phase and in space quadrature, the lines of electric and magnetic intensity being always at right angles to each other where they cut. If the electromagnetic field could suddenly be "frozen" at any instant and a longitudinal section made down the centre of the guide in a plane parallel to the electric field the maxima of the magnetic and electric field components would be found to occur together. In this "frozen" state, a plot of the electric and magnetic intensities along the length of the guide and on the central axis would be generally sinusoidal in character.

Fig. **2 (b)** shows how the currents flow on the inner surface of the waveguide relatively to the magnetic field. Where the current appears to collect on the surface it can be imagined as continuing as a space charge current across to the opposite face of the waveguide. The electric field is, of course, also present, as in Fig. **2 (a)** but it has been omitted in Fig. **2 (b)** to show the lines of current flow more clearly. It should be noticed that no current flows across the longitudinal axis of the wider wall of the waveguide, so that this is the only line along which longitudinal slots or butt joints in the metal can be permitted. In some instruments employing waveguide, e.g. some adjustable attenuators, a slot has to be cut along this line of zero current flow in order that a thin vane can enter. The waveguide operates satisfactorily nevertheless, and without any appreciable loss by radiation from the slot.

The wavelength of the electromagnetic field in the guide is longer than the free space wavelength. Two important velocities are associated with the wave pattern, the group velocity (V_g) which is the speed of transmission of energy, and this must always be less than the velocity of light; and the phase velocity (V_p) which is really a geometrical concept because it exceeds the velocity of light (C). These two velocities are related by $V_p.V_g=C^2$. Space does not permit any further details to be given in this paper, but an explanation is given elsewhere[3, 4].

An important difference between the electromagnetic field in an infinitely long waveguide and that in an open parallel-wire transmission line is that in waveguide there is a component of the field along the direction of transmission while there is no such component in an open parallel-wire line. The mode of transmission is known as an H mode when the component of the electromagnetic field along the guide is magnetic; and it is known as an E mode if the component along the guide is electric. Modes are designated by suffices *l*, *m*, to the letter H or E as applicable. In rectangular guide the suffix *l* denotes the number of half-wave patterns of electric (or magnetic) field across one dimension of the cross-section of the waveguide, and the suffix *m* denotes the number of half-wave patterns across the other dimension. The suffix *l* usually refers to the shorter dimension. The mode of transmission illustrated in Fig. **2** is the $H_{0,1}$ mode, i.e. $l = 0$ and $m = 1$; H denotes that there is a component of magnetic field along the axis of the guide, the suffix 0 denotes that there is no half-wave pattern of field across the narrow dimension, and the suffix 1 denotes a single half-wave pattern of field across the wide dimension of the guide section. The $H_{0,1}$ is called the Principal, or Dominant, mode because it is the simplest that the waveguide can sustain.

It has already been explained that a waveguide behaves as a high-pass filter[3, 4], with a definite cut-off wavelength for each mode of transmission. The most useful mode is the dominant mode, the one with the lowest cut-off frequency, i.e. the longest wavelength. If the transmission band to be used is restricted to the frequency range between this and the cut-off frequency for the next mode, only the wanted mode can propagate freely along the waveguide, which is the condition that the engineer desires to encourage. The cut-off wavelength is twice the wider dimension of the inside of the waveguide, that is five inches for the $2\frac{1}{2}$ in. × $1\frac{1}{4}$ in. waveguide, which is the standard size used by the Post Office for work at about 4000 Mc/s. The shorter dimension, in this case $1\frac{1}{4}$ in., is usually chosen to be half the wider dimension in order to remove higher-order modes from the frequency range between the cut-off of the $H_{0,1}$ mode and that of the next higher mode, $H_{0,2}$. The shorter dimension also controls the breakdown voltage that the waveguide can stand because, as can be seen from Fig. **2**, this is the distance between the points of maximum electric field. The breakdown voltage is not likely to be encountered in telecommunications applications of waveguide however, as only low power is used.

These brief remarks on field patterns have so far referred to a correctly terminated waveguide, or a guide of infinite length. The other extreme is the completely mismatched, e.g. short-circuited, waveguide where all the energy is reflected at the mismatch. In such a case standing-wave patterns are set up, because the incident and reflected waves interact to produce a stationary field pattern in which the positions of maximum electric field intensity coincide with the centres of the loops of magnetic intensity.

2.3. Launching of Waves in a Waveguide

Methods whereby an electromagnetic wave can be launched in a waveguide—and conversely, picked-up again—are illustrated in Figs. **3** (**a**) and **3** (**b**). In the first of these electric coupling is employed, and in the second magnetic coupling. In Fig. **3** (**a**) the electric component of the field is stimulated by a small antenna placed in the waveguide parallel to the direction of the electric field. The antenna is simply the protruding end of the centre conductor of a coaxial cable. In Fig. **3(b)** the loops of magnetic field are stimulated in the waveguide by the current in a wire loop terminating the coaxial feeder which is presumed to be the source of energy. Alternative positions in the guide for the energising loop are shown in Fig. **3(b)**. Except where the wave is launched by a loop on the back plate, both these systems of launching electromagnetic waves should have reflecting plungers terminating the guide on the side where transmission is not required. These plungers are placed at the correct distance to reflect energy back to the launching point so that it is in phase with that starting out along the waveguide. Ideally a perfectly matched sending end that transmits all the energy in the required direction is obtained by this means.

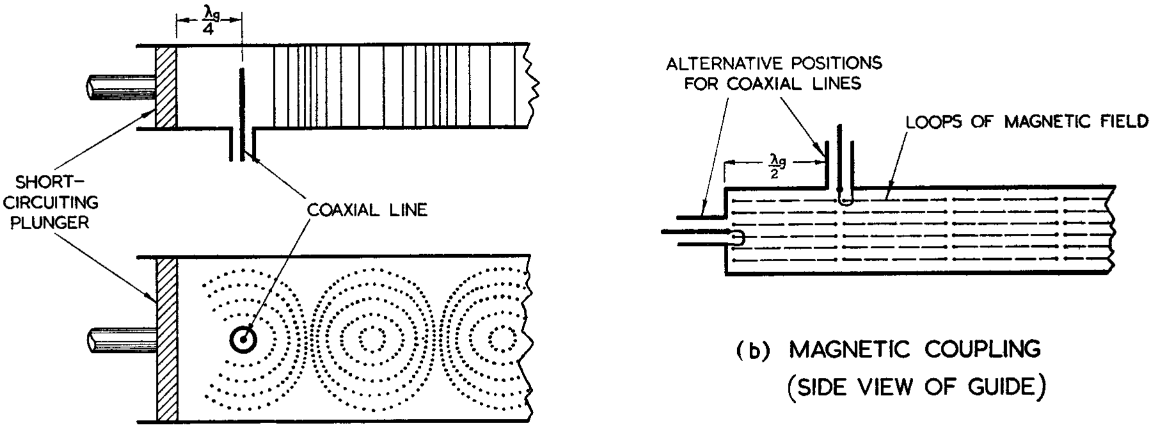
2.4. Waveguide Components

Many ingeniously constructed components have been devised for use in waveguide transmission. There are, for example, attenuators in which a vane covered with a resistive coating projects into the field, dissipating energy by induction; wave-meters employing cylindrical cavities of adjustable lengths which resonates with Q-values that may be as high as 20,000 when in tune with the fields in the waveguide connected to them; crystal detectors connected to small antennae protruding into the guide, Y-type change-over switches, and standing wave indicators. Excellent bandpass, bandstop and narrowband filters can now be built in waveguide. All these have been described[4] in the P.O.E.E. Journal so no further details of them will be given in this paper.

3. VALVES FOR MICROWAVE FREQUENCIES

In this section of the paper the principle of the velocity modulation valve[8] is explained and the klystron and the travelling-wave valve amplifier, both of which use this principle, are described.

Conventionally constructed valves of the space-charge control type such as might be used in domestic radio receivers are not suitable for use at microwave



(b) MAGNETIC COUPLING (SIDE VIEW OF GUIDE)

(a) ELECTRIC COUPLING

Fig. 3.—Launching of $H_{0,1}$ Mode in Waveguide.

frequencies. There are a number of reasons for this, two of the most important being that the periodic time of one cycle of alternating voltage at these super high frequencies is commensurate with the transit time of the electrons between the widely separated electrodes of an ordinary valve; and secondly, the inductances of the electrode connexions within an ordinary valve give impedances that are prohibitively great at these frequencies.

By using extremely delicate constructional techniques, in which valves have grid wire spacing of fractions of a thousandth of an inch and very closely spaced electrodes constructed with great accuracy, triode valves are being made commercially that operate satisfactorily at 2000 and 4000 Mc/s. America has for some years pioneered the development of these minute close-mesh grid triodes; so, also, have some laboratories in Europe and microwave triodes with a substantial length of life can now be guaranteed. In the Post Office, where reliable circuit operation is highly prized, the policy for development in the 4000 Mc/s band has been to encourage wherever possible the introduction of types of microwave valve that appear likely to offer the greatest scope for future development, and for this reason most of the microwave development work within the Post Office has so far been done not with microwave triodes, but with two other types of valve, the klystron and the travelling-wave valve[8]. Both these valves are essentially suitable for microwaves only. They are not adaptations of low-frequency valves because they employ velocity modulation of an electron beam, not space-charge control by a grid. The time required for a stream of electrons to move from one electrode to another is turned to advantage in these valves. In fact, it is intentionally increased until the transit time is equal to several times the duration of one cycle of a signal voltage at the operating frequency. The electron stream is "density modulated" by imposing velocity changes on the electrons at an early point in their flight through the valve; hence they are known as Velocity Modulation Valves.

3.1. The Klystron

The klystron was invented in 1939. Nowadays it is made in a number of different forms designed for particular applications, such as oscillators, narrow band amplifiers, frequency modulators, and frequency multipliers.

The basic principles of all these forms are similar, and are well exemplified in the two-cavity klystron working as an amplifier. This is shown diagrammatically in Fig. **4**. A steady parallel beam of electrons is fired by an electron gun through axial holes in the dished end walls of two successive cylindrical cavity resonators, known as the buncher and catcher respectively, and finally finishes its journey on a collector plate at the end of the tube. When the buncher cavity is made to resonate by some radio frequency source, such as an incoming microwave signal, an r.f. voltage is set up between the two cavity walls, so that the holes (a) and (b) swing rapidly in potential, being alternately positive and negative. When the far wall (b) is positive with respect to the near wall (a), the negative electrons in the beam which are at that time passing between the walls a - b of the buncher cavity will be accelerated in their flight. They will leave (b) with a velocity above the average of the beam and, as they fly on along the path of the beam, they will catch up on the ones in front and a "bunch" of electrons will form. As the resonant cavity potential between the walls (a) and (b) falls, the extra accelerating force on the electron beam also falls; when the potential of (b) swings negative relative to (a), the electrons in the beam near the hole (b) are retarded and the stream thins out. Notice that after the change of velocity has been imparted to the electrons, time must be allowed for sufficient relative movement to occur to give changes of density. This happens in the "drift space," that is, the distance *b c* between the buncher and the catcher, which is long enough to correspond to several radio frequency cycles at the frequency of resonance of the cavity. While the velocity-modulated electrons are traversing the drift space the "bunches" are gradually building up, and at the end of its travel the beam is said to be "density" modulated. A pulsating current has in fact been created, that is to say, the electron beam has been modulated at the frequency of the buncher cavity resonator. The gradual formation of the bunches is shown in Fig. **4** by the increasing concentration of the shading representing the electron beam traversing from left to right. The pulsating electron stream now passes through the hole (c) and between the walls of the second cavity resonator (the catcher) to emerge from (d) and pass on to the collector electrode, which acts as a sink. The catcher sees this passing modulated beam as an alternating field between its walls, and if the frequency of resonance of the cavity is the same, or nearly the same, as that of the modulation on the electron beam, the cavity resonates. Energy can be extracted from it by a small antenna, which "loads" the cavity ; this retards the phase of the resonance relative to the electron pulses, and so draws power from the driving source, the electron beam. The output power therefore comes from the energy in the electron beam, which is obtained from the gun firing the electrons drawn from the cathode.

When the conditions are correct, a useful degree of amplification, for example 20 db, can be obtained from the two-cavity klystron. This amplification can be increased by adding a third cavity (or even more) to amplify the bunching effect a second time before the energy from the beam is finally used to excite a catcher resonator. The simple klystron amplifier can only be used however to amplify a narrow band of input frequency of some 3 Mc/s width, because it relies entirely on resonant cavities : its use is restricted therefore to relatively narrow band microwave signals, or to amplifying single frequencies as in microwave carrier generating equipment. More recent work on multicavity klystrons has shown that, by stagger-tuning the cavities, an appreciably wider passband can be obtained in a klystron amplifier.

The theoretical efficiency of these klystron amplifiers is over 50 per cent., but only about 10 per cent. effective efficiency is obtained in low power valves. Their noise factor is also rather high, which might make them unsuitable for the first stage of a high gain amplifier.

Recent improvements in valve techniques have led to reduction in the noise factor of the klystron with the result that this type of amplifier may yet have a wider field of use in broadband transmission than had at first been supposed.

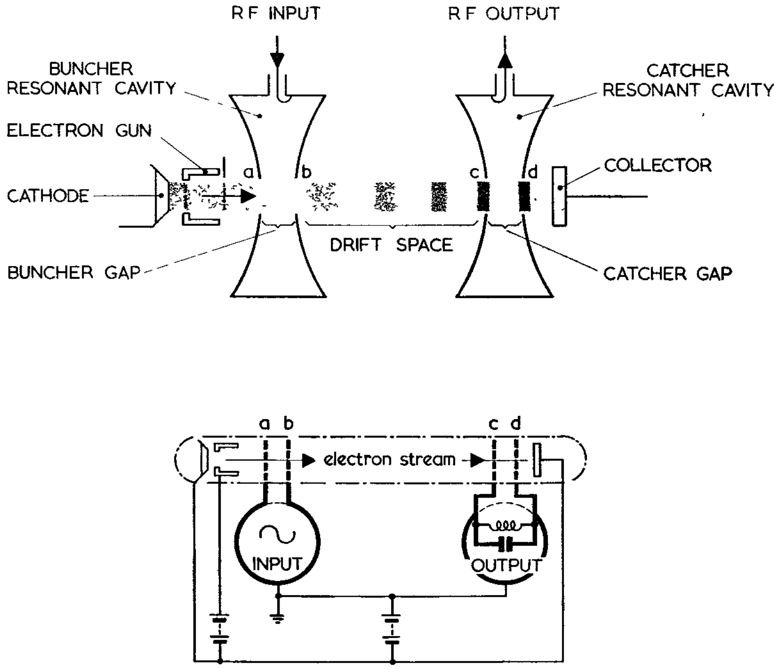


Fig. 4.—The Principle of the Klystron Amplifier.

3.2. Klystron Oscillator and Frequency Multiplier

The klystron amplifier just described can easily be made into an oscillator by feeding back a small amount of power from the collector cavity to the buncher ; a few inches of coaxial cable with the length necessary to get the correct phasing to sustain oscillation makes a suitable feedback loop.

Another interesting application of the klystron is in the frequency multiplier. When the voltages on the two-cavity klystron are correctly adjusted the "bunches" are sharply defined pulses with steep sides, almost rectangular rather than sinusoidal. This means, as Fourier's analysis shows, that there are high-order harmonics of the pulse frequency present in the modulation on the electron beam. Consequently if the catcher resonator is tuned to some harmonic frequency of the signal that is applied to the buncher, the output will consist principally of the harmonic frequency.

This is a most valuable form of frequency multiplier that can be of great value in generating microwave frequency carriers from quartz crystal oscillators. Quartz oscillators provide the most stable source of frequency available to engineers, but they cannot be built satisfactorily for the direct provision of frequencies much above 50 Mc/s. The frequency multiplying klystron provides a tool for expanding the science of quartz crystal controlled carrier generation into the microwave field.

3.3. The Reflex Klystron Oscillator

If the two-cavity klystron is only required to generate oscillations, and not to act as an amplifier, it can be simplified by folding the electron beam back on itself and making one cavity do the work of both the buncher and the catcher. The resulting valve, shown and explained in Fig. **5**, is then known as a reflex klystron. An electron beam is fired from a gun so as to traverse a buncher resonant cavity as previously described. If it is assumed that the state of oscillation is already established, the beam acquires velocity modulation from the alternating field existing between the walls, *a b*, of the metal cavity. Carried by the momentum initially imparted by the gun, the electrons pass beyond the cavity and through the drift space ; but instead of continuing to finish on a positive collector electrode, they meet the repelling field of a negatively charged plate that is interposed half way along the drift space. Without upsetting the bunching effect, this plate reflects the beam back over its own path so that the electrons return across the aperture, *b a*, in the cavity ; if the pulses of beam current (i.e. bunches of electrons) are in the correct phase relationship to the alternating field already prevailing between the walls of the cavity, the voltage induced by them will tend to maintain the state of oscillation. The wall of the resonant cavity acts as a collector plate on which the electron beam can terminate its path. The phase change on the out-and-back journey through the drift space must be $\frac{3}{4}$ cycle, or $(n + \frac{3}{4})$ where n is any whole number. The oscillator output power is drawn from the field in the cavity by a small antenna coupled to a coaxial feeder or waveguide. The output power comes, of course, from the electrons in the beam, the original source of this power being the energy imparted by the gun. About 100 milliwatt output power can be obtained from the CV 2116 which is the reflex klystron that is at present in widespread use in the Post Office laboratories and commercially.

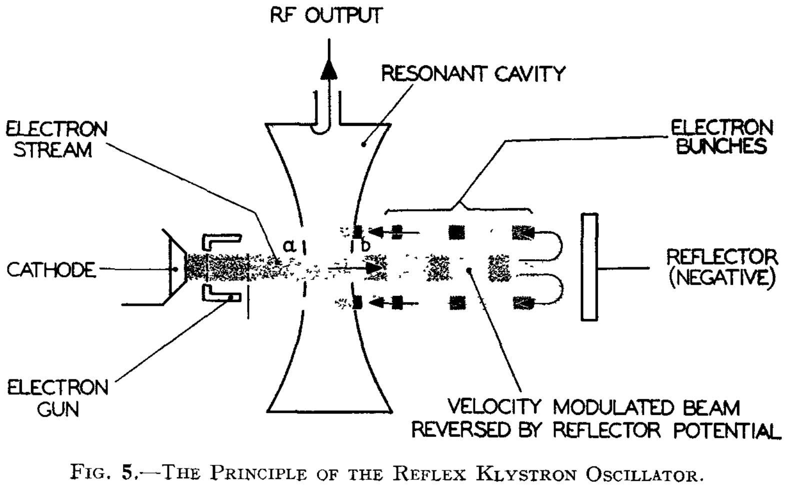


Fig. 5.—The Principle of the Reflex Klystron Oscillator.

it is kept at a steady potential of the order of 2000 volts above the cathode. This potential is adjusted so that the electron beam velocity is slightly greater than that of the longitudinal component of the electromagnetic field of the input signal travelling along the helix. Under these conditions, a continuous interaction takes place down the length of the tube between the electromagnetic wave and the electron beam. Firstly, near the input waveguide, the beam is velocity modulated at the microwave frequency by the incoming low-level electromagnetic wave in just the same way as the klystron beam was modulated by the buncher cavity. Only this time the alternating potential modulating the electron velocity is not due to resonance in a small cavity but to an alternating electromagnetic field travelling down the helix. The distance over which the beam interaction can take place is much greater than in the klystron and the velocity modulation effect is therefore greatly magnified. After a few inches of travel, the electromagnetic field due to the input is rapidly attenuated by its journey round the helix wire with the result that the electron beam is unable to absorb any more velocity modulation ; the middle length of the tube therefore acts as an extended drift space, where bunches can form in the beam as it travels on down the tube. Towards the collector end of the tube, the electron bunches have built up into a strong density modulation, the beam has virtually become a train of pulses, and these induce a field back into the helix, which by the end of the tube has become many times stronger—perhaps 25 db—than the input field received by the amplifier. The energy transferred from the electron beam to the helix is passed on to the output waveguide from the end of the helix, which acts on a small antenna inside the end of the guide. All the stages in the amplification process are indicated in Fig. **8.**

The build-up of the density modulation can be allowed to occur under optimum conditions in a travelling-wave valve, with plenty of distance and a relatively low velocity of electron travel. There are no resonant conditions in the operation of the valve, which is therefore inherently a wideband amplifier, almost independent of frequency over a range of hundreds of megacycles. However, the coupling elements between the waveguide and helix, with their tuning stubs, usually limit the frequency band of this amplifier, but it is still ample for present requirements. One precaution is essential in the construction of this valve. The electromagnetic field at the output end of the helix is so much greater than at the input end that steps must be taken to prevent harmful back-coupling outside and along the helix. The valve will oscillate if this feedback can occur. To prevent this feedback effect, a film of graphite is deposited on the inside of the glass tube in the region of the drift space. This gives a high attenuation between output and input, perhaps as much as 40 db, to the reverse leakage field by dissipating its energy in eddy currents.

A picture of a complete travelling-wave valve amplifier of a type in current use (1956) is shown in Fig. **9.** Various types of valve are available; the highest output power at present practicable for radio systems at 4000 Mc/s is now about 10 watts. Valves for 2000 Mc/s can give more than 20 watts output power. An intermediate size of valve capable of giving a higher gain, say 30 db, and sufficient output to drive the 10-watt valve, is also in common use. Both these valves have a noise factor of 17 or 18 db, which is too high for them to be used in the first stage of an amplifier where the signal is at its lowest level. A third type of travelling-wave valve designed specifically for minimum noise factor has therefore been developed by various manufacturers and noise factors as low as 7 or 8 db can now be achieved in the first amplifying stage using such a low noise valve.

The overall power consumption of the travelling-wave valve is very much increased by the use of a solenoid to focus the electron beam. A d.c. power of about 100 watts is needed to energise this coil and the weight of the amplifier is increased by 80 lbs to provide the copper winding. Recent improvements in this direction include winding the solenoid with aluminium foil to reduce the weight. For intermediate and high-power valves, electrostatic and permanent magnet focusing systems are in an advanced state of development to effect still further savings in weight and in the power required by travelling-wave valve amplifiers.

4. MULTI-CHANNEL MICROWAVE RADIO SYSTEMS: GENERAL PRINCIPLES

It is now desirable to examine in basic principle how waveguide techniques and velocity modulation valves can be combined with other aspects of radio frequency engineering to make up a microwave radio transmitter and receiver suitable for use as a link in a broadband multi-channel telephony network. Ideally, as good a performance should be sought from a broadband radio link as from coaxial cable channel of the same bandwidth ; it would then be possible to use both forms of transmission as links in the trunk network, each being installed on routes to which it is particularly suited. It follows that the radio system must be designed to accept the same signal band as that already standardised for the coaxial cable, which is the r.f. output from a ten supergroup coaxial repeatered pair before any demodulation has taken place. The name "baseband" has been introduced for the wideband signal carried over a broadband transmission system and it usually occupies a frequency band within the range of 60 kc/s to 2852 kc/s, consisting of a block of ten 60-channel supergroups, i.e. 600 telephone channels.

At present, it is more common in this country to transmit television than telephony over microwave radio links, and still wider basebands are already in demand for both purposes. Basebands of 900 or more telephone channels, or a baseband consisting of a television signal plus a few hundred telephone channels would both have applications in the trunk network. Designing equipment suitable for multi-channel telephony is more difficult than for television, because in the former the signal complexity is much

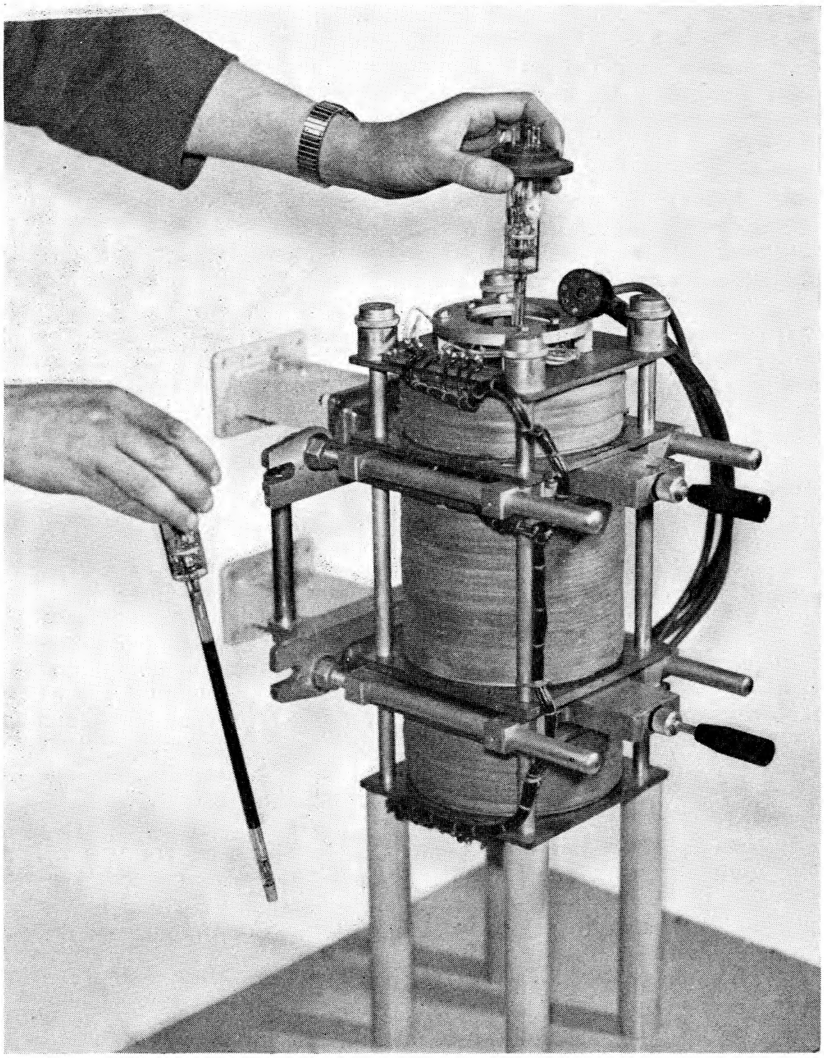


FIG. 9.—TRAVELLING-WAVE VALVE AMPLIFIER (SHOWING VALVE WITHDRAWN).

greater. Intermodulation problems become more acute as the number of channels carried in the baseband is increased. One of the fundamental problems in the design of broadband microwave links is how best to modulate the microwave carrier frequency of, say, 4000 Mc/s with the complex baseband input signal without introducing an unacceptable amount of intermodulation, or noise as it is usually termed, since this is how distortion appears to a subscriber listening on a circuit that has passed over a broadband link. Cable engineers would immediately think of a process of amplitude modulation based on an extension of the coaxial cable terminal translating equipment. This is an admirable process for transmission mediums where the utmost economy of bandwidth is a vital factor, where the path attenuation is inherently constant or at least predictable as in a coaxial cable, and where the path attenuation can conveniently be counteracted by constant gain as with the negative feedback amplifier.

Radio engineers, on the other hand, prefer frequency modulation. They have to use a transmission medium which is liable to wide fluctuations in attenuation due to fading phenomena, but have the advantage that in microwave radio ample frequency spectrum is available for exploitation. Radio also has an advantage over the coaxial cable in that, on a well selected route, the radio path has an attenuation that is independent of frequency over the bandwidths required for multi-channel working. When ample transmission bandwidth is available, the signal-to-noise ratio in a frequency modulation system can be made less than if amplitude modulation is used. Also, a wideband f.m. system in which "amplitude limiting" can be used is more satisfactory than an a.m. system if the input level to the receiver is varying extensively, as it will be when fading is present on the radio path. This advantage arises from the fact that in frequency modulation the signal is represented by the rate of change of frequency of the carrier. The amplitude of the instantaneous frequency components is immaterial. So if the radio receiver possesses automatic gain control, followed by a good limiter and discriminator, it can correct for a wide range of fading without introducing a proportionate degradation of the signal-to-noise ratio. A penalty has to be paid for this advantage of frequency modulation in that, to obtain the good signal-to-noise ratio, modulation sidebands up to a high order have to be transmitted and received ; a microwave radio system loaded with 600 telephone channels may require a radio transmission band 15 to 20 Mc/s wide. There is at present no simple equivalent, with frequency modulation, of the single sideband filtering that is possible in amplitude modulation technique,where one "frequency term," usually the upper or lower sideband, can carry the full intelligence without any resulting degradation of quality.

The actual bandwidth occupied by the frequency modulated carrier that forms the radio signal is dependent on the frequency deviation employed in the frequency modulating process, i.e. on the frequency swing imposed on the carrier, the rate of change of which represents the intelligence to be carried. In a multi-channel telephony f.m. system the deviation is a very important factor : ± 200 kc/s frequency deviation for a single tone on one audio channel at zero test level is a representative value. When all 600 channels are loaded with telephone traffic, probability factors enter the calculation ; but the corresponding peak frequency deviation that results for one per cent. of the busy hour is then approximately 1.6 Mc/s. To obtain an adequate advantage from frequency modulation, five sidebands would be transmitted on each side of the centre carrier frequency, so that the total bandwidth needed to contain the f.m. signal at the busy hour should not be less than ± 8 Mc/s, i.e. 16 Mc/s. Clearly there is no point in making the band-occupancy wider than necessary ; the lower limit to the frequency deviation adopted is set by the fact that the signal-to-noise ratio is also reduced as the test-tone deviation is reduced (i.e. the amount of background noise that results in the subscriber's telephone rises); but at the same time the extent to which intermodulation products are produced in certain parts of the equipment is also made less with smaller deviation (i.e. the noise from this source is reduced). So the value of frequency deviation used in the process of frequency modulation must be a compromise.

Fundamentally, by using frequency modulation the basic thermal noise resulting in an audio channel that has been over the microwave system can be made less than if amplitude modulation had been used. A second source of noise is also unavoidably present in a multi-channel broadband system, namely intermodulation noise. In an f.m. multi-channel link this is unintelligible and similar in character to thermal noise. It is caused by the generation of spurious frequencies at any point in the equipment, and owing to the nature of frequency modulation, no filtering process in the r.f. path can be used to reduce such unwanted intermodulation once it has occurred. This form of distortion is caused, not by non-linearity in amplitude frequency characteristics, but by non-linearity in the group-delay response of the system, i.e. by non-linearity of the curve given by differentiating the phase/frequency relation with respect to frequency. Frequency-selective fading can also give rise to such noise, particularly in channels towards the higher frequency end of the baseband. It should be noted that it is the phase-frequency characteristics and their first differential that are of importance in f.m., just as amplitude-frequency distortion is important in a.m. transmission systems.

4.1. The Transmitter and Receiver

GO and RETURN channels are, in effect, separate radio transmission systems operating on carrier frequencies that may be separated by 50 Mc/s or more. It is, therefore, only necessary to examine the equipment for one direction of transmission in this paper. The whole baseband signal is modulated at the transmitter on to one microwave carrier, and this will be radiated from a paraboloidal dish aerial in the form of a narrow beam. The incoming signal in the return direction may be picked up by the same dish aerial, to be separated by waveguide filters at the point where the feeder enters the building. On some designs of equipment, separate dishes are used for transmitting and receiving which doubles the amount of waveguide feeder needed, but saves a complicated filter installation.

4.1.1 *The Transmitter*

A block diagram of the essential items in a microwave radio transmitter is shown in Fig. **10.** The baseband signal, assumed here to be 600 channel telephony, first frequency-modulates an intermediate-frequency carrier of 70 Mc/s. The resulting wideband signal, centred on 70 Mc/s, then amplitude modulates the microwave carrier at 4000 Mc/s. After amplification in a travelling-wave valve one sideband resulting from this second modulation process is sent over a waveguide feeder to be radiated from the dish aerial. The critical step in this chain is the frequency-modulating of the 70 Mc/s carrier, and the intermediate frequency amplification immediately following. The process of frequency modulating the intermediate frequency carrier with such a wideband complex signal presents a difficult design problem because an extraordinarily high degree of linearity—i.e. freedom from the generation of frequency products not in the original baseband signal—is essential. The f.m. signal at the modulator output spreads over quite a wide band—some 15 to 20 Mc/s—so the intermediate-frequency amplifiers that follow it must be high-quality wideband amplifiers having bandwidths approaching 20 Mc/s with constant group-delay characteristics over the whole passband. In an f.m. system, constancy in group-delay characteristics, both

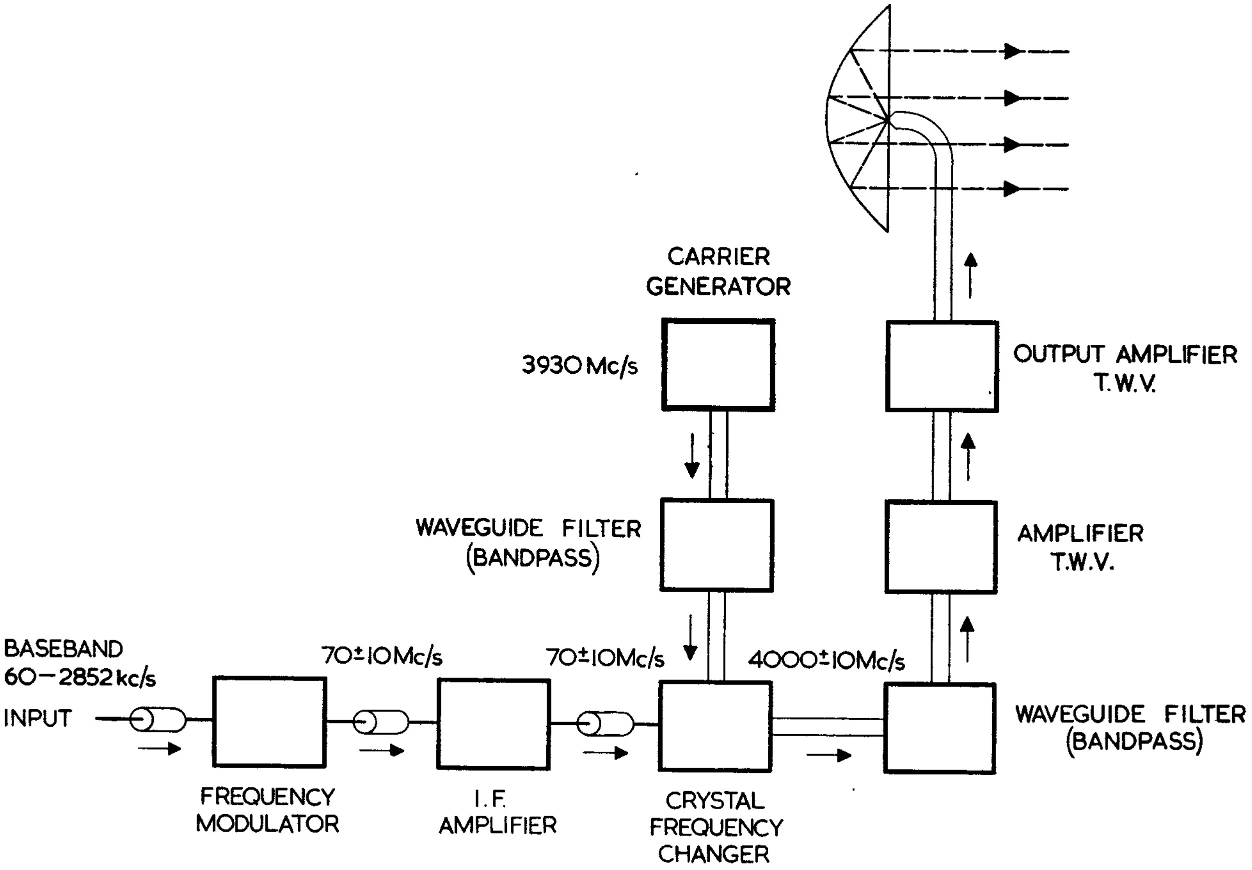


Fig. 10.—Example of a Microwave Terminal Transmitter for 4000 Mc/s.

with time and frequency, is more important than gain stability.

Intermediate-frequency amplifiers are necessary to amplify the f.m. signal to a level at which it can be used to modulate the microwave carrier itself. Two ways of doing this carrier modulation are in current use in Post Office designed equipment. The first is to use a travelling-wave valve as a modulator[9] and the second is to use a balanced crystal mixer. The first looks attractive because the travelling-wave valve gives a gain of about 14 db in the modulating process. The crystal mixer on the other hand is a "static" device (i.e. without valves and requiring no power supplies), in which the modulation process involves a loss of about 10 db. So the travelling-wave valve appears the more economical form of modulator. However, in the first method a large signal voltage is needed across the low impedance of the travelling-wave valve, and this signal power has to be generated in the 70 Mc/s band in the output stage of the i.f. amplifier. To obtain the exacting group-delay characteristic needed in such a high power amplifier over the band of 60 Mc/s to 80 Mc/s has proved most difficult with reasonable sizes of valves. As a result, the i.f. amplifier design problem becomes the limiting factor in a system employing the travelling-wave valve as a microwave modulator. A balanced crystal mixer, on the other hand, requires a lower value of signal input voltage, which can be provided without difficulty in an i.f. amplifier using ordinary valves of low power. A microwave travelling-wave valve amplifier can then be used to supply the gain required. With this arrangement, better overall results have been obtained than with the travelling-wave valve modulator.

It should be noticed that this second stage of frequency changing in the crystal mixer is really an amplitude modulation process that preserves the whole of the f.m. signal in each of its sidebands. So either the sum or difference sideband is all that need be transmitted. In Fig. **10**, the upper sideband [3930 + (70 ± 10 Mc/s)] is selected by a bandpass filter and at this point in the transmitter the signal is therefore represented by a complex form of frequency modulation in a band 20 Mc/s wide centred on a carrier of 4000 Mc/s. The required signal band must now be "cleaned-up" by a bandpass waveguide filter to cut out harmonics of the carrier source, intermediate frequency break-through, and the unwanted a.m. sidebands generated in the crystal frequency changer, before the output amplifier is reached. The latter is simply a travelling-wave valve made to deliver as much power as possible into the run of waveguide leading to the aerial. When the first microwave system was designed for operation in the 4000 Mc/s band the highest output power that could be attained was 2 to 3 watts, but output travelling-wave valves delivering up to 10 watts of power at 4000 Mc/s are now available. The transmitter is connected by a waveguide feeder to the transmitting aerial. This consists of a metal paraboloid, that may be about 10 ft. in diameter, mounted on a suitable tower and radiating a narrow beam towards the receiving aerial some 30 miles away. The waveguide feeder terminates abruptly in an open ended launching unit at the focal point of the paraboloid. The action of this type of aerial is described more fully in the next section.

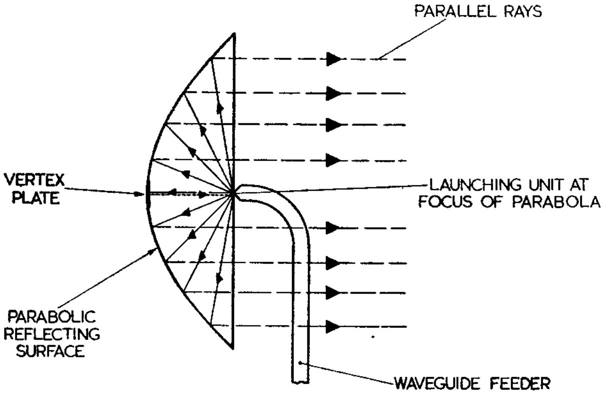


Fig. 11.—The Action of the Dish Aerial.

4.1.2 *The Paraboloid Aerial*

The basic operation of a microwave aerial[10] illustrated in Fig. **11** is very simple. As it is only desired to communicate between two fixed stations, the radiated energy can be restricted to a narrow beam having the two stations on its axis. This is analagous to a searchlight focused to illuminate a fixed object on the horizon. A metal parabolic reflector will produce a beam of radio waves if the electromagnetic energy is launched from its focal point so as to illuminate the surface of the paraboloid, provided that the dimensions of the parabola are several times the wavelength of the electromagnetic radiation. At 4000 Mc/s, the wavelength is 7.5 centimetres, and relative to this, paraboloids with diameter 7 ft. give a gain compared with an isotropic radiator* of as much as 36 db. The gain of a paraboloid is proportional to the square of its diameter and inversely proportional to the square of the wavelength under consideration. The narrower the beam, the higher is the aerial gain. The beam width of a 7 ft. diameter dish is of the order of ± 1.1° to the half-power points, as can be seen from the radiation pattern of such a dish shown in Fig. **12.**

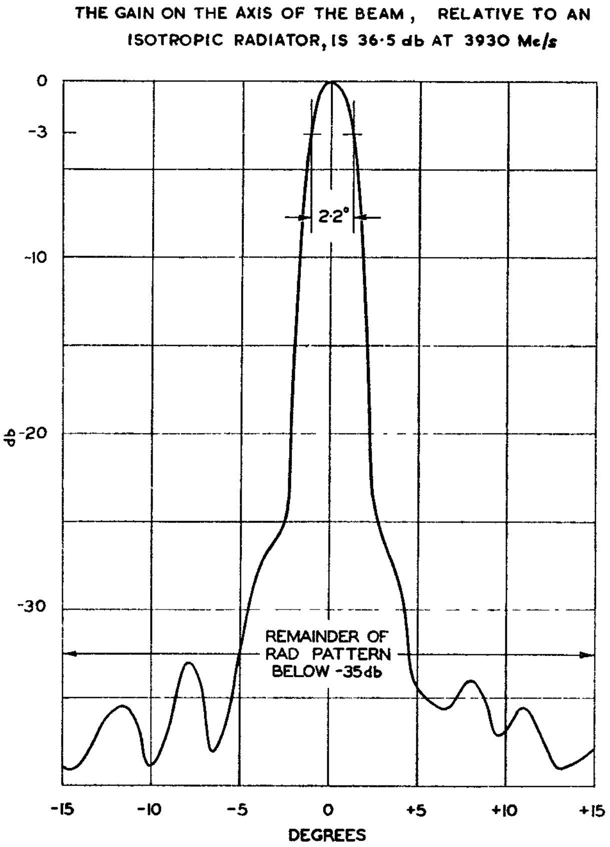


Fig. 12.—The Radiation Diagram Measured for a 7ft. Diameter Dish Aerial.

A launching device is shown diagrammatically in Fig. **13.** It is an open ended waveguide, bevelled off and with a metal post fixed across its narrow dimension. The combined effect is that of a point source from which spherical wave fronts emerge to illuminate the whole aperture of the paraboloid. These electromagnetic waves are reflected from the conducting

---

*An isotropic radiator is one which radiates energy equally in all directions. It is a useful theoretical concept which gives a basis for the comparison of the degree of concentration of radiated energy produced by directional aerials.

surface of the dish and, if the shaping is accurate, they are radiated as a beam of parallel waves. In practice, a launching device is designed so that the intensity of radiation directed at the surface of the paraboloid falls off towards the periphery. This minimises the amount of energy that is lost by spilling over the edge of the reflecting surface. It is also necessary to arrange a small flat circular plate, called the vertex matching plate, at a small adjustable distance from the reflecting surface and on the axis of the paraboloid. This reflects rays back into the launching unit in opposite phase to those falling back into the feeder from the rest of the dish, so neutralising their mismatch effect.

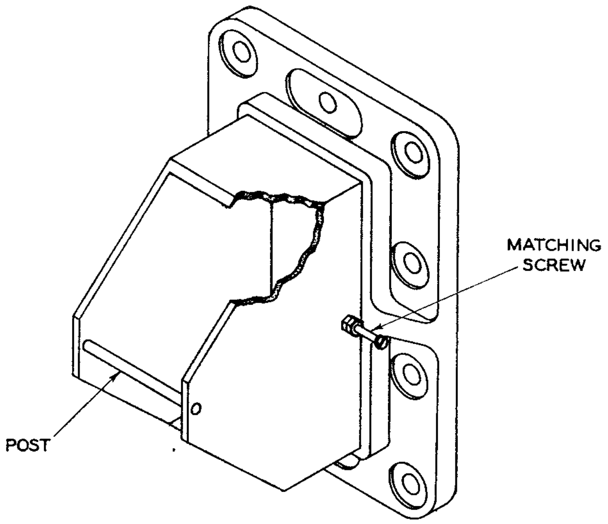


Fig. 13.—Launching Unit.

4.1.3 *The Receiver*

At the receiving station the microwave signals illuminate a paraboloid aerial similar to that used for the transmitter, and are reflected to the focus of the paraboloid. A small pick-up unit similar to the launching unit at the transmitter is situated at this focus, and this converts the electromagnetic energy

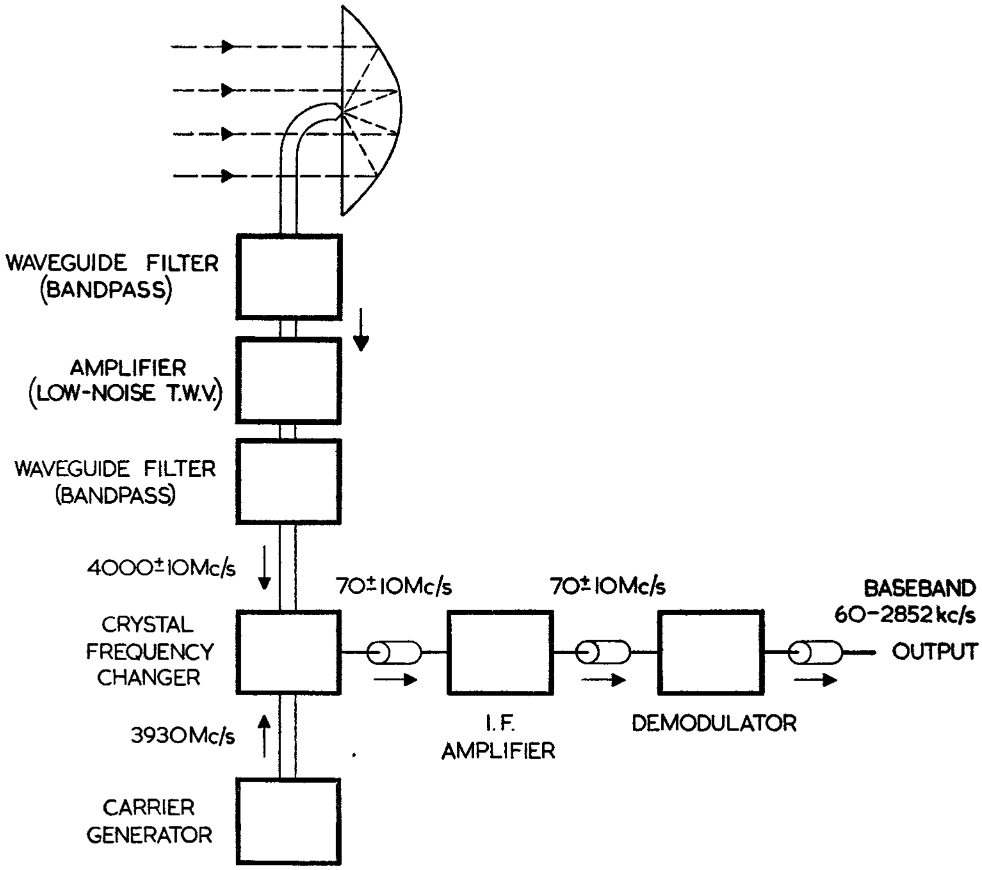


Fig. 14.—Example of a Microwave Terminal Receiver for 4000 Mc/s.

into a mode of propagation that will travel down the waveguide feeder to the receiver, Fig. **14.** Here the waveguide terminates in a bandpass filter that eliminates signals outside the wanted band that may have been picked up by the aerial—e.g. radar pulses, or perhaps some stray field from a microwave radio system on a different carrier frequency. In early microwave receivers the input filter was connected directly to a silicon crystal frequency changer, where it was mixed with a frequency 70 Mc/s lower than the incoming microwave signal carrier. The upper sideband and carrier leaks are easily suppressed, leaving the wanted lower sideband of 70 ± 10 Mc/s, ready for i.f. amplification. In more recent installations, a low-noise travelling-wave valve amplifier has been used in front of the crystal frequency changer. This improves the sensitivity of the receiver and at the same time reduces the noise from the input stage, because the low-noise travelling-wave valve has a noise factor of the order of 8 or 9 db, which is several decibels lower than current types of crystal mixer. An intermediate-frequency amplifier fitted with automatic gain control amplifies the i.f. signal band of 70± 10 Mc/s to a level adequate for the operation of an amplitude limiter; the resulting output is at a constant level independent of fading over the radio path and suitable for satisfactory demodulation in the discriminator. The output from this demodulation process is in the original baseband 60 to 2852 kc/s.

4.2. Radio Repeater Stations

A microwave radio system is not often likely to be so short that only one "hop" is needed. At about 30-mile intervals radio repeater stations will be required as shown in Fig. **15**, in which the signals will be received, amplified, changed in carrier frequency and retransmitted down the route. The interconnexion of the incoming receiver to the outgoing transmitter is best made, at the present state of the technique, at intermediate frequency, 70 Mc/s, because at i.f. it is relatively easy to provide the high amplification necessary. Demodulation from i.f. to baseband frequency is unnecessary at a repeater station.

The carrier frequency radiated by the repeating transmitter must be different from that received from the previous station to avoid the difficulties arising from transmitted energy getting back into the receiver. The most satisfactory way of avoiding this form of interaction is to give sufficient frequency separation between the two carriers for a waveguide filter to provide the necessary discrimination. A frequency shift of some 200 Mc/s is often used between successive radio paths, and the same carrier frequencies can then be re-employed further along the route. The high directivity of the paraboloid aerials helps very substantially.

The use of one standard intermediate frequency, e.g. 70 Mc/s, at all radio repeater stations makes the

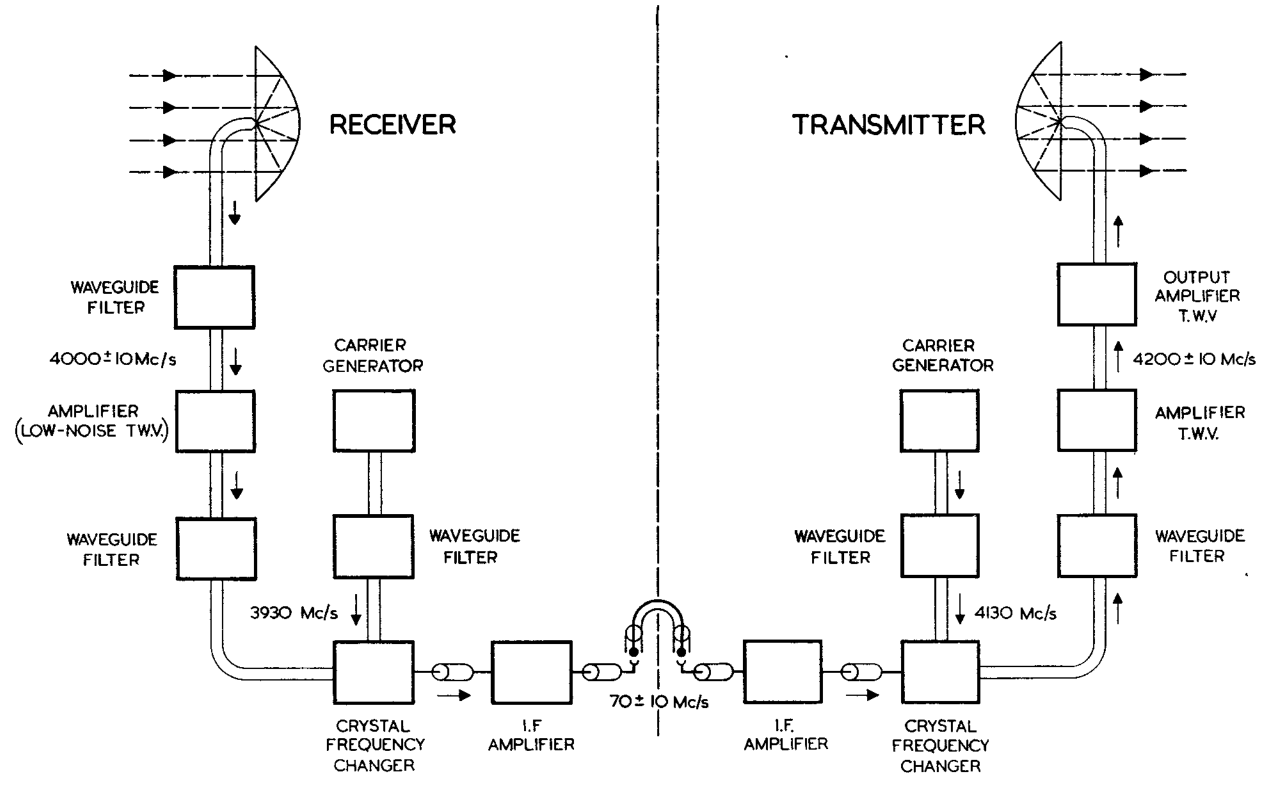


Fig. 15.—Example of a Microwave Repeater Station Using I.F. Amplifiers.

interconnexion of spur systems entering the trunk route relatively straightforward. But at repeater stations where no interconnexion with another route is required, there is no operational reason why the circuit should not be amplified at microwave frequencies without the use of an intermediate frequency. Such a repeater is shown in Fig. **16.** This simplification is only practicable when a microwave amplifier of low noise factor is used at the input stage of the receiver, and when some form of automatic gain control can be included in microwave amplifier stages. The repeater station receiver would then consist of a low-noise travelling-wave valve amplifier, followed by a frequency shifter to change the microwave carrier by about 200 Mc/s. A waveguide bandpass filter would then be used to suppress unwanted signals; two stages of travelling-wave valve amplifiers would follow, leading to an output stage travelling-wave valve amplifier giving about 10 watts to the transmitting aerial.

4.3. Some Considerations concerning the Radio Path

At present, the microwave engineer chooses sites for his stations on the basis that only the ground wave will be used. This means that if a profile is drawn of the terrain from the transmitting aerial to the receiving aerial the path followed by the ground wave must not be intersected by any sizeable obstruction. The path taken by the ground wave is not, however, optically straight, but is curved at a radius usually taken in this country as one and one-third times the earth's radius, because of refraction of the radio waves round the earth's surface. The graph paper often used for plotting these path profiles has ordinates curved at a radius that makes allowance for this refraction. The path of an indisturbed ray is then represented by a straight line on the graph. A typical path profile is shown in Fig. **17.**

The height of the transmitting and receiving paraboloids must be sufficient to provide adequate clearance all along the path, with a tolerance to allow for variation in atmospheric refraction and swaying of the masts supporting the aerials. It is undesirable to mount the paraboloids too high, i.e. to make the path clearance greater than necessary because this gives more opportunity for waves to be reflected from ground obstacles into the receiving aerial. Reflected rays arrive at the dish with a phase lag on the direct ray, the effect of this being interference with the direct wave. This interference gives rise to variation in signal level, i.e. fading. As the fade is caused by vectorial addition of the two or more received rays, the instantaneous strength of the resultant signal can be dependent on the frequency of the ray. This gives rise to frequency selective fading, which is the most difficult form to deal with.

The admissible distance between transmitter and receiver stations is the result of a complex set of circumstances. The path attenuation, which under ideal conditions is known as the free space attenuation, is of great importance, but there are also many other factors to be considered. The free space path attenuation is defined as the ratio of the power sent by a transmitter into an isotropic aerial to the power received at the output of a similar aerial connected to the distant receiver. The 7 ft. diameter paraboloid

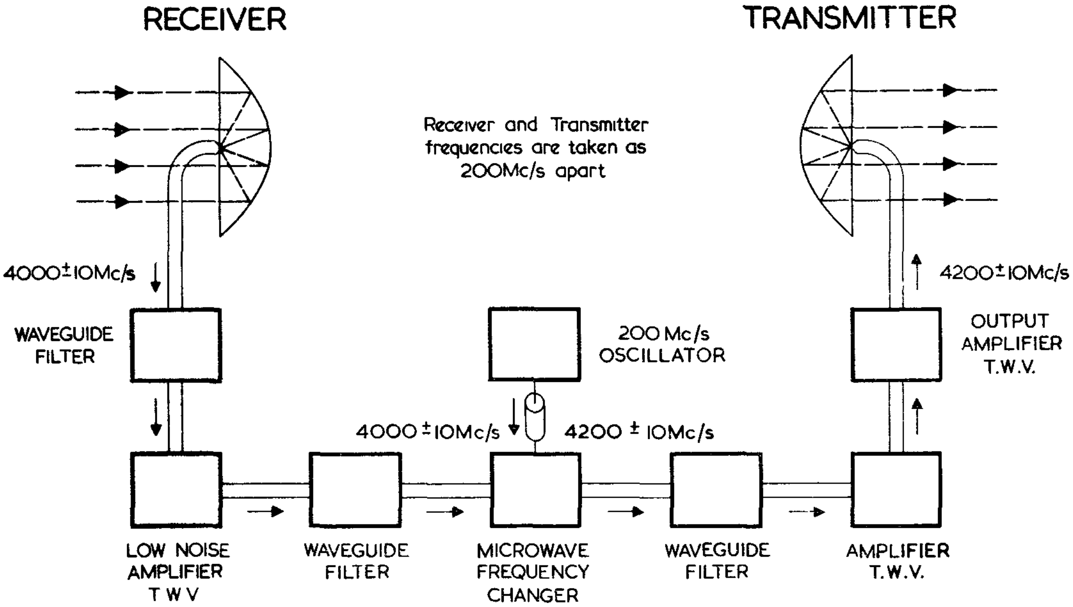


FIG. 16.—EXAMPLE OF A REPEATER STATION HAVING ALL AMPLIFICATION AT MICROWAVE FREQUENCIES.

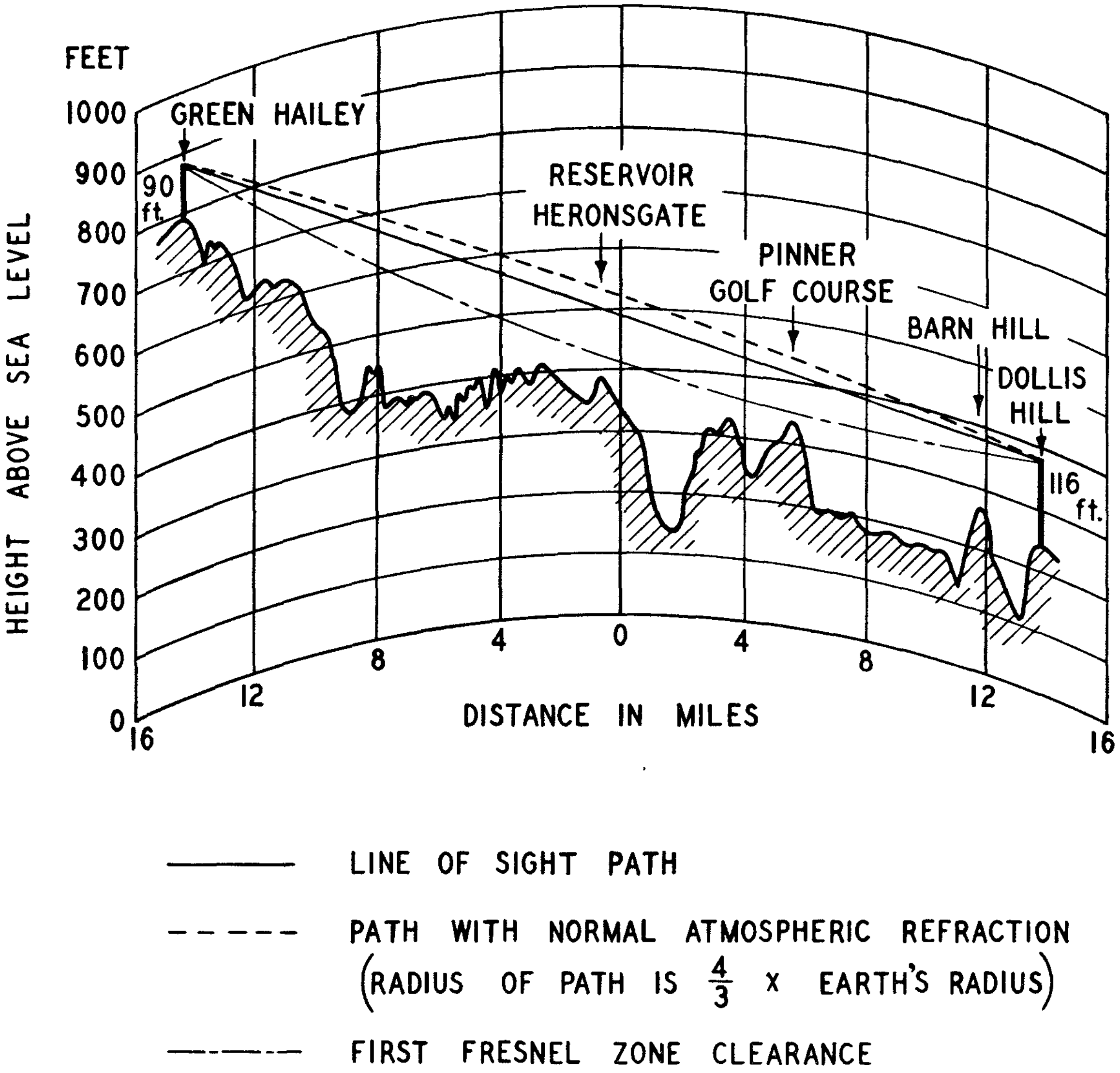


Fig. 17.—Typical Path Profile Diagram.

dish aerials have a gain in the direction of their beam of about 35 db, which means that the field strength of their radiation is 35 db stronger on the axis of the beam than it would be if an isotropic aerial were used instead of paraboloid The receiving aerial gives another 35 db gain ; so that with the two paraboloid aerials in use the effective path loss between the actual transmitter output and receiver input is [free space attenuation less (2 × 35)db, plus waveguide feeder losses].

An additional 20 db is usually added to the path loss to allow for the increased path attenuation that may arise due to fading, which is a factor that is always liable to arise in microwave radio. If now we know the power that the transmitter can send into its aerial and the lowest power level that the receiver can accept in order to produce a signal-to-noise ratio necessary for a trunk circuit, we can deduce the maximum permissible path attenuation. In order to ensure that the specified signal-to-noise ratio is attained, the lowest level that can be accepted at the receiver input from the aerial is carefully calculated, relative to the noise unavoidable in the receiver plus noise from the other sources. The receiver noise factor is chiefly determined by the thermal noise generated in the first stage of the receiver where the signal level is minimum. Amongst other sources of noise, intermodulation noise from the telephone signals on the circuit due to non-linearity of group-delay characteristics in the equipment and frequency selective fading on the radio path are the most serious. The designer aims at getting the best balance between these contributions over the whole system for the conditions when the telephone circuits are busy.

5. FUTURE TRENDS

Broadband microwave radio links are now firmly established in the trunk network of this country[11, 12]. Although their widest application is at present to point-to-point television transmission, it can be forecast with some certainty that the installation of systems which carry as many as six broadband channels of the type described here, working on adjacent carrier frequencies over the same path and by means of branching filters, through one transmitting aerial, will be accepted practice in our future trunk systems. It is obvious that coaxial cable channels and microwave radio channels should be indistinguishable in performance as far as traffic operation is concerned and this condition can now be achieved on the latest types of microwave radio systems.

In the near future, the use of higher microwave frequencies can be foreseen as work is going ahead on equipment for use in frequency bands around 6000 Mc/s and around 11,000 Mc/s. Radio systems operating in any of the four bands known as the 2000 Mc/s, 4000 Mc/s, 6000 Mc/s and 11,000 Mc/s bands may eventually be operating over common routes, and single aerial working will be desirable. Work is therefore going ahead on the development of very broadband aerials, feeders and combining filters whereby one radiator can send or receive in more than one of these frequency ranges.

Alongside this development in radio links there will be research and investigation into the techniques of transmission in circular waveguide at about 50,000 Mc/s. The problems in the latter field appear to be great but undoubtedly the experience that has been gained in bringing microwave links to their present stage of development will be valuable in work on millimetric transmission.

It is with great pleasure that the author acknowledges the assistance so willingly given him by his colleagues in the Radio Divisions at Dollis Hill in the preparation of this paper.

6. REFERENCES

1. Corke, R. L., Ephgrave, E. V., Hooper J., and Wray, D. "A 4000 Mc/s Radio System for the Transmission of Four Telephony Supergroups (240 circuits)." P.O.E.E.J. Vol. 50, Part 2, p.106 (1957).
2. Bray, W. J. "The Possibilities of Super-High Frequency Radio and Waveguide Systems for Telecommunications." I.P.O.E.E. Printed Paper No. 197 (1948).
3. Southworth, G. C. "Principles and Applications of Waveguide Transmission." Van Nostrand (1950).
4. Floyd, C. F., Rawlinson, W. A. "An Introduction to the Principles of Waveguide Transmission." P.O.E.E.J. Vol. 47, Part 2, p.63 ; Vol. 47, Part 3, p.153 (1954).

   Ravenscroft, I. A., White, R. W. "A Frequency Modulator for Broadband Radio Relay Systems." P.O.E.E.J. Vol. 48, Part 2, p.108 (1954).
5. Barlow, H. M. "Microwaves and Waveguides." Constable (1947).
6. Pryce, M. H. L. "Waveguides." J.I.E.E. Vol. 93, Part 3A, p.33 (1946).
7. Hobbs, J. G. "A Pressurized Waveguide System." P.O.E.E.J. Vol. 49, Part 1, p.52 (1956).
8. Bray, W. J. "Valves for Use at Frequencies above 3000 Mc/s." P.O.E.E.J. Vol. 43, Part 3, p.148 ; Part 4, p.187 (1950).
9. Bray, W. J. "The Travelling-Wave Valve as a Microwave Phase-Modulator and Frequency-Shifter." J.I.E.E. Vol. 99, Part 3, p.15 (1952).
10. Corke, R. L., Hooper, J. "Aerials for 4000 Mc/s Radio Links." P.O.E.E.J. Vol. 50, Part 3, p.179 (1957).
11. Bray, W. J. "A Survey of Microwave Radio Communication." Electronic Engineering, Vol. 30, No. 363, p.226 (May, 1958).
12. Floyd, C. F., White, R. W. "Microwave Link Development in the Radio Laboratories of the Post Office Engineering Department." Electronic Engineering, Vol. 30, No. 363, p.253 (May, 1958).