MICROWAVE TUBES

Microwave tubes are devices which generate or amplify electromagnetic radiation in the frequency range of 0.3 GHz to 300 GHz (microwave frequencies); they are based on the interaction between electromagnetic radiation and a stream of electrons inside a vacuum envelope (the tube). Compared with solid state microwave devices, microwave tubes operate at much higher power levels. Average output power ratings for state-of-the-art, single microwave tubes and for single solid state microwave devices are plotted versus frequency in Fig. 1 for the decades from 1950 to 1990 and for 2005. It can be seen that in 1990 microwave tubes were 1000 times more powerful than the most powerful solid state devices at a frequency of 1 GHz, and 100,000 times more powerful at a frequency of 100 GHz. In 2005, 900 kilowatt continuous wave (CW) operation had been demonstrated in a microwave tube at 140 GHz with no comparable advance in solid state device capabilities.

Because of their compactness solid state devices are usually the preferred choice for low power systems, with microwave tubes preferred in high power systems. The breakpoint comes for system average output power of approximately 100 watts. There, the greater efficiency of microwave tubes (typically, 50% versus 25% for solid state devices) results in a more compact overall system when a microwave tube output stage is combined with a smaller power supply.

The superior efficiency of microwaves may be understood from the fact that in vacuum the electrons do not pass through a background material which would imped their movement. Thus, the heating of a background material is not a limiting factor of high power operation. Also, the electron trajectories are not randomized by collisions with a background material so that after passing through the microwave generation region the energy spectrum of the spent electrons is concentrated in a relatively narrow energy range; this facilitates energy recovery from the spent electrons and high overall device efficiency.

PRINCIPLES OF OPERATION

Electrons that are accelerated (or decelerated) emit electromagnetic radiation. However, unless the positions of the electrons form an ordered pattern (bunching), the emitted radiation will be incoherent; that is, the phase of the electromagnetic wave emitted by an electron will be random compared with the phases of the waves emitted by the other electrons. To achieve powerful radiation the emitted waves must add up in phase (coherent radiation) and this requires bunching.

The microwave tube contains a structure (the circuit) which supports electromagnetic waves that can interact with the electron beam to form microbunches of electrons. An unbunched electron beam passing through the vacuum tube with axial velocity, v_z, is shown in Fig. 2(a). The periodic axial electric field component of an electromagnetic wave (transverse magnetic mode) is also shown in this figure and this field will exert a force on the electrons which will concentrate them into bunches as shown in Fig. 2(b).

When the phase of the bunches is arranged with respect to the wave electric field as shown in this figure, the electrons are decelerated. The decrease in electron energy is accompanied by an equal increase in the energy of the electromagnetic wave. This can be regarded as coherent radiation of microwaves by the electrons, the bunching being required for coherence. In order for the wave to keep extracting energy from the beam its axial phase velocity must match the electron axial velocity; this condition is called beam/wave synchronism.

The bunching process results from excitation of the natural modes of an electron beam with charge density, ρ, streaming with axial velocity, v_z, in the presence of a constant, externally-applied, axial magnetic field, B_0. These modes of oscillation are of two types:

1. Space charge waves which involve the plasma frequency,

   $$\omega_p = \sqrt{\frac{e\rho}{m\epsilon_0}}$$

   where e and m are, respectively, the charge and mass of an electron, and ε_0 is the permittivity of free space, and
2. Cyclotron waves which involve the electron cyclotron frequency,

   $$\omega_c = \frac{eB_0}{m}$$

The propagation of a particular wave is described by its dispersion equation which is a relationship between its frequency, ω, and its axial wavenumber, β. The space charge waves on an electron beam obey the dispersion equation

$$\omega = \beta v_z \pm \omega_p F \tag{1}$$

where F, the space charge reduction factor, depends on the finite transverse geometry of the waveguide; for an electron beam filling a hollow cylindrical waveguide with conducting walls of radius, a,

$$F = \left[1 + \left(\frac{2.405}{\beta a}\right)^2\right]^{-1/2}$$

Thus, F approaches unity as βa becomes large. In Eq. (3), the plus sign refers to the fast space charge wave while the minus sign is for the slow space charge wave.

If the electrons also have a velocity component transverse to the axis, $v_\perp$, then cyclotron waves may exist in addition to the space charge waves. The dispersion equation for the cyclotron waves is

$$\omega = \beta v_z \pm \omega_c \tag{2}$$

In Eq. (5), the plus sign refers to the fast cyclotron wave and the minus sign refers to the slow cyclotron wave.

Finally in this section, we note that the microwave tube can be either an oscillator or an amplifier. Oscillators have no microwave input signal and effectively amplify noise;

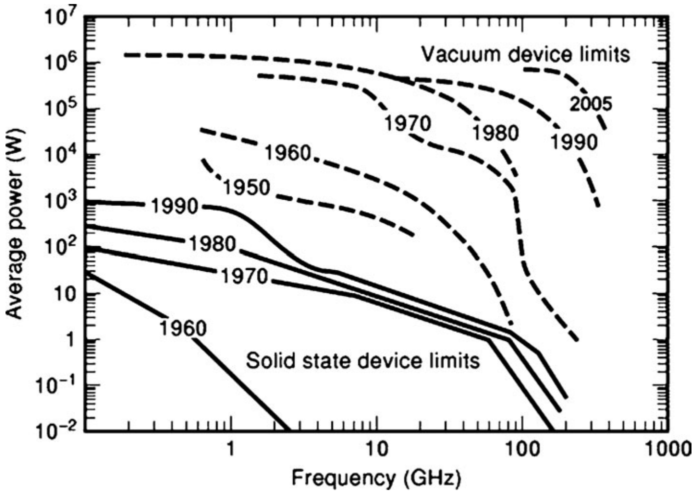

Figure 1. Histogram of power available from a single microwave oscillator or amplifier as a function of frequency. The solid lines represent solid state device limits. The dashed lines represent vacuum electronics device limits.

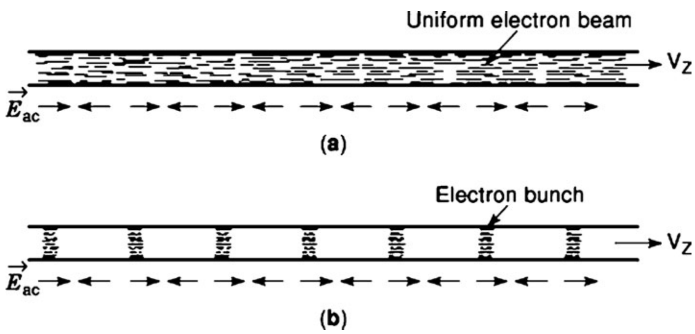

Figure 2. Figure 2(a) depicts an unbunched beam of electrons passing through a vacuum tube together with the periodic axial electric field of an electromagnetic wave. Figure 2(b) shows a bunched electron beam with the bunches arranged to be decelerated by the wave field.

they are most commonly used in heating applications such as domestic cooking, industrial processing of materials, and heating of the ionized gas (plasma) in a controlled fusion reactor to the temperature required for thermonuclear ignition. Amplifiers do have a microwave input signal which is strengthened by its interaction with the electron beam to produce an output signal that is much stronger than the input; the output signal tracks the frequency and phase of the input signal. Amplifiers are used in communications and radar systems and in other systems that require phase control, such as high energy particle accelerators.

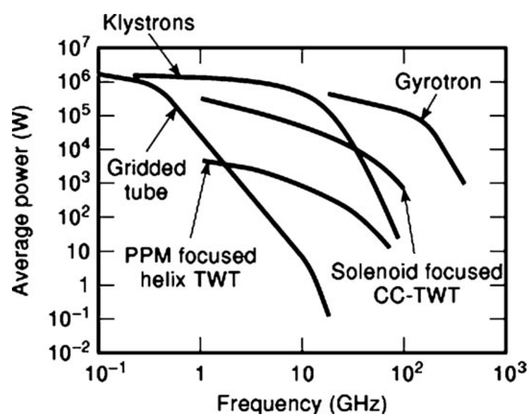

Figure 3. The average power capability of a single microwave tube versus frequency shown for some major types of microwave tube.

TYPES OF MICROWAVE TUBES

There are a number of important types of microwave tubes which differ with regard to the configuration of the circuit inside the vacuum envelope and/or with regard to the electrode configuration used for generating the electron beam. These differing configurations lead to a variety of combinations of performance characteristics (e.g., operating frequency, power, bandwidth, oscillator or amplifier operation). The average power capability of some of the more important types of microwave tubes are plotted in Fig. 3 as a function of frequency.

In Table 1 the important features and applications of each of the major types of microwave tubes is indicated. Each tube type is identified as either an oscillator or amplifier, depending on its most usual deployment; however, we have also indicated the complementary tubes which use similar configurations. We will now describe the circuit configuration, the electron beam configuration, the process of electron bunching, and the process of microwave amplification in each of the major tube types.

Traveling Wave Tube (*TWT*) Amplifiers

The configuration of a helix TWT amplifier is sketched in Fig. 4. The Pierce electron gun ideally produces a solid cylindrical electron beam which streams through the circuit along the lines of the externally applied axial magnetic field with velocity v_z and without appreciable transverse velocity. The circuit is a helix which supports the propagation of slow electromagnetic waves; that is, the phase

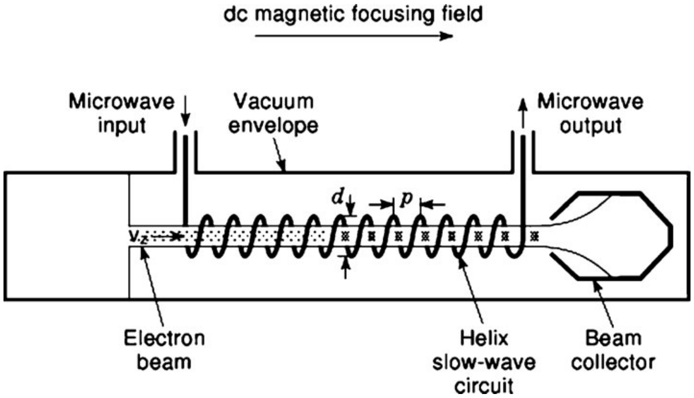

Figure 4. Configuration of a helix traveling wave tube amplifier.

Table 1. Major Types of Microwave Tubes

Tube Type	Circuit	Electron Beam	Advantages	Most Common Applications	Complimentary Tube
Traveling Wave Tube (TWT) Amplifier	Periodic waveguide; helix or coupled cavity (cc)	Solid cylindrical beam produced by Pierce electron gun	Wide bandwidth	Communications; jammers	Backward wave oscillator (BWO); wide tunability, used for spectroscopy
Klystron Amplifier	Resonant, small-gap cavities separated by cutoff drift tubes	Solid cylindrical beam produced by Pierce electron gun	High gain[a] High efficiency[b]	Radar; electron accelerators for medical applications and high energy physics research	Reflex klystron oscillator
Magnetron Oscillator	Coaxial configuration of inner cathode cylinder and outer anode which contains periodic arrangement of resonant cavities	Rotating electron beam in annular space between cathode and anode	Rugged Low cost	Domestic cooking; industrial heating of materials	Cross field amplifier (CFA); used in radar
Gyrotron Oscillator	Resonant cavity employing high order transverse electric mode (e.g., $TE_{M,1}$)	Annular beam of spiraling electrons produced by magnetron injection gun (MIG)	High average power at millimeter wavelengths (30–300 GHz)	Plasma heating in controlled thermonuclear fusion research (CTFR)	Gyroklystron amplifier, used in millimeter wave radar (35 GHz, 94 GHz)

[a] Gain is the ratio of power in the output microwave signal to power in the input microwave signal.
[b] Efficiency is the fraction of electron beam power that is converted to microwave output power.

velocity of the wave in the axial direction is less than the speed of light, c. For a helix of period p and diameter d, the axial phase velocity is

$$v_p = c\frac{p}{\sqrt{p^2 + (\pi d)^2}}$$

and if v_p is made equal to the initial value of electron velocity, v_z, beam/wave synchronism will be achieved. Bunching and deceleration of the electrons can then occur as was pictured in Fig. 2; the process can be regarded as an interaction between the slow electromagnetic wave of the helix circuit and the slow space charge wave of the electron beam. In Fig. 5, the dispersion curves of the circuit wave and of the slow space charge wave are sketched. They are seen to be approximately in synchronism (i.e., almost touching) over a wide range of frequencies (one to three octaves) with maximum value of frequency just a little smaller than $2\pi v_{z0}/a$.

Amplification may then occur over this wide range of frequencies. The amplifier linear gain in dB is given by

$$G(\mathrm{dB}) = -9.54 + 3.75\,\frac{\omega L}{v_z}\left(\frac{\omega_p}{\omega}\right)^{3/2} \tag{3}$$

where L is the length of the helix circuit. In Eq. (7) the first term on the right-hand side is the insertion loss caused by excitation of beam modes which do not grow.

The amplification process saturates when v_z is decreased from its initial value by deceleration to such an

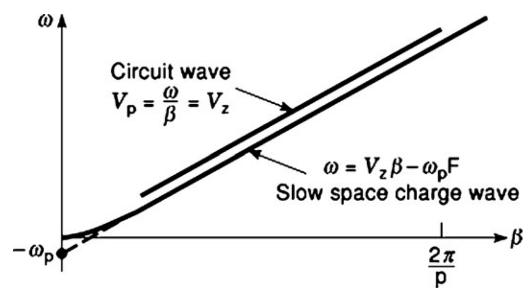

Figure 5. Dispersion curves of the helix circuit wave and the slow space charge wave.

extent that the synchronism, $v_z = v_p$, is no longer maintained to an adequate degree. Single pass efficiency is on the order of only 10% but this may be increased to approximately 50% by the use of techniques to recover energy in the spent electron beam, such as depressed collectors.

The helix circuit is especially capable of wide bandwidth but it is rather delicate and will not support a very large power rating, especially as frequency rises (see Fig. 3). The coupled cavity periodic circuit, which also supports slow waves, is much more robust and is capable of supporting larger powers; however, its bandwidth is more limited.

A miniaturized helix TWT is used as the output power stage of the 100 W continuous wave (*CW*) microwave power module (*MPM*). The MPM is more compact overall than a system with a solid state output stage because of the 50% efficiency of the TWT. This tube also achieves a gain of 50 dB in a length of 22 cm and it covers a frequency of range of 4.5 to 18 GHz. Coupled cavity TWTs have a much smaller bandwidth of only a few percent, but they have achieved 700 W average power at 94 GHz.

Magnetron

Magnetrons are the most ubiquitous of microwave tubes, used by the tens of millions in domestic microwave ovens. They also have a celebrated history, enabling high-power radar in World War II and credited for the victory of the Allies in the Battle of Britain and perhaps the entire war. The primary reason for the magnetron being the earliest radar power tube and its present widescale domestic application is the simplicity of its structure. In contrast to the TWT amplifier sketched in Fig. 4, the magnetron has no electron gun. Instead, the anode and cathode are coaxial with the annular space between them functioning as the region in which the electron stream and the electromagnetic waves interact.

A cross section of the coaxial magnetron geometry is sketched in Fig. 6. There is a dc voltage, V_0, applied between the anode and cathode which produces a radial dc electric field

$$E_0 = \frac{V_0}{r\ell n(b/a)} \approx \frac{V_0}{2r}\frac{b+a}{(b-a)} \tag{4}$$

where r is the radial coordinate and a and b are the cathode and anode radii, respectively. A dc magnetic field, B_0, is applied in the axial direction. Under the influence of the crossed electric and magnetic fields, the electrons execute a cycloidal motion which can usually be decomposed into small orbit Larmor rotations at the electron cyclotron frequency and a lower azimuthal motion around the annulus with velocity

$$\bar{v}_\phi = \frac{\bar{E}_0 \times \bar{B}_0}{B_0^2} \tag{5}$$

Cavities which are resonant at the operating frequency are cut into the anode block and arranged periodically around the azimuth. For the π-mode in which the field in adjacent cavities are 180° out of phase as shown in Fig. 6, the fringing fields at radius r in the annular space appear to rotate with phase velocity

$$v_p = \frac{2\omega r}{N} \tag{6}$$

where N is the number of cavities.

An interaction between the rotating electron cloud and the electromagnetic fields can then lead to a growing electromagnetic wave in a manner related to the process in the TWT. This requires synchronism between the electron azimuthal velocity given by Eq. (9) and the phase velocity given by Eq. (10). For electrons at the center of the annular space, that is, $r = (b + a)/2$ and with E_0 related to V_0 by Eq. (8) the synchronism condition gives

$$V_0 = B_0\omega(b^2 - a^2)/N \tag{7}$$

This type of synchronism relationship between V_0 and B_0 is known as a Buneman–Hartree equation.

There is also an inequality that V_0 must satisfy to ensure that the dc electron trajectories will not strike the anode. This is known as the Hull cutoff condition and is

$$V_0 < \frac{1}{8}\frac{e}{m}B_0^2\frac{(b^2-a^2)^2}{b^2} \tag{8}$$

As the electromagnetic wave grows, energy is extracted from the rotating electron cloud. The electrons in the process are forced outward to new radial positions where their potential energy is lower. The magnetron process may therefore be viewed as converting electron potential energy to electromagnetic wave energy. The electron kinetic energy, however, remains sufficient to maintain the synchronism between v_ϕ and v_p until the electron eventually reads the anode. Because of this mechanism for maintaining a synchronous interaction, magnetrons have relatively large efficiency compared with the single pass efficiency of TWT amplifiers.

The 2.45 GHz magnetrons used in ovens for domestic cooking typically operate at better than 50% efficiency with average output power of 600 watts. Other magnetrons have been developed with efficiency as great as 85% and with average power of hundreds of kilowatts.

Klystrons

Although magnetrons are high power and efficient microwave oscillators they are not suitable for applications which require high-gain amplifiers; for such applications klystrons have been the devices of choice. The layout of a two-cavity klystron is sketched in Fig. 7. Interaction between the electron beam and electromagnetic waves occurs only while the electrons are passing through narrow gaps which form the capacitive regions of the resonant cavities; the drift tube between the cavities is cutoff for electromagnetic waves.

Each resonant cavity has a coaxial outer region which is inductive with inductance

$$\mathcal{L} = \frac{1}{\pi}\sqrt{\frac{\mu_0}{\epsilon_0}}\ln\left(\frac{b}{a}\right)\frac{1}{\omega}\tan\left(\frac{\omega L}{2c}\right)$$

where μ_0 is the permeability of free space. This inductance may be considered to be in parallel with the narrow gap region that has capacitance

$$\mathcal{C} = \frac{\epsilon_0\pi a^2}{d}$$

The resonant frequency of the cavity will be $\omega_\mathrm{r} = 1/\mathcal{LC}$. Each cavity will also be characterized by its unloaded quality factor,

$$Q_0 = \frac{\omega_\mathrm{r}\mathcal{C}}{G_\mathrm{W}}$$

where G_W is the wall conductance whose nonzero value is a measure of the microwave power that is lost in heating the cavity walls.

When the electron beam passes through the gap in the first cavity, it is modulated in velocity by the microwave

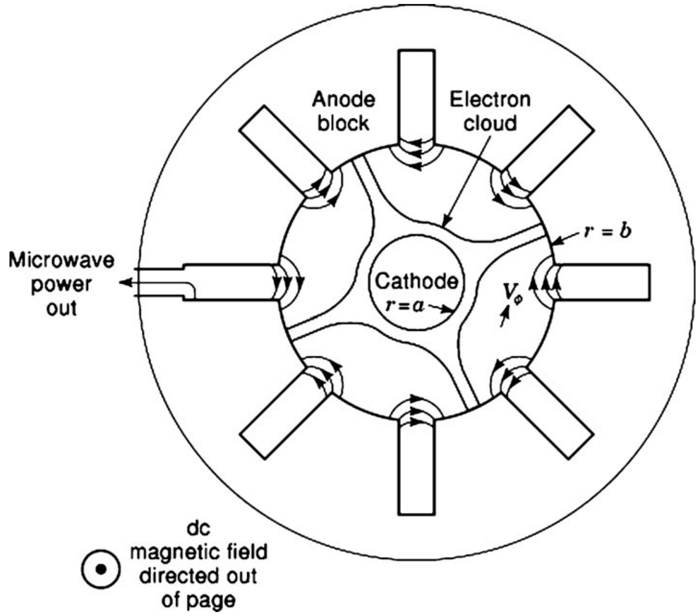

Figure 6. Configuration of a co-axial magnetron oscillator.

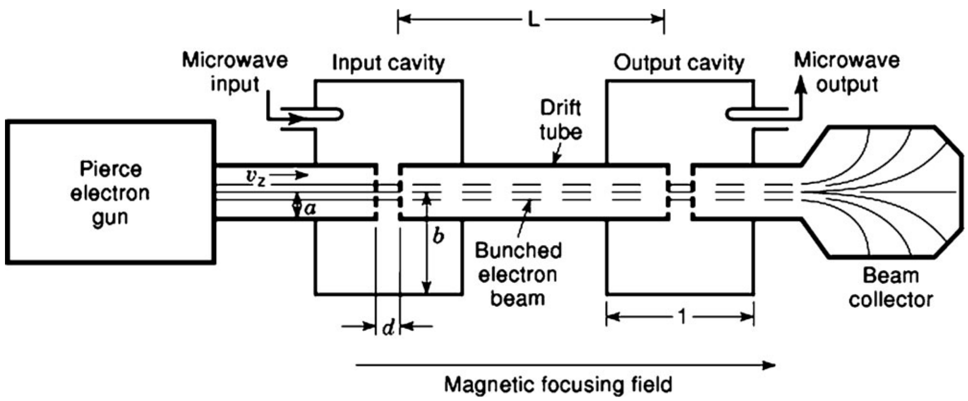

Figure 7. Configuration of a two-cavity klystron amplifier.

field in the gap. This leads to excitation of both the slow space charge wave and the fast space charge wave which grow and phase interfere in the drift tube. The interference leads to axial bunching of the electron as shown in Fig. 7, and when such a bunched beam streams through the gap in the output cavity it excites microwave fields there that may be much stronger than the fields in the input cavity.

In the regime of small signal linear operation, gain is optimum when the distance between the gaps in the two cavities is chosen to be

$$L = \frac{\pi}{2} \frac{v_z}{\omega_p F}$$

Then, the linear gain is

$$G = \frac{1}{\pi^2} \left(\frac{I_0}{V_0}\right)^2 \left(\frac{\omega L}{v_z}\right)^2 \frac{G_L}{G_i(G_o + G_L)^2} \tag{9}$$

where we have assumed that the gap width d is much less than the wavelength; G_i and G_o are the G_W conductances representing wall losses in the input cavity and output cavity, respectively; G_L is the conductance representing power coupled from the output cavity into the load. The electron beam voltage and current are given by V_0 and I_0, respectively.

While it is in general much more difficult to analyze nonlinear behavior, a nonlinear analysis of the two cavity klystron has been carried out in the limit of small space charge effects; that is

$$\omega_p F \ll v_z/L$$

In this limit the efficiency of converting electron kinetic energy to microwave energy in the output cavity has been shown to be given by

$$\eta_E = J_1(X) \tag{10}$$

where η_E is called the electronic efficiency, J_1 is the Bessel function of the first kind of order one, and the beam bunching parameter is given by

$$X = \frac{1}{\pi} \frac{E_i d}{V_0} \frac{\omega L}{v_z}$$

where E_i is the magnitude of the microwave electric field developed across the gap in the input cavity. The electronic

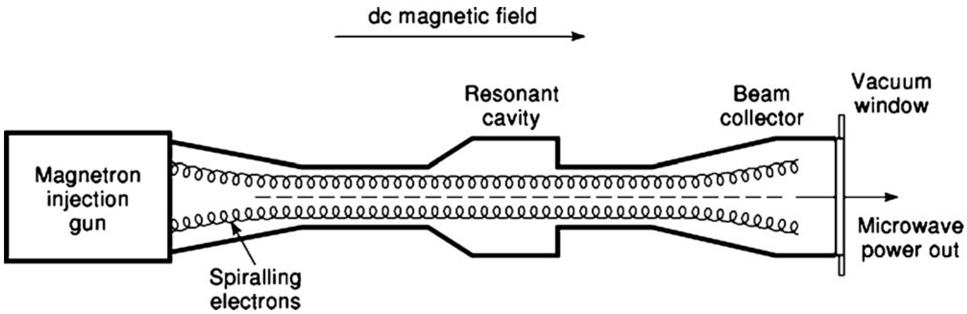

Figure 8. Configuration of a gyrotron oscillator. The strong dc magnetic field which is required is usually provided by a superconducting solenoid.

efficiency as given by Eq. (19) has a maximum value of $\eta_E = 58.2\%$ when the beam bunching parameter $X = 1.841$.

Even higher efficiency, and certainly much higher gain than is indicated by Eq. (17), is attainable in klystron amplifiers with more than two cavities. A five-cavity, 11.4 GHz klystron amplifier has been developed at the Stanford Linear Accelerator Center for driving the next generation of electron/positron accelerators for high-energy physics research. It has a gain of 50 dB with peak output power of 56 MW in 1.5 μs long pulses. The pulse repetition frequency is 180 pps, the electron beam in the klystron is focused with permanent magnets, and klystron output efficiency is 60%.

Gyrotrons

As capable as klystrons are, they do become limited in power rating as frequency rises to the millimeter wave regime ($\gtrsim$30 GHz). This is true because their cutoff drift tubes and their resonant cavities shrink in size with the wavelength. A relatively new vacuum electronics device which has operated successfully using a highly overmoded circuit is the gyrotron. The configuration of a gyrotron oscillator is sketched in Fig. 8.

The magnetron injection gun produces an annulus of electrons which travel along the circuit spiraling around the lines of the axial dc magnetic field. An important parameter of such an electron beam is the ratio of perpendicular velocity, $v_\perp$, to axial velocity, v_z. Usually $v_\perp/v_z$ is in the range of 1.0 to 2.0. The low value gives greater stability against spurious oscillation while the high value gives greater efficiency.

A cross section of the electron beam is shown schematically in Fig. 9 where the electrons are initially seen to have random phase in their electron orbits. Also shown in Fig. 9 is E_0, the azimuthal electric field of a TE_{0n} mode of the cylindrical gyrotron cavity. An electron such as # 1 will be decelerated by the electron beam and its mass will decrease (this is a relativistic effect) leading to an increase in its cyclotron frequency as

$$\omega_c = \frac{eB_0}{m} = \frac{eB_0}{m_0}\sqrt{1-(v_z^2+v_\perp^2)/c^2}$$

where m_0 is the electron rest mass. Similarly, an electron with phase like electron # 2 will be accelerated by E_0 and its cyclotron frequency will decrease.

This modulation of the cyclotron frequencies can lead to phase bunching in the cyclotron orbits as shown in Fig. 10.

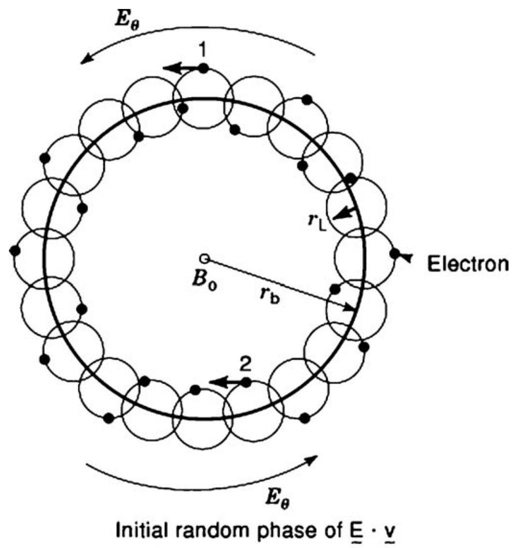

Figure 9. Cross section of the annulus of spiraling electrons in a gyrotron circuit showing the initial random phases.

If the electromagnetic wave is propagating axially at the same speed as the electrons and switching its polarity at the cyclotron frequency in the beam frame ($v_z = 0$), it can continuously decelerate the electrons and extract energy from their decrease in transverse velocity.

The process of phase bunching and energy extraction may be regarded as an interaction between a fast ($v_p > c$), transverse electric (*TE*), electromagnetic wave and the fast cyclotron wave of the electron beam. The dispersion curves of these two waves is plotted in Fig. 11. The point of grazing intersection, where the two curves just touch, is the usual point of operation. Simultaneous solution of the two dispersion equations plotted in Fig. 11 for the case of grazing intersection gives the following equation which may be used to design a gyrotron oscillator. The cutoff frequency of the operative TE mode is given by

$$\omega_n^2 = \omega_c^2\frac{c^2}{c^2-v_z^2} \tag{11}$$

Also, the axial wave number is given by

$$\beta = \frac{\omega_c v_z}{c^2-v_z^2} \tag{12}$$

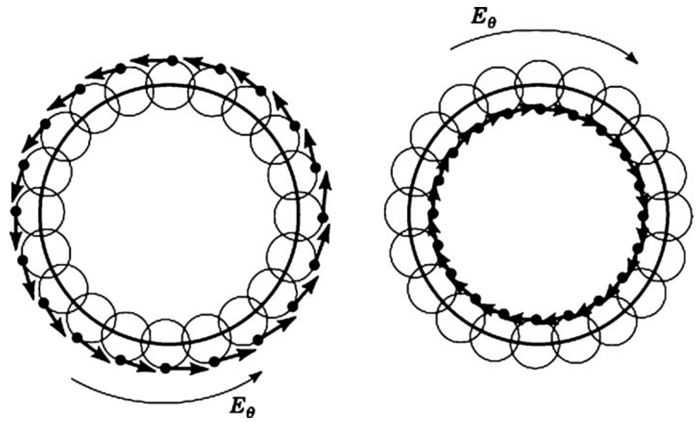

Figure 10. Electrons in a gyrotron which are phase-bunched in their cyclotron orbits. The relationship between the phase of the electrons and the phase of the azimuthal field of a TE_{0n} electromagnetic wave is shown on alternating half-cycles of the cyclotron frequency.

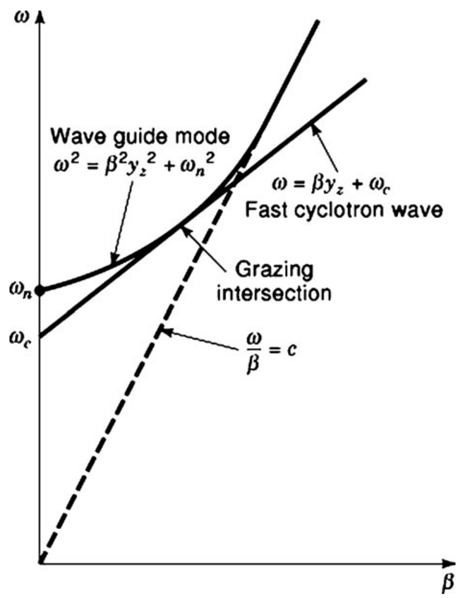

Figure 11. Dispersion curves for the TE electromagnetic wave with cutoff frequency, ω_n, and for the fast cyclotron wave.

For example, if the electron energy, the ratio $v_\perp/v_z$, and the dc magnetic field were specified, then for a given $TE_{m,n,p}$ mode, Eq. (22) could be used to determine the cavity radius and Eq. (23) could be used to determine the cavity length.

We also note that there is a threshold value that $v_\perp$ must exceed in order to turn on the gyrotron. This is given approximately by the inequality

$$v_\perp > \left(0.1\frac{\overline{\omega}_p^2 \omega_c^3 v_z c^2}{\beta \omega_n^4}\right)^{1/4}$$

where $\mathring{\omega}_p$ is the plasma frequency averaged over the cavity cross section.

Gyrotron oscillators are quite efficient in converting the transverse kinetic energy of the spiraling electrons into microwave energy; however, the axial electron energy is not utilized. Overall, the output efficiency of a gyrotron oscillator is typically in the range of 30% to 40%. This is also subject to improvement by techniques for recovering energy from the spent electron beam.

Gyrotron oscillators developed for the plasma heating application have had peak output power of 1038 kW and average output power of 198 kW at a frequency of 140 GHz. There is also an active gyrotron amplifier research and development program; a 94 GHz gyroklystron has been produced with an average power of 2.5 kW and a bandwidth of 0.35%; the average power rating is several times larger than the most capable 94 GHz coupled cavity TWT amplifier. Finally, gyroklystrons are being evaluated as drivers for high-energy electron accelerators, especially if these are operated at microwave frequency much larger than at present (say, $\geq$20 GHz); a 20 GHz gyroklystron amplifier has been demonstrated with pulsed output power of 30 MW.

FUTURE DIRECTIONS

There is a continuing and vigorous program of research and development of microwave tubes to meet the needs of advanced applications. The microwave power module (*MPM*) combines three elements: (1) a low noise, high gain, solid state input amplifier; (2) a compact, high efficiency, vacuum traveling wave tube functioning as output power booster; and (3) an integrated electronic power supply. The MPM, as mentioned previously, achieves 100 W average power levels over an extended frequency range in a package that is more compact and lighter than an all solid-state system, and it is especially attractive for deployment on platforms where weight and prime power are at a premium. Current thrusts in MPM research aim at developing a three-octave bandwidth capability which will cover the frequency range of 2 to 18 GHz in a single module. Work is also under way on developing a high frequency MPM which will cover the range of 18 to 40 GHz; this push to millimeter wavelengths is of special interest for satellite communications. There has also been preliminary consideration of developing an MPM-like system with 100 W CW capability in the frequency range 84 to 104 GHz; this module would involve a serpentine folded waveguide circuit rather than a helix circuit in order to realize the 100 W average power rating at such a short wavelength ($\sim$3 mm).

For applications which require higher power than TWTs but which do not need such an extended bandwidth, gyrotron amplifiers are being developed. For 94 GHz radar, a four-cavity, TE_{01} mode gyroklystron is under construction that will have 40 dB gain, 0.8% bandwidth, peak power of 80 kW and average power of 10 kW. Gyrotron amplifier circuits with wider bandwidth capabilities (e.g., gyro-TWTs and gyro-twystrons) are being considered for future development. Also, the use of higher order modes is being considered to increase the amplifier average power.

Klystron amplifiers at 11.4 GHz for driving electron-positron colliders in high energy physics research are also under development. The aim is to extend the 56 MW output power already achieved to 75 MW. Improvements in efficiency are also sought since the 7000 klystrons which will be required to drive the 1 TeV NEXT collider which is being planned at the Stanford Linear Accelerator Center will represent consumption of large amounts of average power.

For electron-positron colliders at 3 to 10 TeV energy, a higher microwave frequency will likely be chosen. Gyroklystrons may then be the optimum choice of amplifier. Current experimental studies at 17.1 GHz are aimed at demonstrating an output peak power of 100 MW. Efficiency could be enhanced to the 50% level by using depressed collectors in this device. Design studies have indicated that similar performance might be achievable at 34 GHz with the use of a superconducting solenoid to provide the gyroklystron magnetic field. Typically, such amplifiers for driving colliders operate with a duty factor of 3×10^{-4} so that 100 MW peak power would correspond to about 30 kW average power.

Higher average power has already been achieved in gyrotron oscillator, one of which has operated at 900 kilowatts CW for 30 minutes at a frequency of 140 GHz. These types of oscillators, which are intended for plasma heating and current drive in controlled thermonuclear fusion research, are currently being developed with a goal of 1 megawatt average power at 170 GHz for plasma heating in the International thermonuclear Experimental Reactor (ITER). They have also found application in a non-lethal weapon system for control of hostile crowds; that system known as Area Denial Technology (ADT) operates at 94 GHz. Lower power (10 kilowatt average) gyrotron oscillators are being developed at millimeter wavelengths with an emphasis on minimizing system cost so that they may be widely adopted by industry for material processing applications.

Finally, we note that progress in materials research and in computer science are enabling rapid advances in microwave tube performance. Producing vacuum output windows which would allow for the passage of very high average power microwave and fabricating focusing magnets which are compact and lightweight are among the major technological challenges in high-power microwave electronics. Diamond windows are very promising for high-power devices. High temperature superconductors promise to make microwave tubes that require high magnetic fields (e.g., gyrotrons) practical for an increased number of applications.

Time dependent, multimode computer codes have been developed which have effectively been applied to modeling the operation of a variety of microwave generators and have led to improving their design. The creation of an integrated computational framework for microwave tubes for initial design to production has been initiated. Extensive software tools are incorporated including thermo-mechanical analysis codes and electromagnetic computational codes. This will allow for interactive study of the performance of the microwave tube being designed.

These advances will not only allow for higher power ratings of microwave tubes at higher frequencies but will also allow for production of microwave power systems that are less costly, lighter in weight, more compact, and more efficient. The enhanced capabilities of microwave tubes will be exploited to improve the performance of radar and communication systems, to enable new industrial processing techniques and to extend the reach of basic and applied research.

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Additional Reading

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