13
MICROWAVE TUBES AND CIRCUITS

The preceding chapter discussed passive microwave devices. It is now necessary to study active ones. This chapter deals with microwave tubes and circuits, and the next one discusses microwave semiconductor devices and associated circuitry. The order of selection is mainly historical, in that tubes preceded semiconductors by some 20 years.

The limitation for tubes on the one hand, and transistors and diodes on the other, is one of size at microwave frequencies. As frequency is raised, devices must become smaller. The powers handled fall, and noise rises. The overall result at microwave frequencies is that tubes have the higher output powers, while semiconductor devices are smaller, require simpler power supplies and, more often than not, have lower noise and greater reliabilities.

There are three general types of microwave tubes. The first is the ordinary gridded tube, invariably a *triode* at the highest frequencies, which has evolved and been refined to its utmost. Then there is the class of devices in which brief, though sometimes repeated, interaction takes place between an electron beam and an RF voltage. The *klystron* exemplifies this type of device.

The third category of device is one in which the interaction between an electron beam and an RF field is continuous. This is divided into two subgroups. In the first, an electric field is used to ensure that the interaction between the electron beam and the RF field is continuous. The *traveling-wave tube (TWT)* is the prime example of this interaction. It is an amplifier whose oscillator counterpart is called a *backward-wave oscillator (BWO)*. The second subgroup consists of tubes in which a magnetic field ensures a constant electron beam–RF field interaction. The *magnetron*, an oscillator, uses this interaction and is complemented by the *cross-field amplifier (CFA)*, which evolved from it.

Each type of microwave tube will now be discussed in turn, and in each case state-of-the-art performance figures will be given. Also, comparisons will be drawn showing the relative advantages and applications of competing devices.

Objectives

Upon completing the material in Chapter 13, the student will be able to:

- **Understand** limitations of conventional electronic devices at microwave frequencies.
- **Describe** tube requirements at UHF.
- **Draw** a picture and explain the operation of the multicavity klystron.
- **Compare** the reflex and multicavity klystron amplifiers.
- **Explain** the operation of a cavity magnetron.
- **Discuss** the traveling-wave tube (TWT) and its applications.

13.1 LIMITATIONS OF CONVENTIONAL ELECTRONIC DEVICES

Conventional electronic devices are useless at microwave frequencies, because of a number of limitations which will now be explained. *It should be noted that such limitations also afflict transistors at UHF and above*, and they, too, are exotic versions of the lower-frequency devices. These limitations cannot be completely overcome. However, it is possible to extend the useful range to well over 10 GHz, as will be seen.

As frequency is raised, vacuum tubes suffer from two general kinds of problems. The first is concerned with interelectrode capacitances and inductances, and the second is caused by the finite time that electrons take to travel from one electrode to another in a tube. Noise tends to increase with frequency, and thus microwave tubes are invariably triodes, these being the least noisy tubes.

The *skin effect* causes very significant increase in series resistance and inductance at UHF, unless tubes have been designed to minimize the effect. Also, *dielectric losses* increase with frequency. Accordingly, unless tubes and their bases are made of the lowest-loss dielectrics, efficiencies are reduced so much that proper amplification cannot be provided.

At low frequencies, it is possible to assume that electrons leave the cathode and arrive at the anode of a tube *instantaneously*. This can most certainly not be assumed at microwave frequencies. That is to say, *the transit time becomes an appreciable fraction of the RF cycle*. Several awkward effects result from this situation. One of them is that the grid and anode signals are no longer 180° out of phase, thus causing design problems, especially with feedback in oscillators. Another important effect—possibly the most important—is that the grid begins to take power from the driving source. *The power is absorbed* (and dissipated) *even when the grid is negatively biased.*

Finally, the increased input conductance increases input noise. Long before 1 GHz is reached, ordinary RF tubes have a noise figure very much in excess of 25 dB. As a conclusion, it is true to say that when any tube (or transistor) eventually fails at high frequencies, *transit time is the "killer,"* in one way or another.

13.2 MULTICAVITY KLYSTRON

The design of the multicavity klystron, together with all the remaining tubes described in this chapter, relies on the fact that transit time will sooner or later terminate the usefulness of any orthodox vacuum tube. They therefore use the transit time, instead of fighting it. The klystron was invented just before World War II by the Varian brothers as a source and amplifier of microwaves. It provided much higher powers than had previously been obtainable at these frequencies.

13.2.1 Operation

Figure 13.1 schematically shows the principal features of a two-cavity amplifier klystron. It is seen that a high-velocity electron beam is formed, focused (external magnetic focusing is omitted for simplificity) and sent down a long glass tube to a collector electrode which is at a high positive potential with respect to the cathode. The beam passes gap A in the *buncher* cavity, to which the RF signal to be amplified is applied, and it is then allowed to drift freely, without any influence from RF fields, until it reaches gap B in the output or *catcher* cavity. If all goes well, oscillations will be excited in the second cavity which are of a power much higher than those in the buncher cavity, so that a large output can be achieved. The beam is then collected by the collector electrode.

The cavities are reentrant and are also tunable (although this is not shown). They may be integral or demountable. In the latter case, the wire grid meshes are connected to rings external to the glass envelope, and cavities may be attached to the rings. The *drift space* is quite long, and the transit time in it is put to use. The gaps must be short so that the voltage across them does not change significantly during the passage of a particular bunch of electrons; having a high collector voltage helps in this regard.

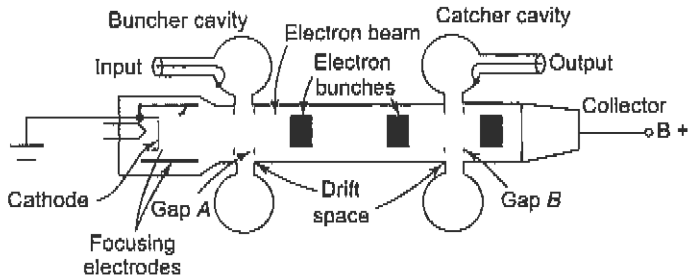

Fig. 13.1 *Klystron amplifier schematic diagram.*

It is apparent that the electron beam, which has a constant velocity as it approaches gap *A*, will be affected by the presence of an RF voltage across the gap. The extent of this effect on any one electron will depend on the voltage across the gap when the electron passes this gap. It is thus necessary to investigate the effect of the gap voltage upon individual electrons.

Consider the situation when there is no voltage across the gap. Electrons passing it are unaffected and continue on the collector with the same constant velocities they had before approaching the gap (this is shown at the left of Fig. 13.2). After an input has been fed to the buncher cavity, an electron will pass gap *A* at the time when the voltage across this gap is zero and going positive. Let this be the *reference electron y*. It is of course unaffected by the gap, and thus it is shown with the same slope on the *Applegate diagram* of Fig. 13.2 as electrons passing the gap before any signal was applied.

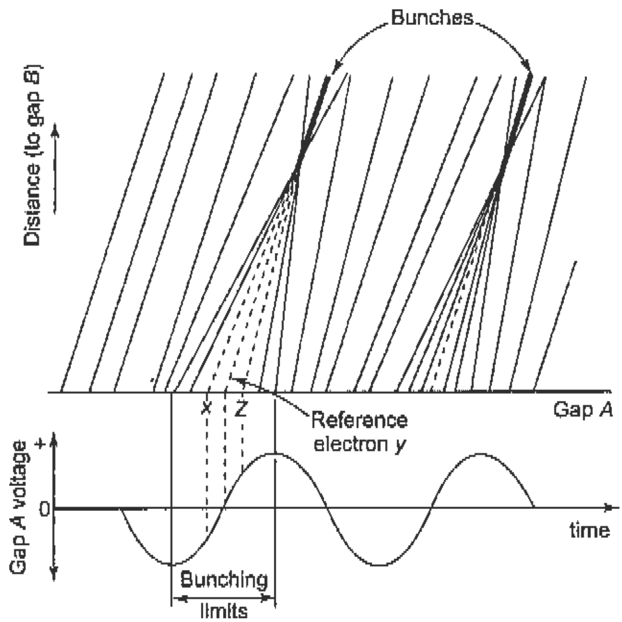

Fig. 13.2 *Applegate diagram for klystron amplifier.*

Another electron, z, passes gap A slightly later than y. Had there been no gap voltage, both electrons would have continued past the gap with unchanged velocity, and therefore neither could have caught up with the other. Here, electron z is slightly accelerated by the now positive voltage across gap A, and given enough time, it will catch up with the reference electron. As shown in Fig. 13.2, it has enough time to catch electron y easily before gap B is approached. Electron x passes gap A slightly before the reference electron. Although it passed gap A before electron y, it was retarded somewhat by the negative voltage then present across the gap. Since electron y was not so retarded, it has an excellent chance of catching electron x before gap B (this it does, as shown in Fig. 13.2).

As electrons pass the buncher gap, they are *velocity-modulated* by the RF voltage existing across this gap. Such velocity modulation would not be sufficient, in itself, to allow amplification by the klystron. Electrons have the opportunity of catching up with other electrons in the drift space. When an electron catches up with another one, it may simply pass it and forge ahead. It may exchange energy with the slower electron, giving it some of its excess velocity, and the two bunch together and move on with the average velocity of the beam. As the beam progresses farther down the drift tube, so the bunching becomes more complete, as more and more of the faster electrons catch up with bunches ahead. Eventually, the current passes the catcher gap in quite pronounced bunches and therefore varies cyclically with time. This variation in current density is known as *current modulation*, and this is what enables the klystron to have significant gain.

It will be noted from the Applegate diagram that bunching can occur once per cycle, centering on the reference electron. The limits of bunching are also shown. Electrons arriving slightly after the second limit clearly are not accelerated sufficiently to catch the reference electron, and the reference electron cannot catch any electron passing gap A just before the first limit. Bunches thus also arrive at the catcher gap once per cycle and deliver energy to this cavity. In ordinary vacuum tubes, a little RF power applied to the grid can cause large variations in the anode current, thus controlling large amounts of dc anode power. Similarly in the klystron, a little RF power applied to the buncher cavity results in large beam current pulses being applied to the catcher cavity, with a considerable power gain as the result. Needless to say, the catcher cavity is excited into oscillations at its resonant frequency (which is equal to the input frequency), and a large sinusoidal output can be obtained because of the *flywheel effect* of the output resonator.

13.2.2 Practical Considerations

The construction of the klystron lends itself to two practical microwave applications—as a multicavity power amplifier or as a two-cavity power oscillator.

Multicavity Klystron Amplifier The bunching process in a two-cavity klystron is by no means complete, since there are large numbers of out-of-phase electrons arriving at the catcher cavity between bunches. Consequently, more than two cavities are always employed in practical klystron amplifiers. Four cavities are shown in the klystron amplifier schematic diagram of Fig. 13.3 and up to seven cavities have been used in practice. Partially bunched current pulses will now also excite oscillations in the intermediate cavities, and these cavities in turn set up gap voltages which help to produce more complete bunching. Having the extra cavities helps to improve the efficiency and power gain considerably. The cavities may all be tuned to the same frequency, such *synchronous tuning* being employed for narrowband operation. For broadband work, for example with UHF klystrons used as TV transmitter output tubes, or 6-GHz tubes used as power amplifiers in some satellite station transmitters, *stagger tuning* is used. Here, the intermediate cavities are tuned to either side of the center frequency, improving the bandwidth very significantly. It should be noted that cavity Q is so high that stagger tuning is a "must" for bandwidths much over 1 percent.

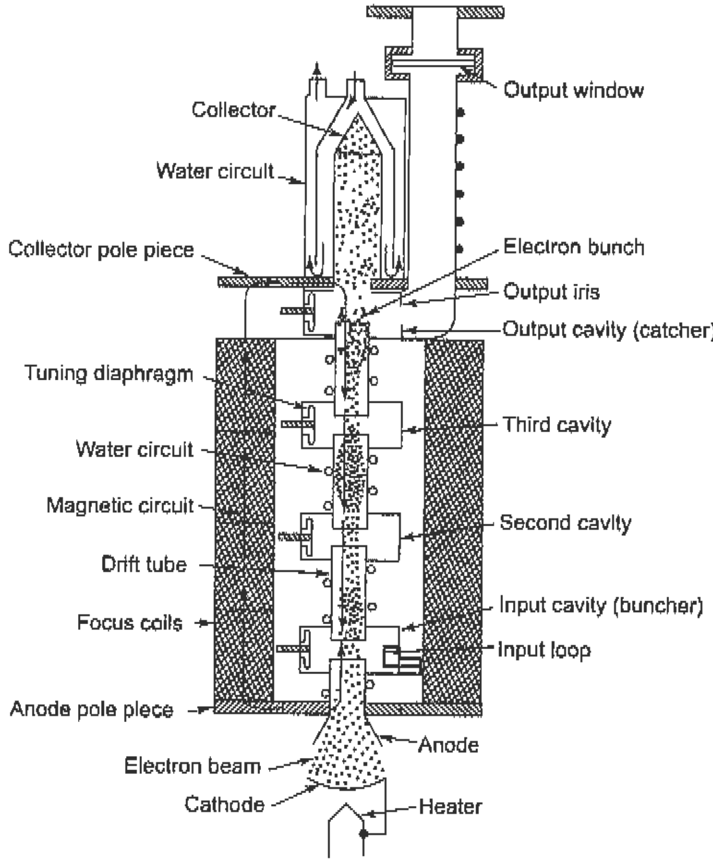

Fig. 13.3 *Four-cavity klystron amplifier schematic diagram. (Courtesy of Varian Associates, Inc.)*

Two-cavity Klystron Oscillator If a portion of the signal in the catcher cavity is coupled back to the buncher cavity, oscillations will take place. As with other oscillators, the feedback must have the correct polarity and sufficient amplitude. The schematic diagram of such an oscillator is as shown in Fig. 13.1, except for the addition of a (permanent) feedback loop. Oscillations in the two-cavity klystron behave as in any other feedback oscillator. Having been started by a switching transient or noise impulse, they continue as long as dc power is present.

Performance and Applications The multicavity klystron is used as a medium-, high- and very high-power amplifier in the UHF and microwave ranges, for either continuous or pulsed operation. The frequency range covered is from about 250 MHz to over 95 GHz.

Table 13.1 summarizes the power requirements of the major applications for klystron amplifiers and shows how the devices are able to meet them. The gain of klystrons is also adequate. It ranges from 30–35 dB at UHF to 60-65 dB in the microwave range. Such high gain figures mean that the klystron is generally the only nonsemiconductor device in high-power amplifiers.

TABLE 13.1 *Klystron Amplifier Performance and Applications*

APPLICATION AND TYPE OF REQUIREMENT	FREQ. RANGE, GHz	NEEDED POWER, max.	AVAILABLE POWER max.
UHF TV transmitters (CW)	0.5-0.9	55 kW	100 kW
Long-range radar (pulsed)	1.0-12	10 MW	20 MW
Linear particle accelerator (pulsed)	2.0-3.0	25 MW	40 MW
Troposcatter links (CW)	1.5-12	250 kW	1000 kW
Earth station transmitter (CW)	5.9-14	8 kW	25 kW

Developments in Klystron are aimed at improving efficiency, providing longer lives, and reducing size; typical efficiency is 35 to 50 percent. To improve reliability and MTBF (mean time between failures), tungsten-iridium cathodes are now being used to reduce cathode temperature and thus provide longer life. As regards size, a typical 50-kW UHF klystron, as shown in Fig. 13.3, may be over 2 m long, with a weight of nearly 250 kg. As may be gathered from Fig. 13.3, a large proportion of the bulk is due to the magnet, often as much as two-thirds. A 100-kW peak (2.5-kW average) X-band klystron may be 50 cm long and may weigh about 30 kg, if it uses permanent-magnet focusing. It is possible to reduce this weight to one-third by using *periodic permanent-magnet (PPM)* focusing. In this system (see Section 13.5.2), the beam is focused by so-called magnetic lenses, which are small, strong magnets along the beam path. In between them, the beam is allowed to defocus a little. The use of grids for modulation purposes (see Fig. 13.4) has been rediscovered and evolved further.

The two-cavity klystron oscillator has fallen out of favor, having been displaced by CW magnetrons, semiconductor devices and the high gain of klystron and TWT amplifiers.

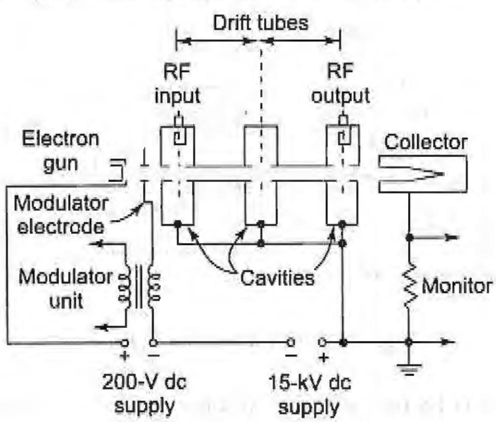

Fig. 13.4 *Three-cavity klystron pulsed amplifier with modulating grid. (Beck and Deering, "A Three-cavity L-band Pulsed Klystron Amplifier," Proc. IEE (London), vol. 105B.)*

Further Practical Aspects Multicavity klystron amplifiers suffer from the noise caused because bunching is never complete, and so electrons arrive at random at the catcher cavity. This makes them too noisy for use in receivers, but their typically 35-dB noise figures are more than adequate for transmitters.

Since the time taken by a given electron bunch to pass through the drift tube of a klystron is obviously influenced by the collector voltage, this voltage must be regulated. Indeed, the power supplies for klystrons are quite elaborate, with a regulated 9 kV at 750-mA collector current required for a typical communications klystron. Similarly, when a klystron amplifier is pulsed, such pulses are often applied to the collector. They should be flat, or else frequency drift (within limits imposed by cavity bandwidth) will take place during the pulse. As an alternative to this, and also because collector pulsing takes a lot of power, modulation of a special grid has been developed, as shown in Fig. 13.4. A typical "gain" of 20 is available between this electrode and the collector, thus reducing the modulating power requirements twenty fold. Amplitude modulation of the klystron can also be applied via this grid. However, if amplitude linearity is required, it should be noted that the klystron amplifier begins to saturate at about 70 percent of maximum power output. Beyond this point, output still increases with input but no longer linearly. This saturation is not a significant problem, all in all, because most of the CW applications of the multicavity klystron involve frequency modulation. Under such conditions, e.g., in a troposcatter link, the klystron merely amplifies a signal that is already frequency-modulated and at a constant amplitude.

13.3 REFLEX KLYSTRON

It is possible to produce oscillations in a klystron device which has only one cavity, through which electrons pass twice. This is the reflex klystron, which will now be described.

13.3.1 Fundamentals

The reflex klystron is a low-power, low-efficiency microwave oscillator, illustrated schematically in Fig. 13.5. It has an electron gun similar to that of the multicavity klystron but smaller. Because the device is short, the beam does not require focusing. Having been formed, the beam is accelerated toward the cavity, which has a high positive voltage applied to it and, as shown, acts as the anode. The electrons overshoot the gap in this cavity and continue on to the next electrode, *which they never reach.*

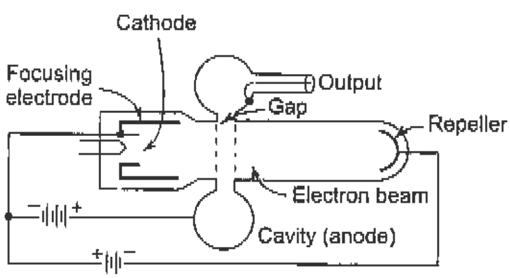

Fig. 13.5 *Reflex klystron schematic.*

This *repeller* electrode has a fairly high negative voltage applied to it, and precautions are taken to ensure that it is not bombarded by the electrons. Accordingly, electrons in the beam reach some point in the repeller space and are then turned back, eventually to be dissipated in the anode cavity. If the voltages are properly adjusted, the returning electrons given more energy to the gap than they took from it on the outward journey, and continuing oscillations take place.

Operation As with the multicavity klystron, the operating mechanism is best understood by considering the behavior of individual electrons. This time, however, the reference electron is taken as one that passes the gap on its way to the repeller at the time when the gap voltage is zero and going negative. This electron is of course unaffected, overshoots the gap, and is ultimately returned to it, having penetrated some distance into the repeller space. An electron passing the gap slightly earlier would have encountered a slightly positive voltage at the gap. The resulting acceleration would have propelled this electron slightly farther into the repeller space, and the electron would thus have taken a slightly longer time than the reference electron to return to the gap. Similarly, an electron passing the gap a little after the reference electron will encounter a slightly negative voltage. The resulting retardation will shorten its stay in the repeller space. It is seen that, around the reference electron, earlier electrons take longer to return to the gap than later electrons, and so the conditions are right for bunching to take place. The situation can be verified experimentally by throwing a series of stones upward. If the earlier stones are thrown harder, i.e., acclerated more than the later ones, it is possible for all of them to come back to earth simultaneously, i.e., in a bunch.

It is thus seen that, as in the multicavity klystron, velocity modulation is converted to current modulation in the repeller space, and one bunch is formed per cycle of oscillations. It should be mentioned that bunching is not nearly as complete in this case, and so the reflex klystron is much less efficient than the multicavity klystron.

Transit Time As usual with oscillators, it is assumed that oscillations are started by noise or switching transients. Accordingly, what must now be shown is that the operation of the reflex klystron is such as to maintain these oscillations. For oscillations to be maintained, the transit time in the repeller space, or the time taken for the reference electron from the instant it leaves the gap to the instant of its return, must have the correct value. This is determined by investigating the best possible time for electrons to leave the gap and the best possible time for them to return.

The most suitable departure time is obviously centered on the reference electron, at the 180° point of the sine-wave voltage across the resonator gap. It is also interesting to note that, ideally, no energy at all goes into velocity-modulating the electron beam. It admittedly takes some energy to accelerate electrons, but just as much energy is gained from retarding electrons. Since just as many electrons are retarded as accelerated by the gap voltage, the total energy outlay is nil. This actually raises a most important point: *energy is spent in accelerating bodies (electrons in this case), but energy is gained from retarding them*. The first part of the point is obvious, and the second may be observed by means of a very simple experiment, for which the apparatus consists of a swing and a small member of the family. Once the child is swinging freely, retard the swing with some part of the body and measure the amount of energy absorbed (if still standing!).

It is thus evident that the best possible time for electrons to return to the gap is when the voltage then existing across the gap will apply maximum retardation to them. This is the time when the gap voltage is maximum positive (on the right side of the gap in Fig. 13.5). Electrons then fall through the maximum negative voltage between the gap grids, thus giving the maximum amount of energy to the gap. The best time for electrons to return to the gap is at the 90° point of the sine-wave gap voltage. Returning after 1¾ cycles obviously satisfies these requirements, it may be stated that

$$T = n + \tfrac{3}{4}$$

where T = transit time of electrons in repeller space, cycles

n = any integer

Modes The transit time obviously depends on the repeller and anode voltages, so that both must be carefully adjusted and regulated. Once the cavity has been tuned to the correct frequency, both the anode and repeller voltages are adjusted to give the correct value of T from data supplied by the manufacturer. Each combination of acceptable anode-repeller voltages will provide conditions permitting oscillations for a particular value of n. In turn, each value of n is said to correspond to a different reflex klystron *mode*, practical transit times corresponding to the range from 1¾ to 6¾ cycles of gap voltage. Modes corresponding to $n = 2$ or $n = 3$ are the ones used most often in practical klystron oscillators.

13.3.2 Practical Considerations

Performance Reflex klystrons with integral cavities are available for frequencies ranging from under 4 to over 200 GHz. A typical power output is 100 mW, but overall maximum powers range from 3 W in the X band to 10 mW at 220 GHz. Typical efficiencies are under 10 percent, restricting the oscillator to low-power applications.

Tuning The frequency of resonance is mechanically adjustable, with the adjustable screw, bellows or dielectric insert the most popular. Such *mechanical tuning* of reflex klystrons may give a frequency variation which ranges in practice from ±20 MHz at X band to ±4 GHz at 200 GHz. *Electronic tuning* is also possible, by adjustment of the repeller voltage. The tuning range is about ±8 MHz at X band and ±80 MHz for submillimeter klystrons. The device is also very easy to frequency-modulate, simply by the application of the modulating voltage to the repeller.

Repeller Protection It is essential to make sure that the repeller of a klystron never draws current by becoming positive with respect to the cathode. Otherwise, it will very rapidly be destroyed by the impact of high-velocity electrons as well as overheating. A cathode resistor is often used to ensure that the repeller cannot be more positive than the cathode, even if the repeller voltage fails. Other precautions may include a protective diode across the klystron or an arrangement in which the repeller voltage is always applied before the cathode voltage. Manufacturers' specifications generally list the appropriate precautions.

Applications The klystron oscillator has been replaced by various semiconductor oscillators in a large number of its previous applications, in new equipment. It will be found in a lot of existing equipment, as a:

1. Signal source in microwave generators
2. Local oscillator in microwave receivers
3. Frequency-modulated oscillator in portable microwave links
4. Pump oscillator for parametric amplifiers

The reflex klystron is still a very useful millimeter and submillimeter oscillator, producing more power at the highest frequencies than most semiconductor devices, with very low AM and FM noise.

13.4 MAGNETRON

The *cavity* (or *traveling wave*) *magnetron* high-power microwave oscillator was invented in Great Britain by Randall and Boot. It is a diode which uses the interaction of magnetic and electric fields in a complex cavity to provide oscillations of very high peak power (the original one gave in excess of 100 kW at 3 GHz). It is true to say that without the cavity magnetron, microwave radar would have been greatly delayed and would have come too late to have been the factor it was in World War II.

The cavity magnetron, which will be referred to as the *magnetron*, is a diode, usually of cylindrical construction. It employs a *radial electric field*, an *axial magnetic field* and an anode structure with permanent cavities. As shown in Fig. 13.6, the cylindrical cathode is surrounded by the anode with cavities, and thus a radial dc electric field will exist. The magnetic field, is axial, i.e., has lines of magnetic force passing through the cathode and the surrounding interaction space. The lines are thus at right angles to the structure cross section of Fig. 13.6. The magnetic field is also dc, and since it is perpendicular to the plane of the radial electric field, the magnetron is called a *crossed-field* device.

The output is taken from one of the cavities, by means of a coaxial line as indicated in both Fig. 13.6, or through a waveguide, depending on the power and frequency. The output coupling loop leads to a cavity resonator to which a waveguide is connected, and the overall output from this magnetron is via waveguide. The rings interconnecting the anode poles are used for *strapping*, and the reason for their presence will be explained. Finally, the anode is normally made of copper, regardless of its actual shape.

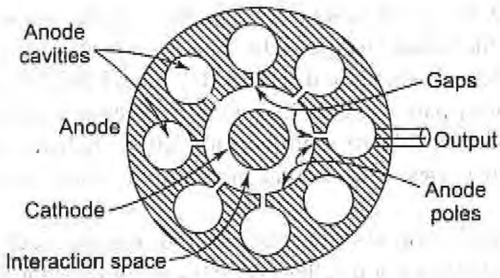

Fig. 13.6 *Cross section of hole-and-slot magnetron.*

The magnetron has a number of resonant cavities and must therefore have a number of resonant frequencies and/or modes of oscillation. Whatever mode is used, it must be self-consistent. For example, it is not possible for the eight-cavity magnetron (which is often used in practice) to employ a mode in which the phase difference between the adjacent anode pieces is 30°. If this were done, the total phase shift around the anode would be $8 \times 30° = 240°$, which means that the first pole piece would be 120° out of phase with itself! Simple investigation shows that the smallest practical phase difference that can exist here between adjoining anode poles is 45°, or $\pi/4$ rad, giving a self-consistent overall phase shift of 360° or 2π rad. This $\pi/4$ mode is seldom used in practice because it does not yield suitable characteristics, and the π mode is preferred for rather complex reasons. In this mode of operation, the phase difference between adjacent anode poles is π rad or 180°.

Effect of Magnetic Field Since any electrons emitted by the magnetron cathode will be under the influence of the dc magnetic field, as well as an electric field, the behavior of electrons in a magnetic field must first be investigated.

A moving electron represents a current, and therefore a magnetic field exerts a force upon it, just as it exerts a force on a wire carrying a current. The force thus exerted has a magnitude proportional to the product Bev, where e and v are the charge and velocity of the electron, respectively, and *B is the component of the magnetic field in a plane perpendicular to the direction of travel of the electron.* This force exerted on the electron is perpendicular to the other two directions. If the electron is moving forward horizontally, and the magnetic field acts vertically downward, the path of the electron will be curved to the left. Since the magnetic field in the magnetron is constant, the force of the magnetic field on the electron (and therefore the radius of curvature) will depend solely on the forward (radial) velocity of the electron.

Effect of Magnetic and Electric Fields When magnetic and electric fields act simultaneously upon the electron, its path can have any of a number of shapes dictated by the relative strengths of the mutually perpendicular electric and magnetic fields. Some of these electron paths are shown in Fig. 13.7 *in the absence of oscillations* in a magnetron, in which the electric field is constant and radial, and the axial magnetic field can have any number of values.

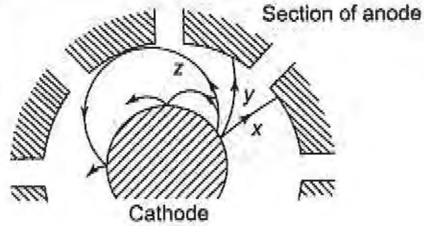

Fig. 13.7 *Electron paths in magnetron without oscillations, showing effect of increasing magnetic field.*

When the magnetic field is zero, the electron goes straight from the cathode to the anode, accelerating all the time under the force of the radial electric field. This is indicated by path x in Fig. 13.7. When the magnetic field has a small but definite strength, it will exert a lateral force on the electron, bending its path to the left (here). Note, as shown by path y of Fig. 13.7, that the electron's motion is no longer rectilinear. As the electron approaches the anode, its velocity continues to increase radially as it is accelerating. The effect of the magnetic field upon it increases also, so that the path curvature becomes sharper as the electron approaches the anode.

It is possible to make the magnetic field so strong that electrons will not reach the anode at all. The magnetic field required to return electrons to the cathode after they have *just grazed* the anode is called the *cutoff field*. The resulting path is z in Fig. 13.7. Knowing the value of the required magnetic field strength is important because this cutoff field just reduces the anode current to zero in the absence of oscillations. If the magnetic field is stronger still, the electron paths as shown will be more curved still, and the electrons will return to the cathode even sooner (only to be reemitted). All these paths are naturally changed by the presence of any RF field due to oscillations, but the state of affairs without the RF field must still be appreciated, for two reasons. First, it leads to the understanding of the oscillating magnetron. Second, it draws attention to the fact that unless a magnetron is oscillating, all the electrons will be returned to the cathode, which will overheat and ruin the tube. This happens because in practice the applied magnetic field is greatly in excess of the cutoff field.

13.4.1 Operation

Once again it will be assumed that oscillations are capable of starting in a device having high-Q cavity resonators, and the mechanism whereby these oscillations are maintained will be explained.

π-mode Oscillations As explained in the preceding section, self-consistent oscillations can exist only if the phase difference between adjoining anode poles is $n\pi/4$, where n is an integer. For best results, $n = 4$ is used in practice. The resulting π-mode oscillations are shown in Fig. 13.8 at an instant of time when the RF voltage on the top left-hand anode pole is maximum positive. It must be realized that these are oscillations. A time will thus come, later in the cycle, when this pole is instantaneously maximum negative, while at another instant the RF voltage between that pole and the next will be zero.

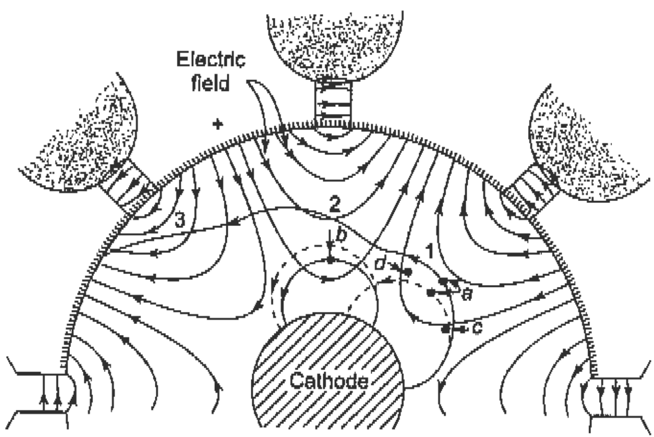

Fig. 13.8 *Paths traversed by electrons in a magnetron under π-mode oscillations. (From. F. E. Terman, Electronic and Radio Engineering, McGraw-Hill, New York.)*

In the absence of the RF electric field, electrons *a* and *b* would have followed the paths shown by the dotted lines *a* and *b*, respectively, but the RF field naturally modifies these paths. This RF field, incidentally, exists inside the individual resonators also, but it is omitted here for simplicity. The important fact is that each cavity acts in the same way as a short-circuited quarter-wave transmission line. Each gap corresponds to a maximum voltage point in the resulting standing-wave pattern, with the electric field extending into the anode interaction space, as shown in Fig. 13.8.

Effect of Combined Fields on Electrons The presence of oscillations in the magnetron brings in a *tangential* (RF) component of electric field. When electron *a* is situated (at this instant of time) at point 1, the tangential component of the RF electric field opposes the tangential velocity of the electron. The electron is retarded by the field and gives energy to it (as happened in the reflex klystron). Electron *b* is so placed as to extract an equal amount of energy from the RF field, by virtue of being accelerated by it. For oscillations to be maintained, more energy must be given to the electric field than is taken from it. Yet, on the face of it, this is unlikely to be the case here because there are just as many electrons of type *a* as of type *b*. Note that electron *a* spends much more time in the RF field than electron *b*. The former is retarded, and therefore the force of the dc magnetic field on it is diminished; as a result, it can now move closer to the anode. If conditions are arranged so that by the time electron *a* arrives at point 2 the field has reversed polarity, this electron will once again be in a position to give energy to the RF field (though being retarded by it). The magnetic force on electron *a* diminishes once more, and another interaction of this type occurs (this time at point 3). This assumes that at all times the electric field has reversed polarity each time this electron arrives at a suitable interaction position. In this manner, "favored" electrons spend a considerable time in the interaction space and are capable of orbiting the cathode several times before eventually arriving at the anode.

However, an electron of type *b* undergoes a totally different experience. It is immediately accelerated by the RF field, and therefore the force exerted on it by the dc magnetic field increases. This electron thus returns to the cathode even sooner than it would have in the absence of the RF field. It consequently spends a much shorter time in the interaction space than the other electron. Hence, although its interaction with the RF field takes as much energy from it as was supplied by electron *a*, *there are far fewer interactions of the b type* because such electrons are always returned to the cathode after one, or possibly two, interactions. On the other hand, type *a* electrons give up energy repeatedly. It therefore appears that more energy is given to the RF oscillations than is taken from them, so that oscillations in the magnetron are sustained. The only real effect of the "unfavorable" electrons is that they return to the cathode and tend to heat it, thus giving it a dissipation of the order of 5 percent of the anode dissipation. This is known as *back-heating* and is not actually a total loss, because it is often possible in a magnetron to shut off the filament supply after a few minutes and just rely on the back-heating to maintain the correct cathode temperature.

Bunching It may be shown that the cavity magnetron, like the klystrons, causes electrons to bunch, but here this is known as the *phase-focusing effect*. This effect is rather important. Without it, favored electrons would fall behind the phase change of the electric field across the gaps, since such electrons are retarded at each interaction with the RF field. To see how this effect operates, it is most convenient to consider another electron, such as *c* of Fig. 13.8.

Electron *c* contributes some energy to the RF field. However, it does not give up as much as electron *a*, because the tangential component of the field is not as strong at this point. As a result, this electron appears to be somewhat less useful than electron *a*, but this is so only at first. Electron *c* encounters not only a diminished tangential RF field but also a component of the *radial* RF field, as shown. This has the effect of accelerating the electron radially outward. As soon as this happens, the dc magnetic field exerts a stronger force on electron *c*, tending to bend it back to the cathode but also accelerating it somewhat in a counterclockwise direction. This, in turn, gives this electron a very good chance of catching up with electron *a*. In a similar manner, electron *d* (shown in Fig. 13.8) will be retarded tangentially by the dc magnetic field. It will therefore be caught up by the favored electron; thus, a bunch takes shape. In fact, it is seen that being in the favored position means (to the electron) being in a position of equilibrium. If an electron slips back or forward, it will quickly be returned to the correct position with respect to the RF field, by the phase-focusing effect just described.

Figure 13.9 shows the wheel-spoke bunches in the cavity magnetron. These bunches rotate counterclockwise with the correct velocity to keep up with RF phase changes between adjoining anode poles. In this way a continued interchange of energy takes place, with the RF field receiving much more than it gives. The RF field changes polarity. Each favored electron, by the time it arrives opposite the next gap, meets the same situation of there being a positive anode pole above it and to the left, and a negative anode pole above it and to the right. It is not difficult to imagine that the electric field itself is rotating counterclockwise at the same speed as the electron bunches. The cavity magnetron is called the *traveling-wave magnetron* precisely because of these rotating fields.

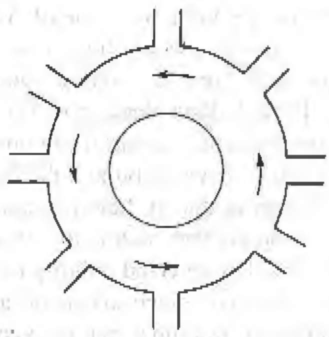

Fig. 13.9 *Bunched electron clouds rotating around magnetron cathode (individual electron paths not shown).*

13.4.2 Practical Considerations

The operating principles of a device are important but do not give the entire picture of that particular device. A number of other significant aspects of magnetron operation will now be considered.

Strapping Because the magnetron has eight (or more) coupled cavity resonators, several different modes of oscillation are possible. The oscillating frequencies corresponding to the different modes are not the same. Some are quite close to one another, so that, through *mode jumping*, a 3-cm π-mode oscillation which is normal for a particular magnetron could, spuriously, become a 3.05-cm 3/4 π-mode oscillation. The dc electric and magnetic fields, adjusted to be correct for the π mode, would still support the spurious mode to a certain extent, since its frequency is not too far distant. The result might well be oscillations of reduced power, at the wrong frequency.

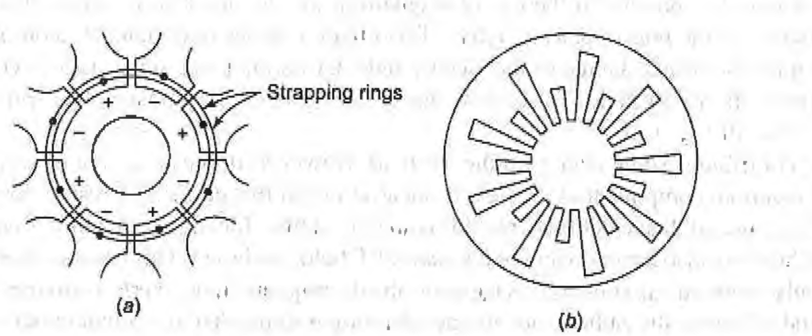

Fig. 13.10 *(a) Hole-and-slot magnetron with strapping; (b) rising-sun magnetron anode block.*

Magnetrons using identical cavities in the anode block normally *employ strapping* to prevent mode jumping. Such strapping is seen in Fig. 13.10*a* for the hole-and-slot cavity arrangement. Strapping consists of two rings of heavy-gauge wire connecting alternate anode poles. These are the poles that should be in phase with each other for the π mode. The reason for the effectiveness of strapping in preventing mode jumping may be simplified by pointing out that, since the phase difference between alternate anode poles is other than 2π rad in other modes, these modes will quite obviously be prevented. The actual situation is somewhat more complex.

Strapping may become unsatisfactory because of losses in the straps in very high-power magnetrons or because of strapping difficulties at very high frequencies. In the latter case, the cavities are small, and there are generally a lot of them (16 and 32 are common numbers), to ensure that a suitable RF field is maintained in the interaction space. This being so, so many modes are possible that even strapping may not prevent mode jumping. A very good cure consists in having an anode block with a pair of cavity systems of quite dissimilar shape and resonant frequency. Such a *rising-sun* anode structure is shown in Fig. 13.10*b* and has the effect of isolating the π-mode frequency from the others. Consequently the magnetron is now unlikely to oscillate at any of the other modes, because the dc fields would not support them. Note that strapping is not required with the rising-sun magnetron.

Frequency Pulling and Pushing It should be recognized that the resonant frequency of magnetrons can be altered somewhat by changing the anode voltage. Such *frequency pushing* is due to the fact that the change in anode voltage has the effect of altering the orbital velocity of the electron clouds of Fig. 13.9. This in turn alters the rate at which energy is given up to the anode resonators and therefore changes the oscillating frequency, cavity bandwidth permitting. The effect of all this is that power changes will result from inadvertent changes of anode voltage, but *voltage tuning* of magnetrons is quite feasible.

Like any other oscillator, the magnetron is susceptible to frequency variations due to changes of load impedance. This will happen regardless of whether such load variations are purely resistive or involve load reactance variations, but it is naturally more severe for the latter. The frequency variations, known as *frequency pulling*, are caused by changes in the load impedance reflected into the cavity resonators. They must be prevented, all the more so because the magnetron is a power oscillator. Unlike most other oscillators, it is not followed by a buffer.

The various characteristics of a magnetron, including the optimum combinations of anode voltage and magnetic flux, are normally plotted on *performance charts* and *Rieke diagrams*. From these the best operating conditions are selected.

13.4.3 Types, Performance and Applications

Magnetron Types The magnetron, perhaps more than any other microwave tube, lends itself to a variety of types, designs and arrangements. Magnetrons using hole-and-slot, vane and rising-sun cavities have already been discussed. A very high-power (5 MW pulsed at 3 GHz) magnetron is shown in Fig. 13.11. It features an anode that is about three times normal length and thus has the required volume and external area to allow high dissipation and therefore output power. A magnetron such as this may stand over 2 m high, and have a weight in excess of 60 kg without the magnet.

A most interesting feature of Fig. 13.11 is that it shows a coaxial magnetron. The cross section of a coaxial magnetron structure, similar to the one of Fig. 13.11, is shown in Fig. 13.12. It is seen that there is an integral coaxial cavity present in this magnetron. The tube is built so that the Q of this cavity is much higher than the Q's of the various resonators, so that it is the coaxial cavity which determines the operating

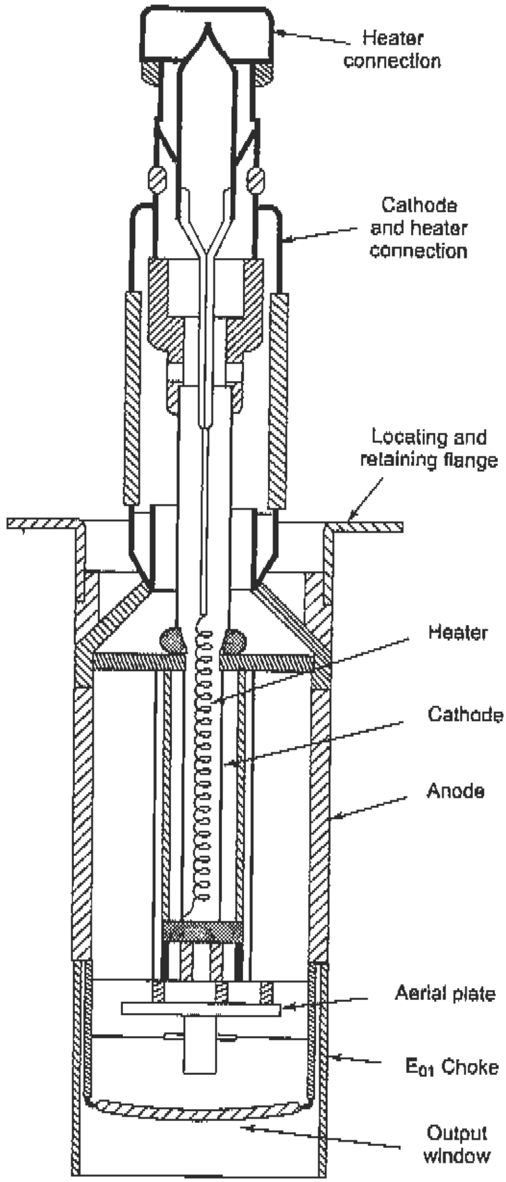

Fig. 13.11 *Pulsed magnetron construction (magnets omitted); 5-MW "long-anode" coaxial magnetron. (Courtesy of English Electric Valve Co. Ltd.)*

frequency. Oscillations in this cavity are in the coaxial $TE_{0,1}$ mode, in which the electric field is circular. It is possible to attenuate the resonator modes without interfering with the coaxial mode, so that mode jumping is all but eliminated. Frequency pushing and pulling are both significantly reduced, while the enlarged anode area, as compared with a conventional magnetron, permits better dissipation of heat and consequently smaller size for a given output power. The MTBF of coaxial magnetrons is also considerably longer than that of conventional ones.

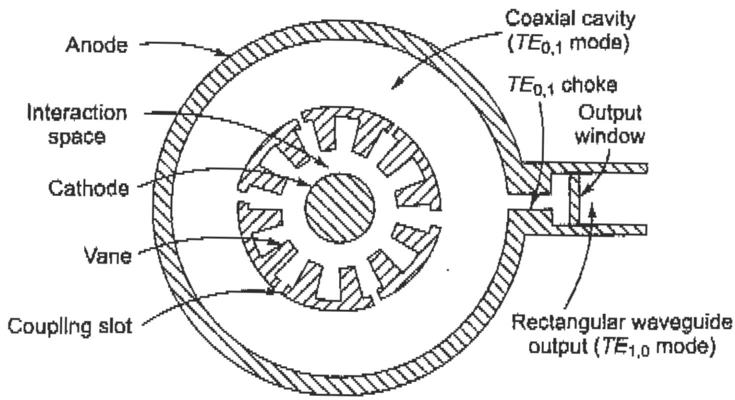

Fig. 13.12 *Cross section of coaxial magnetron; the magnetic field (now shown) is perpendicular to the page.*

Frequency-agile (or *dither-tuned*) magnetrons are also available. They may be conventional or coaxial, the earlier ones having a piston which can be made to descend into the cavity, increasing or decreasing its volume and therefore its operating frequency. The piston is operated by a processor-controlled servomotor, permitting very large frequency changes to be made quickly. This is of advantage in radar, where it may be required to send a series of pulses each of which is at a different radio frequency. The benefits of doing this are improved resolution and more difficulty (for the enemy) in trying to jam the radar. Dither tuning by electronic methods, yielding very rapid frequency changes, during the transmission of one pulse, if required, with a range typically 1 percent of the center frequency. The methods used have included extra cathodes, electron injection and the placing of PIN diodes inside the cavity.

Voltage-tunable magnetrons (VTMs) are also available for CW operation, though they are not very efficient. For this and other reasons they are not suited to pulsed radar work. These use low-Q cavities, cold cathodes (and hence back-heating) and an extra *injection electrode* to help bunching. The result is a magnetron whose operating frequency may be varied over an octave range by adjusting the anode voltage. Very fast sweep rates, and indeed frequency modulation, are possible.

Performance and Applications The traditional applications of the magnetron have been for pulse work in radar and linear particle accelerators. The *duty cycle* (fraction of total time during which the magnetron is actually ON) is typically 0.1 percent. The powers required range from 10 kW to 5 MW, depending on the application and the operating frequency. The maximum available powers range from 10 MW in the UHF band, through 2 MW in the X band, to 10 kW at 100 GHz. Current efficiencies are of the order of 50 percent; a significant size reduction is being achieved, especially for larger tubes, with the aid of two advancements. One is the development of modern permanent magnet materials, which has resulted in reduced electromagnet bulk. The other advance is in cathode materials. By the use of such substances as thoriated tungsten, much higher cathode temperatures (1800°C compared with 1000°C) are being achieved. This helps greatly in overcoming the limitation set by cathode heating from back bombardment.

VTMs are available for the frequency range from 200 MHz to X band, with CW powers up to 1000 W (10 W is typical). Efficiencies are higher, up to 75 percent. Such tubes are used in sweep oscillators, in *telemetry* and in missile applications.

Fixed-frequency CW magnetrons are also available; they are used extensively for industrial heating and microwave ovens. The operating frequencies are around 900 MHz and 2.5 GHz, although typical powers range from 300 W to 10 kW. Efficiencies are typically in excess of 70 percent.

13.5 TRAVELING-WAVE TUBE (TWT)

Like the multicavity klystron, the TWT is a *linear-beam* tube used as a microwave amplifier. Unlike the klystron, however, it is a device in which the *interaction between the beam and the RF field is continuous*. The TWT was invented independently by Kompfner in Britain and then Pierce in the United States, shortly after World War II. Each of them was dissatisfied with the very brief interaction in the multicavity klystron, and each invented a *slow-wave structure* in which *extended interaction* took place. Because of its construction and operating principles, as will be seen, the TWT is capable of enormous bandwidths. Its main application is as a medium- or high-power amplifer, either CW or pulsed.

13.5.1 TWT Fundamentals

In order to prolong the interaction between an electron beam and an RF field, it is necessary to ensure that both are moving in the same direction with approximately the same velocity. This relation is quite different from the multicavity klystron, in which the electron beam travels but the RF field is stationary. The problem that must be solved is that an RF field travels with the velocity of light, while the electron beam's velocity is unlikely to exceed 10 percent of that, even with a very high anode voltage. The solution is to retard the RF field with a slow-wave structure. Several such structures are in use, the helix and a waveguide coupled-cavity arrangement being the most common.

Description A typical TWT using a helix is shown in Fig. 13.13. An electron gun is employed to produce a very narrow electron beam, which is then sent through the center of a long axial helix. The helix is made positive with respect to the cathode, and the collector even more so. Thus the beam is attracted to the collector and acquires a high velocity. It is kept from spreading, as in the multicavity klystron, by a dc axial magnetic field, whose presence is indicated in Fig. 13.13 though the magnet itself is not shown. The beam must be narrow and correctly focused, so that it will pass through the center of the helix without touching the helix itself.

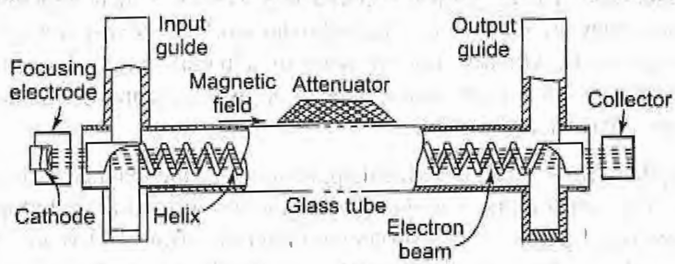

Fig. 13.13 *Helix-type traveling-wave tube; propagation along the helix is from left to right. (F. Harvey, Microwave Engineering, Academic Press Inc. (London) Ltd.)*

Signal is applied to the input end of the helix, via a waveguide as indicated, or through a coaxial line. This field propagates around the helix with a speed that is hardly different from the velocity of light in free space. However, the speed with which the electric field advances *axially* is equal to the velocity of light multiplied by the ratio of helix pitch to helix circumference. This can be made (relatively) quite slow and approximately equal to the electron beam velocity. The axial RF field and the beam can now interact continuously, with the beam bunching and giving energy to the field. Almost complete bunching is the result, and so is high gain.

Operation The TWT may be considered as the limiting case of the multicavity klystron, one that has a very large number of closely spaced gaps, with a phase change that progresses at approximately the velocity of the electron beam. This also means that there is a lot of similarity here to the magnetron, in which much the same process takes place, but around a closed circular path rather than in a straight line.

Bunching takes place in the TWT through a process that is a cross between those of the multicavity klystron and the magnetron.

Electrons leaving the cathode at random quickly encounter the weak axial RF field at the input end of the helix, which is due to the input signal. As with the passage of electrons across a gap, velocity modulation takes place and with it, between adjacent turns, some bunching. Once again it takes theoretically no power to provide velocity modulation, since there are equal numbers of accelerated and retarded electrons. By the time this initial bunch arrives at the next turn of the helix, the signal there is of such phase as to retard the bunch slightly and also to help the bunching process a little more. Thus, the next bunch to arrive at this point will encounter a somewhat higher RF electric field than would have existed if the first bunch had not made its mark.

The process continues as the wave and electron beam both travel toward the output end of the helix. Bunching becomes more and more pronounced until it is almost complete at the output end. Simultaneously the RF wave on the helix grows (exponentially, as it happens) and also reaches its maximum at the output end. This situation is shown in Fig. 13.14.

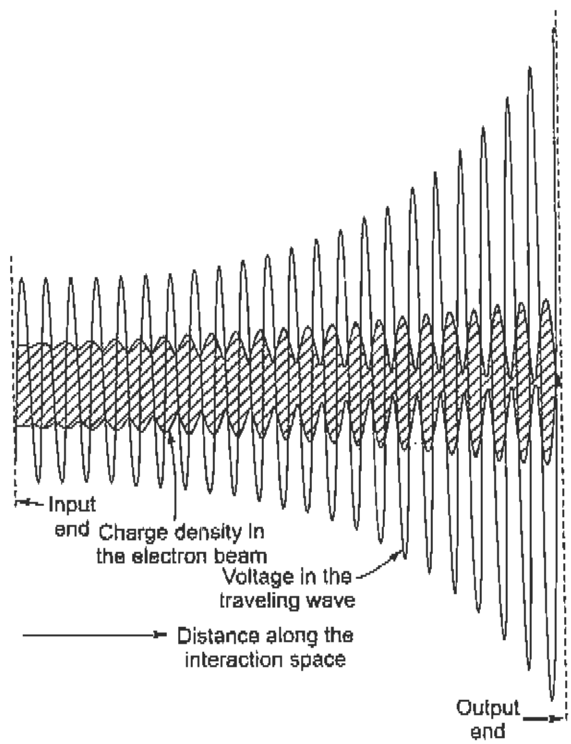

Fig. 13.14 *Growth of signal and bunching along traveling-wave tube. (Reich, Skalnik, Ordung, and Krauss, Microwave Principles, D. Van Nostrand Company, Inc., Princeton, N.J.)*

The interaction between the beam and the RF field is very similar to that of the magnetron. In both devices electrons are made to give some of their energy to the RF field, through being slowed down by the field, and in both devices a phase-focusing mechanism operates. It will be recalled that this tends to ensure that electrons bunch and that the bunches tend to keep arriving in the most favored position for giving up energy. There is at least one significant difference between the devices, and it deals with the methods of keeping the velocity of the beam much the same as that of the RF field, even though electrons in the beam are continually retarded. In the magnetron this is done by the dc magnetic field, but since there is no such field here (no component of it at right angles to the direction of motion of the electrons, at any rate), the axial dc electric field must provide the energy. A method of doing this is to give the electron beam an initial velocity that is slightly greater than that of the axial RF field. The extra initial velocity of electrons in the beam balances the retardation due to energy being given to the RF field.

13.5.2 Practical Considerations

Among the points to be considered now are the various types of slow-wave structures in use, prevention of oscillations, and focusing methods.

Slow-wave Structures Although the helix is a common type of slow-wave structure in use with TWTs, it does have limitations as well as good points. The best of the latter is that it is inherently a nonresonant structure, so that enormous bandwidths can be obtained from tubes using it. On the other hand, the helix turns are in close proximity, and so oscillations caused by feedback may occur at high frequencies. The helix may also be prevented from working at the highest frequencies because its diameter must be reduced with frequency to allow a high RF field at its center. In turn, this presents focusing difficulties, especially under operating conditions where vibration is possible. Care must be taken to prevent high power from being intercepted by the (by now very small-diameter) helix; otherwise the helix tends to melt.

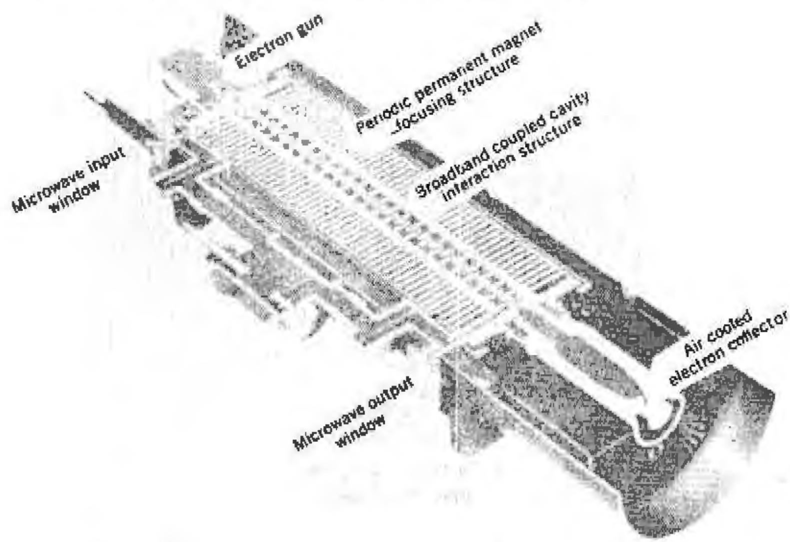

Fig. 13.15 *Cross section of high-power traveling-wave tube, using a coupled-cavity slow-wave structure and periodic permanent-magnet focusing. (Courtesy of Electron Dynamics Division, Hughes Aircraft Company.)*

A suitable structure for high-power and/or high-frequency operation is the *coupled-cavity* circuit, used by the TWT of Fig. 13.15. It consists of a large number of coupled (actually, *over*coupled) cavities and is reminiscent of a klystron with a very large number of intermediate cavities. Essentially, there is a continuous phase shift progressing along the adjoining cavities. Because these are overcoupled, it may be shown that the system behaves as a bandpass filter. This gives it a good bandwidth in practice but not as good as the exceptional bandwidth provided by helix TWTs. This type of slow-wave structure tends to be limited to frequencies below 100 GHz, above which *ring-bar* and other structures may be employed.

Prevention of Oscillations Figure 13.14 shows the exponential signal growth along the traveling-wave tube, but it is not to scale—the actual gain could easily exceed 80 dB. Oscillations are thus possible in such a high-gain device, especially if poor load matching causes significant reflections along the slow-wave structure. The problem is aggravated by the very close coupling of the slow-wave circuits. Thus all practical tubes use some form of attenuator (which has the subsidiary effect of somewhat reducing gain). Both forward and reverse waves are attenuated, but the forward wave is able to continue and to grow past the attenuator, because bunching is unaffected. With helix tubes, the attenuator may be a lossy metallic coating (such as aquadag or Kanthal) on the surface of the glass tube. As shown in Fig. 13.15, with a coupled-cavity slow-wave structure there are really several (three, in this case) loosely coupled, self-contained structures, between which attenuation takes place. It should be noted that Fig. 13.14 shows a simplified picture of signal and bunching growth, corresponding to a TWT without an attenuator.

Focusing Because of the length of the TWT, focusing by means of a permanent magnet is somewhat awkward, and focusing with an electromagnet is bulky and wasteful of power. On the other hand, the solenoid does provide an excellent focusing magnetic field, so that it is often employed in high-power (ground-based) radars. The latest technique in this field is the integral solenoid, a development that makes the assembly light enough for airborne use. Fig. 13.16 shows the cross section of a TWT with this type of focusing.

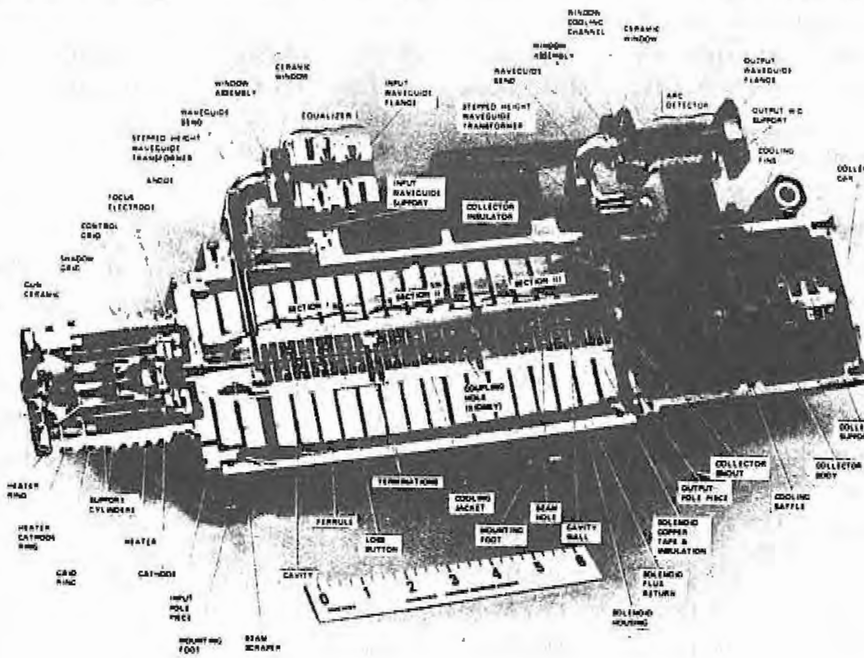

Fig. 13.16 *Cross section of complete 9-kW pulsed X-band traveling-wave tube, with a three-section coupled-cavity slow-wave structure and integral solenoid focusing. (Courtesy of Electron Dynamics Division, Hughes Aircraft Company.)*

To reduce bulk, *periodic permanent-magnet* (PPM) focusing is very often used. This PPM focusing was mentioned in connection with klystron amplifiers and is now illustrated in Fig. 13.15. PPM is seen to be a system in which a series of small magnets are located right along the tube, with spaces between adjoining magnets. The beam defocuses slightly past each pole piece but is refocused by the next magnet. Note that the individual magnets are interconnected. The system illustrated is the so-called radial magnet (as opposed to axial magnet) PPM.

13.5.3 Types, Performance and Applications

The TWT is the most versatile and most frequently used microwave tube. There are broadly four types, each with particular applications and performance requirements. These are now described.

TWT Types The most fruitful method of categorizing traveling-wave tubes seems to be according to size, power levels and type of operation. Within each category, various slow-wave structures and focusing methods may be used.

The first TWTs were broadband, low-noise, low-level amplifiers used mainly for receivers. That is now a much-diminished application, because transistor amplifiers have much better noise figures, much lower bulk and comparable bandwidths. They are not as radiation-immune as the TWT and not as suitable for hazardous environments. The TWX19, whose performance is given in Table 13.2, is typical of such tubes. It comes all enclosed with its power supply and draws just a few watts from the mains. The package measures about 30 × 5 × 5 cm and weighs about 1½ kg.

TABLE 13.2 *Typical Traveling-Wave Tubes*

MAKE AND MODEL	FREQUENCY RANGE, GHz	POWER OUT, max.	DUTY CYCLE	NOISE FIGURE, dB	POWER GAIN, dB	FOCUSING
EEV* N1047M	2.7–3.2	1.5 mW	CW	4.0	24	Solenoid
M-OV† TWX19	7–12	1 mW	CW	11.0	38	PPM
TMEC‡ M9346	26.5–40	5 mW	CW	17.0	40	?
EEV* N1073	3.55–5	16 W	CW		41	PPM
Hughes 677H	5.9–6.4	125 W	CW		45	PPM
Hughes 551H	2–4	1 kW	CW		30	Solenoid
Hughes 614H	5.9–6.4	8 kW	CW		40	Solenoid
Hughes 876H	14.0–14.5	700 W	CW		43	PPM
Hughes 870H	14.0–14.5	5 kW	CW		35	Integral solenoid
Hughes 819H	54.5–55.5	5 kW	CW		20	Solenoid
Hughes 985H	84–86	200 W	CW		47	PPM
Ferranti LY70	2.7–3.7	10 kW	2.5%		48	PPM
Hughes 8754H	9–18	1.5 kW	8.0%		45	PPM
Hughes 835H	16–16.5	200 kW	1.0%		60	PPM
EEV* N1061	9–9.45	900 kW	0.5%		33	Solenoid
Hughes 562H§	2–4	200 W/1 kW	CW/5%		30/30	PPM
EEV* N10011§	9–10.5	210/820W	CW/50%		29/49	PPM

* English Electric Valve Company. † M-O Valve Company. ‡ Teledyne MEC. § Dual-mode tubes.

The second type is the CW power traveling-wave tube. It is represented by several of the entries in Table 13.2 (all those that produce watts or kilowatts of CW). The 677H is typical, weighing just under 2¾A kg and measuring 7 × 7 × 41 cm. The major application for this type of TWT is in satellite communications, either in satellite earth stations (types 614H and 870H in Table 13.2) or aboard the satellites themselves (type 677H). This type is also increasingly used in CW radar and electronic counter- measures (ECM); indeed, tubes such as type 819H in Table 13.2 are designed for this application.

Pulsed TWTs are representative of the third category, and several are shown in Table 13.2. They are considerably bigger and more powerful than the preceding two types. A representative tube is the Hughes 797H, illustrated in Fig. 13.16. This TWT produces 9 kW in the X band, with a duty cycle of 50 percent. It weighs just over 20 kg, draws 2.5 A at 8 kV dc and measures 53 × 15 × 20 cm.

The fourth type is the newest, still under active development. It comprises *dual-mode* TWTs. These are types with military applications, capable of being used as either CW or pulsed amplifiers. They are comparable in size, power, weight and mains requirements to the medium-power communications TWTs. The type 562H tube in Table 13.2 weighs 4.5 kg and is 45 cm long. Although the TWT in general represents a fairly mature technology, the dual-mode tube does not.

Performance Low-level, low-noise TWTs are available in the 2- to 40-GHz range, and three are shown in Table 13.2. Such tubes generally use helixes and have octave bandwidths or sometimes even more. Their gains range from 25 to 45 dB and noise figures from 4 to 17 dB, while typical power output is 1 to 100 mW. They tend now to be used mostly for replacement purposes, having been displaced by transistor (FET or bipolar) amplifiers in most new equipment except in specialized applications.

By virtue of their applications, CW power tubes are made essentially in two power ranges—up to about 100 W and over about 500 W. Several of them are featured in Table 13.2. The frequency range covered is from under 1 to over 100 GHz, with typically 2 to 15 percent bandwidths. Available output powers exceed 10 kW with gains that may be over 50 kB, and efficiencies are in the 25 to 35 percent range with normal techniques, with a so-called *depressed collector* efficiencies can exceed 50 percent. This is a system in which the collector potential is made lower than the cathode potential to reduce dissipation and improve efficiency. The tube of Fig. 13.16 uses the depressed collector technique. TWTs of this type employ the helix when octave bandwidths are required and the coupled-cavity structure for narrower band-widths. Focusing is PPM most often, and a noise figure of 30 dB is typical. For space applications, reliabilities of the order of 50,000 hours (nearly 6 years) mean time between failures are now available.

Over the frequency range of approximately 2 to 100 GHz, pulsed TWTs are available with peak outputs from 1 to about 250 kW typically. However, powers in the megawatt range are also possible. Bandwidths range from narrow (5 percent) to three octaves with helix tubes at the lower end of the power range. All manners of focusing and slow-wave structures are employed. Duty cycles can be much higher than for magnetrons or klystrons, 10 percent or higher being not uncommon. All other performance figures are as for CW power TWTs.

Dual-mode TWTs are currently available for the 2- to 18-GHz spectrum. Power outputs range up to 3 kW pulsed and 600 W CW, with a maximum 10:1 *pulse-up ratio* (peak pulse power to CW ratio for the same tube), which should be raised even more in the near future. The remaining data are as for single-mode pulsed TWTs, and two dual-mode tubes are shown in Table 13.2.

Applications As has been stated, traveling-wave tubes are very versatile indeed. The low-power, low-noise ones have been used in radar and other microwave receivers, in laboratory instruments and as drivers for more powerful tubes. Their hold on these applications is much more tenuous than it was, because of semiconductor advances. As will be seen next transistor amplifiers, *tunnel* diodes and *Schottky* diodes can handle a lot of this work, while the TWT never could challenge *parametric amplifiers* and *masers* for the lowest-noise applications.

Medium- and high-power CW TWTs are used for communications and radar, including *ECM*. The vast majority of space-borne power output amplifiers ever employed have been TWTs because of the high reliability, high gain, large bandwidths and constant performance in space. The majority of satellite earth stations use TWTs as output tubes, and so do quite a number of tropospheric scatter links. Broadband microwave links also use TWTs, generally employing tubes in the under 100-W range. CW traveling-wave tubes are also used in some kinds of radar, and also in radar jamming, which is a form of ECM. In this application, the TWT is fed from a broadband noise source, and its output is transmitted to confuse enemy radar.

CW tubes will of course handle FM and may be used either to amplify AM signals or to generate them. For AM generation, the modulating signal is fed to the previously mentioned special grid. However, it must be noted that the TWT, like the klystron amplifier, begins to saturate at about 70 percent of maximum output and ceases to be linear thereafter. Although this does not matter when amplifying FM signals, it most certainly does matter when AM signals are being amplified or generated, and in this case the tube cannot be used for power outputs exceeding 70 percent of maximum.

Pulsed tubes find applications in airborne and ship-borne radar, as well as in high-power ground-based radars. They are capable of much higher duty cycles than klystrons or magnetrons and are thus used in applications where this feature is required.

13.6 OTHER MICROWAVE TUBES

Various other microwave tubes will now be introduced and briefly discussed. They are the *crossed-field amplifier* (CFA), *backward-wave oscillator*.

13.6.1 Crossed-Field Amplifier

The CFA is a microwave power amplifier based on the magnetron and looking very much like it. It is a cross between the TWT and the magnetron in its operation. It uses an essentially magnetron structure to provide an interaction between crossed dc electric and magnetic fields and an RF field. It uses a slow-wave structure similar to that of the TWT to provide a continuous interaction between the electron beam and a *moving RF field*. (It will be noted that in the magnetron, interaction is with a *stationary RF field*.)

Operation The cross section of a typical CFA is shown in Fig. 13.17; the similarity to a coaxial magnetron is striking in its appearance. It would have been even more striking if, as used in practice, a vane slow-wave structure had been shown, with waveguide connections. The helix is illustrated here purely to simplify the explanation. Practical CFAs and magnetrons are very difficult to tell apart by mere looks, except for one unmistakable giveaway: unlike magnetrons, CFAs have RF *input* connections.

As in the magnetron, the interaction of the various fields results in the formation of bunched electron clouds. An input signal is supplied and receives energy from electron clouds traveling in the same direction as the RF field. In the TWT, signal strength grows along the slow-wave structure, and gain results. It will be seen in Fig. 13.17 that there is an area free of the slow-wave structure. This provides a space in which electrons drift freely, isolating the input from the output to prevent feedback and hence oscillations. An attenuator is sometimes used also, similar to the TWT arrangement.

In the tube shown, the direction of the RF field and the electron bunches is the same; this is a *forward-wave* CFA. *Backward-wave* CFAs also exist, in which the two directions are opposed. There are also CFAs which have a grid located near the cathode in the drift-space area, with an accelerating anode nearby. They are known as *injected-beam* CFAs.

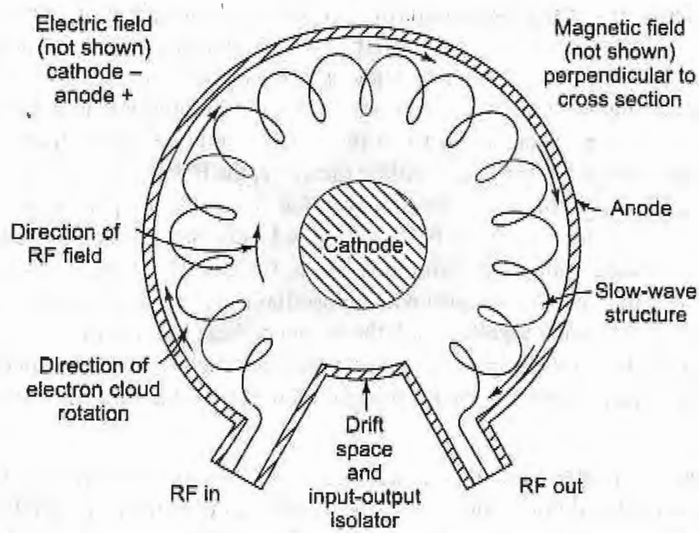

Fig. 13.17 *Simplified cross section of continuous-cathode, forward-wave crossed-field amplifier.*

Practical Considerations The majority of crossed-field amplifiers are pulsed devices. CW and dual-mode CFAs are also available, although their performance and other details tend to be shrou d in military secrecy. However, dual-mode operation is easier for CFAs than for TWTs because here both the electric and the magnetic fields can be switched to alter power output. Thus 10:1 or higher power ratios for dual-mode operations are feasible.

Pulsed CFAs are available for the frequency range from 1 to 50 GHz, but the upper frequency is a limit of existing requirements rather than tube design. CFAs are quite small for the power they produce (like magnetrons), and that is a significant advantage for airborne radars. The maximum powers available are well over 10 MW in the UHF range (with an excellent efficiency of up to 70 percent), 1 MW at 10 GHz (efficiency up to 55 percent) and 400 kW CW in the S-band. The excellent efficiency contributes to the small relative size of this device and of course to its use. Duty cycles are up to about 5 percent, better than magnetrons but not as high as TWTs. Bandwidths are quite good at up to 25 percent of center frequency (and one octave for some injected-beam CFAs). The relatively low gains available, typically 10 to 20 dB, are a disadvantage, in that the small size of the tube is offset by the size of the driver, which the klystron or TWT, with their much higher gains, would not have required.

A typical forward-wave CFA is the Varian SFD257. It operates over the range 5.4 to 5.9 GHz, producing a peak power of 1 MW with a duty cycle of 0.1 percent. The efficiency is 50 percent, gain 13 dB, and noise figure approximately 36 dB, a little higher than for a corresponding klystron. The anode voltage is 30 kV dc, and the peak anode current is 70 A. The tube, like a number of magnetrons, uses back-heating for the cathode, and indeed both it and the anode are liquid-cooled. The whole package, with magnet, weighs 95 kg and looks just like a high-power magnetron with an extra set of RF terminals. Crossed-field amplifiers are used almost entirely for radar and electronic countermeasures.

13.6.2 Backward-Wave Oscillator

A backward-wave oscillator (BWO) is a microwave CW oscillator with an enormous tuning and overall frequency coverage range. It operates on TWT principles of electron beam-RF field interaction, generally using a helix slow-wave structure. In general appearance the BWO looks like a shorter, thicker TWT.

Operation If the presence of starting oscillations may be assumed, the operation of the BWO becomes very similar to that of the TWT. Electrons are ejected from the electron-gun cathode, focused by an axial magnetic field and collected at the far end of the glass tube. They have meanwhile traveled through a helix slow-wave structure, and bunching has taken place, with bunches increasing in completeness from the cathode to the collector. An interchange of energy occurs, exactly as in the TWT, with RF along the helix growing as signal progresses toward the collector end of the helix. Unlike the TWT, the BWO does not have an attenuator along the tube. As a simplification, oscillations may be thought of as occurring simply because of reflections from an imperfectly terminated collector end of the helix. There is feedback, and the output is collected from the *cathode end* of the helix, toward which reflection took place. Because the helix is essentially a nonresonant structure, bandwidth (if one may use such a term with an oscillator) is very high, and the operating frequency is determined by the collector voltage together with the associated cavity system.

Bandwidth is limited by the interaction between the beam and the slow-wave structure. To increase this interaction, the BWO has a ring cathode which sends out a hollow beam, with maximum intensity near the helix.

Practical Aspects Backward-wave oscillators are used as signal sources in instruments and transmitters. They can also be made broadband noise sources, whose output, amplified by an equally wideband TWT, is transmitted as a means of enemy radar confusion. The frequency spectrum over which BWOs can be made to operate is vast, stretching from 1 to well over 1000 GHz. The Thomson-CSF CO 08 provides about 50 mW CW over the range 320 to 400 GHz, while 0.8 mW CW has been reported, from another BWO, at 2000 GHz. The normal output range of BWOs is 10 to 100 mW CW, but tubes with outputs over 20 W, at quite high frequencies, have also been produced. The tuning range of a BWO is an octave typically, up to about 40 GHz. At higher frequencies multiple helixes or coupled cavities are used, with a consequent bandwidth reduction to typically a half-octave. At the lower end of the spectrum, frequency ranges over 3:1 are possible from the one tube. The ITT F-2513 produces an average of 25 mW over the range 1.3 to 4.0 GHz. The rate at which the BWO frequency may be changed is very high, being measured in gigahertz per microsecond.

Permanent magnets are normally used for focusing, since this results in simplest magnets and smallest tubes. Solenoids are used at the highest frequencies, since it has been found that they give the best penetration and distribution for the axial magnetic field. A recent development in this respect has been the use of samarium-cobalt permanent magnets to reduce weight and size.

The Siemens RWO 170 is a typical BWO and produces an average power output of 10 mW. It is electronically tunable over the range from 60 GHz (at which the collector voltage is 500 V) to 110 GHz (collector voltage 2500 V). The average collector current is 12 to 15 m A and dissipation about 30 W. Together with its power supply and magnet, it weighs 2 kg.

Multiple-Choice Questions

Each of the following multiple-choice questions consists of an incomplete statement followed by four choices (a, b, c, and d). Circle the letter preceding the line that correctly completes each sentence.

1. A microwave tube amplifier uses an axial magnetic field and a radial electric field. This is the
   a. reflex klystron
   b. coaxial magnetron
   c. traveling-wave magnetron
   d. CFA
2. One of the following is unlikely to be used as a pulsed device. It is the
   a. multicavity klystron
   b. BWO
   c. CFA
   d. TWT