10. Chapter 10 The Radar Transmitter

10.1. ***INTRODUCTION***

Role of the Transmitter in Radar. If a radar systems designer could ask for anything he or she wanted in a radar transmitter, that wish might be something like the following:

Provide the necessary transmitted energy with the needed average and peak power, as well as the required stability and low noise for good doppler processing; operate with high efficiency; have wide bandwidth and be easily tunable; be readily modulated in amplitude, frequency, or phase as necessary; have high reliability and long life; require minimum maintenance; have no dangerous X-ray emissions; require no personnel to operate; be of an affordable price; and be of reasonable size and weight for the desired application.

Of course, not all of these desirable attributes can be achieved in any given radar transmitter application. Compromises need to be made depending on the application.

The radar equation for a surveillance radar (one that has to cover a fixed volume of space on a regular basis) indicates that the maximum range of such a radar is proportional to $(P_{av}A)^{1/4}$, where P_{av} is the average power of the transmitter and A is the area of the antenna aperture. [1] A fundamental measure of the radar range performance is therefore the *power-aperture product*. One can obtain a long range by having a large antenna, a large transmitter, or a combination of both. It is not usual, under most circumstances, for a radar to have a huge, costly antenna and a small, inexpensive transmitter, or vice versa. There has to be a reasonable balance between these two major subsystems of a radar. (In a surveillance radar, straightforward calculus will show that under simple assumptions the minimum total cost of a radar occurs when the cost of the transmitter equals the cost of the antenna; but this is true only when there are no criteria, other than minimum cost, that have to be satisfied—and there are usually other criteria that need to be considered.)

As is well known in radar, the doppler effect is extensively used to detect moving targets in the presence of large clutter echoes. It is the basis for several of the chapters in this Handbook. Some transmitter types, however, are far better than others when the radar has to employ the doppler-shifted signal to detect moving targets in the midst of heavy clutter echoes.

Examination of the basic radar equation for detection of targets at long range indicates that the average power is far more important than the peak power as a measure of the radar's capability. A vacuum tube[*] with a given average power can usually be designed to handle the high voltages associated with a large peak power without breakdown. A solid-state transmitter cannot. In the past, average powers of radar transmitters have been from a small fraction of a watt to the order of a megawatt.

Types of Radar Transmitters. The very first "radars," such as those used by Heinrich Hertz (the first radar scientist) in the late 1880s and the shipboard radar invented by Christian Hulsmeyer (the first radar engineer) in the early 1900s used the *spark gap* as the transmitter. It was a very poor transmitter, but that is not unusual in the early days of a new and different development. The DeForest *grid-controlled vacuum tube* (triode) was invented shortly thereafter, and by the early 1930s, it had been well developed to where it was successfully and extensively used in those countries that built the first VHF and UHF radars used for air defense early in World War II. Some UHF radars effectively used the grid-controlled vacuum tube well into the early part of the current century. It has been a very competitive power source for UHF radar applications. The drawback of the grid-controlled vacuum tube is that transit-time effects limit its application at microwave frequencies, but variants of grid-controlled vacuum tubes have been successfully used up to about 1000 MHz.

The barrier of transit time effects was overcome with the invention of the microwave cavity *magnetron* early in World War II in 1940 by the United Kingdom (UK). The introduction of the magnetron allowed high-power radar to be successfully developed for use at the higher frequencies where smaller size antennas could be used. (It is of interest to note that the Japanese invented the magnetron before the UK did, and Soviet Union engineers published a paper describing their magnetron in the March 1944 issue of *Proceedings of the Institute of Radio Engineers*, now the *Proceedings of the IEEE*; but the wartime chaos in the military developments of both the Soviet Union and Japan was such that these inventions were not fully exploited by these two countries during WWII.) The invention of the magnetron was important because it allowed radar to be developed for use at microwave frequencies rather than be limited to VHF and UHF frequencies. It caught the German electronic countermeasures effort off guard because they had no idea that the United Kingdom and the United States could produce microwave radar. The success of the magnetron was a large factor in the effective application of military radar by the United States and the United Kingdom during World War II.

The magnetron is an example of what is called a *crossed-field tube* in that it employs a magnetic field and an electric field that are orthogonal to one another. The magnetron is an oscillator but the grid-controlled vacuum tube could be operated as either an oscillator or an amplifier. The other electronic tubes mentioned in this chapter are usually operated as amplifiers. Amplifiers at microwave frequencies have generally produced higher powers than oscillators; but, probably more important, they allow the use of stable, modulated waveforms needed for waveforms in radars that depend on the use of pulse compression and for the doppler effect to detect moving targets in clutter.

The microwave *klystron* amplifier was invented before the magnetron and was described in a paper in the May 1939 issue of the *Journal of Applied Physics*. For the most part, the klystron amplifier was ignored during WWII and didn't attract

the attention of radar engineers until the announcement in a paper in the November 1953 *Proceedings of the IEEE* by Stanford University engineers of the development of an S-band multicavity klystron capable of 20 MW peak power and 2.4 kW average power for use in a linear accelerator. This was a great accomplishment in its time. The high power, high efficiency, good stability, and wide bandwidth (at high power) of the microwave klystron amplifier have caused some radar design engineers to say that the klystron should be the first microwave power source to consider when designing a new high-performance radar. (There was, at one time, a single-cavity klystron oscillator called the *reflex klystron* that was of low power and mainly used as a receiver local oscillator, but it has generally been replaced by solid-state devices and is not discussed further in this chapter.)

The klystron is an example of *a linear-beam tube* because the direction of the dc electric field that accelerates the electron beam coincides with the axis of the magnetic field that focuses and confines the beam. It generates a highly concentrated high-energy linear beam of electrons that interacts with the microwave structure (two or more microwave cavities) to achieve amplification. Another example of the linear-beam tube is the *traveling wave tube* (TWT) amplifier. It generally can do almost what a klystron can do, but it is capable of very wide bandwidth at low powers, which the klystron is not. The TWT usually has slightly less gain than a klystron and less stability. It should be noted, however, that as the power of a TWT increases, its bandwidth decreases; and as the power of a klystron amplifier increases, its bandwidth increases. Thus, at the high powers needed for many radar applications, the bandwidths of these two types of linearbeam tubes are approximately comparable.

There also have been *hybrids* of the klystron and the TWT that have been of interest for radar applications, and which have interesting characteristics.

The *crossed-field amplifier*, like the magnetron, is a crossed-field tube that employs a magnetic field orthogonal to the electric field. It is capable of wide bandwidth and generally is of smaller size and does not require the very high voltages of the linearbeam tube. Although it has some advantages not found in other tubes, it has lower gain than linear-beam amplifiers (so multiple stages of amplification are required), and its noise level is higher than the linear-beam tube, which makes it less capable for detecting moving targets in clutter.

The *gyrotron*, which can be either an oscillator or an amplifier, is an RF[*] power source that can produce very high power at millimeter wavelengths. Conventional microwave power sources utilize resonant structures in which the phase velocity of the electromagnetic field propagating along the RF structure is slowed so as to be close to the electron beam velocity. Thus, they are known as *slow-wave tubes*. The characteristic size of the increments of the RF structure of slow-wave tubes is typically a fraction of a wavelength. They become smaller as the frequency is increased (wavelength is decreased). Smaller size means that a tube cannot dissipate heat as well as a larger tube, so that the power capability of microwave power tubes decreases approximately inversely as the square of the frequency. The gyrotron, on the other hand, does not have this type of frequency dependence since it uses what is called a *fast-wave* structure. This is usually a smooth waveguide or a large resonator. No attempt is made to reduce the propagation velocity of the electromagnetic wave within this structure. The electron beam is not close to the RF structure so it is not as limited in size as are the structures of

slow-wave tubes. The larger size of the fast-wave tube means that it can handle larger power at the higher frequencies. The gyrotron has mainly been of significance for high-power applications at millimeter-wave frequencies.

The *solid-state transistor amplifier* has been of interest for radar applications. Such interest in solid state has also been due, in part, to its completely replacing vacuum tubes in receiver and computer applications. The solid-state transmitter is discussed in Chapter 11, and a brief comparison of it with the vacuum tube transmitter is given at the end of this chapter. The chief advantages of a solid-state radar transmitter are that it can operate with wide bandwidths; it has the potential for long life; and it is favored by some buyers of radar. It cannot, however, employ high peak-power waveforms. The limitation on peak power in a solid-state transmitter results in compromises that have to be made in the design of the overall radar system.

Oscillator Versus Amplifier. The power amplifier is often preferred over the power oscillator as the transmitter power source in high power, high performance radar systems. In an amplifier, the signal to be transmitted is precisely generated at a low power level and is then amplified to achieve the required power to be radiated from the antenna. Amplifiers have the advantage of being able to provide stable waveforms, coded or frequency modulated pulse compression waveforms, frequency agility, as well as combining and arraying.

The magnetron is an oscillator that has less flexibility and is usually noisier than a linear-beam amplifier. Each time a pulse is transmitted, its phase is different from the phase of previous pulses. That is, its phase is random from pulse to pulse. To detect the doppler frequency shift for MTI processing, the phase cannot change in a random manner at the receiver from pulse to pulse. This limitation is overcome by taking a sample of the random phase of each transmitted pulse and using it to reset the phase of the local oscillator in the receiver to match the phase of the transmitted signal. This is sometimes called *coherent on receive*. Generally, the MTI improvement factor that can be obtained with a magnetron is not as good as can be obtained with a linear-beam amplifier.

In the past, there might have been debate as to whether to use an oscillator or an amplifier for a high-performance radar transmitter. There is usually no question that the amplifier is usually the preferred choice, except in situations where the low cost of a magnetron transmitter is more important than the lower MTI improvement factor it provides compared to a linear-beam transmitter. The magnetron oscillator, however, has been used in some short or medium range radars and in the widely popular civil marine radar (Chapter 22), which requires only a small power transmitter and has no need for MTI capability.

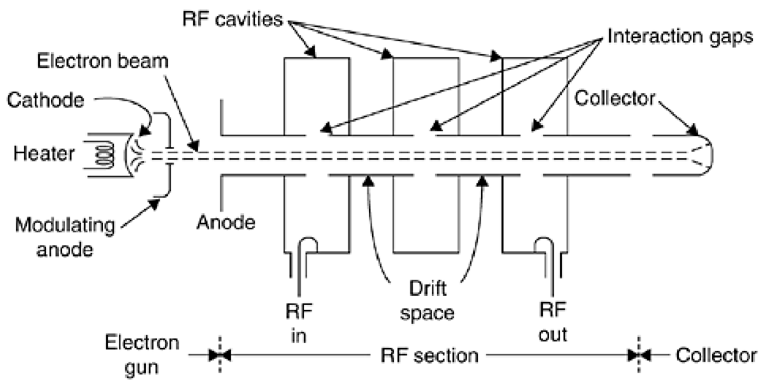
10.2. ***LINEAR-BEAM AMPLIFIERS***[2]

The klystron, TWT, and hybrids of the two have been important sources of RF power for many successful radar systems. The electrons emitted from the cathode are formed into a long cylindrical beam that receives the full potential energy of the electric field before the beam enters the microwave interaction region. The electron beam, generated by an "electron gun," essentially flows in a straight line in linear-beam tubes to interact with a microwave circuit to produce amplification of an input signal. The major difference among the several types of linear-beam tubes is the type of microwave circuit employed and the nature of the interaction that produces amplification. Transit-time effects, which limit the high frequency performance of grid-controlled tubes, are taken advantage of in linear-beam tubes to velocity modulate the uniform electron beam to create bunches of electrons from which RF energy can be extracted at the output of the tube. Linear-beam tubes as amplifiers can produce high power with good efficiency and high gain and with wide bandwidth. They have been capable of producing average powers of a megawatt, as well as average powers of many kilowatts in a size suitable for use in a military fighter/attack aircraft.

Klystron. The klystron amplifier has been an important RF power source for many radar applications. As mentioned, it is capable of high average and high peak power, high gain, good efficiency, stable operation, low interpulse noise, large bandwidth at high power; and being an amplifier, it can work well with the frequency and phase modulated waveforms needed for pulse compression. Klystrons have operated at frequencies from UHF to millimeter wavelengths and have found use in such diverse applications as airport surveillance radars where the average powers might be more than one kilowatt, in airborne military aircraft where the average power might be of the order of 10 kW or more, and in long range detection of intercontinental ballistic missiles where the average power per tube can be greater than 100 kW.

Figure 10.1 depicts the principal parts of a three-cavity klystron. At the left is the*heater* that heats the cathode and the *cathode* that emits a stream of electrons that are collimated into a narrow cylindrical beam of high electron density. The *electron gun* that generates the beam consists of the *cathode*, the *modulating anode* (also called the *beam control grid*), and the *anode*. The modulating anode provides the means to pulse the electron beam on and off. The *RF cavities* are the microwave equivalent of a resonant circuit. Electrons are not intentionally collected at the anode (as they are in grid-controlled tubes and crossed-field tubes), but in the *collector*, shown at the right-hand side of the illustration, after the electron beam has given up its RF energy at the output cavity. A low-power signal is applied to the input of the first cavity and appears at the *interaction gap*. Those electrons in the beam that arrive at the first interaction gap when the input signal voltage is at a maximum (the positive peak of the sine wave) are speeded up compared to those electrons that arrive at the gap when the input signal voltage is a minimum (the negative trough of the sine wave).

Figure 10.1 Representation of the principal parts of a three-cavity klystron amplifier



In the first *drift space*, those electrons speeded up during the peak of one cycle catch up to those that were slowed down during the minimum of the previous RF cycle. The result is that the electrons become "bunched" periodically. This bunching can be thought of as producing a modulation of the density of electrons. The bunches pass through the interaction space of the second cavity, which reinforces the *density modulation* to enhance the bunching. This process of impressing a time variation in velocity that results in bunching of the electrons of an initially uniform electron beam is called *velocity modulation*. Three or more RF cavities might be used. The interaction gap of the output cavity is placed at the point of maximum bunching so that the RF power can be extracted from the density modulated electron beam by a coupling loop in a lower power tube or by a waveguide (not shown) in a high power tube. In essence, the dc energy of the electron beam at the first cavity is converted to RF energy at the output cavity by the velocity modulation process. The larger the number of cavities the greater can be the gain of the klystron. The gain of a four-cavity klystron can be more than 60 dB, depending on the bandwidth. After the bunched electrons deliver their RF power to the output, the spent electrons are removed by the *collector* electrode.

An axial magnetic field is employed to counteract the mutual repulsion of the electrons that form the electron beam. The magnetic field confines the electrons to a relatively long, thin beam and prevents them from dispersing. It can be generated by a long solenoid that has iron shielding around its outside diameter, or by a lighter weight periodic-permanent-magnetic (PPM) system that consists of a series of magnetic lenses.

A multicavity klystron can have its bandwidth increased by stagger tuning the cavities, similar to the manner in which stagger tuning is done in an IF amplifier of a superheterodyne receiver to obtain broader bandwidth. It is more complicated, however, to do this in the klystron since the velocity modulation that appears at each interaction gap contributes a component to the exciting current at the succeeding gaps, something that does not occur in an IF amplifier. The early VA-87 four-cavity S-band klystron had a 20 MHz bandwidth and a gain of 61 dB when its four cavities were synchronously tuned, but when stagger-tuned, its bandwidth was 77 MHz (2.8%) and again of 44 dB. [3]

Theory shows that the bandwidth of a klystron can be significantly increased by increasing its current and thus its power. A 10 MW peak power klystron, for example, can have an 8% bandwidth as compared to a 200 kW tube, which might have a 2% bandwidth, and a 1 kW tube having only a 0.5% bandwidth. High-power multicavity klystrons can be designed with bandwidths as large as 10 to 12%. The klystron is sometimes thought of as having a narrow bandwidth and the traveling wave tube is thought of as having wide bandwidth; but at the high power levels needed for long range radars, their bandwidths are comparable. It is sometimes unfortunate that this fact is not always understood. [4]

The klystron, as an example of a linear-beam tube, is capable of high power because the generation of the electron beam, its interaction with the electromagnetic field, and the collection of the spent electrons are performed in separate parts of the tube where the generated heat can be dissipated effectively.

The klystron and other linear-beam tubes can have long life. Gilmour[5] reports that the mean time between failures (MTBF) of 11 different applications of klystrons in radar systems varied from 75,000 hours to 5,000 hours, with an average of 37,000 hours for all 11 applications. (There are 8,760 hours in a year.) The VA-842

high-power klystron tube used in the original Ballistic Missile Early Warning System had a demonstrated life in excess of 50,000 hours. Symons [6] reports that one of the BMEWS tubes that he designed was still operating after 240,000 hours when the radar in Greenland was replaced by the solid-state Pave Paws radar. The VA-812E was also a high-power UHF klystron that had a 20 MW peak power, 25 MHz 1 dB bandwidth, 40 dB gain, and an average power of 300 kW at a duty cycle of 0.015 and a 40 μs pulse width.

The VA-87E (originally developed by Varian Associates, Inc) is a 6-cavity S-band pulse klystron that operates from 2.7 to 2.9 GHz, produces a peak power of from 1 to 2 MW, an average power up to 3.5 kW, has a gain of about 50 dB, an efficiency between 45 and 50%, and a 1 dB bandwidth of 39 MHz. It has demonstrated a meantime-between-failures of 72,000 hours. It was used in the ASR-9 airport surveillance radar and in the WSR-88D Nexrad doppler weather radar (where its operating band is from 2.7 to 3.0 GHz), as well as in other radars.

Very high-power klystrons are employed in linear accelerators such as found at the Stanford Linear Accelerator Center.[7] Klystrons for this application, for example, might have 75 MW peak power with 50% efficiency using solenoid magnets; or 60–75 MW peak power with 60% efficiency using periodic permanent magnets.

Improvements to the klystron as a radar power source are discussed later in the subsection on hybrids, of which the clustered-cavity klystron is a good example of what can be provided in the way of high power and wide bandwidth.

Multiple-Beam Klystron (MBK). The klystron amplifier is an important tube for high-power, high-performance radar applications. However, it requires a large voltage when high power is needed. High voltage results in greater size and the need for shielding from the X-rays that are generated. In a klystron, the power available for conversion of the dc power of the electron beam to RF power of an electromagnetic wave is given by the product of the beam current and the beam voltage. [8] Although klystrons have been operated at very high voltages, it is usually preferred to operate it at a lower voltage, if possible, because lower voltages generally make the power supplies simpler, lighter, and more reliable. [9] A reduction of beam voltage in a conventional klystron means an increase of the beam current in order to maintain the same power. An increase in beam current, however, results in an increase in the current density where space charge effects may not be negligible, and the repulsive forces that occur among the electrons are increased and can cause the electron density bunches to lose coherence. The result is a decrease in efficiency. Higher current densities also require stronger magnets to keep the electron beam confined, leading to larger volume and weight. Thus, simply lowering the beam voltage and increasing the current density does not usually provide a net advantage.

The limitations of lower beam voltage, however, can be overcome by separating the single electron beam into a number of smaller beams, called *beamlets*, so that each of the beamlets has a low enough current density to avoid the undesirable repulsive effects of a high current-density beam. According to Nusinovich et al., [9] each beamlet is transported down its own individual drift channel (a metallic-walled tube), parallel to, but isolated from, the other beamlets. They are allowed to interact only over the small axial extent of the cavity gap. After passing by the cavity gap, the beamlets reenter their individual drift channels and propagate in isolation from one another. Such klystrons are called *multiple-beam klystrons*, or *MBK*. It has been said [10] that the number of beamlets in an MBK might be from 6 to 60.

The chief motivation for the multiple-beam klystron is the efficient generation of high RF power at a lower voltage than in a conventional klystron. Because of its lower voltage (two or three times lower), an MBK can be more compact, have a lower magnet weight (up to ten times less), be of lower weight and volume, generate less X-rays, have high electronic efficiency (up to 65 percent), and have the potential for a higher instantaneous bandwidth than does a conventional klystron. [9] The lower voltages at which they operate result in power supplies that can be simpler, lighter, cheaper, and more reliable. The MBK can have a high output-power-to-weight ratio that might be two to three times greater than that of an equivalent single-beam klystron. They can also have reduced noise and less phase sensitivity to deviations in voltage, which aids in the detection of low cross-section moving targets in clutter. Compared to a crossed-field amplifier, they have a larger dynamic range. Compared to a TWT, they are capable of higher peak and average powers, and they are less sensitive to vibrations.

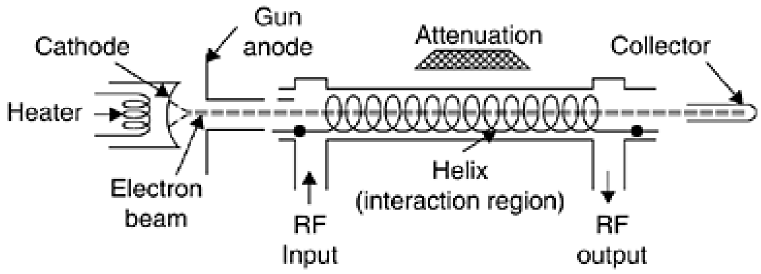
The Russian company known as Federal State Unitary Enterprise, RPC Istok [11] (usually shortened to Istok) has been productive in the development of MBKs for radar. At X band, they report an MBK with 24 beamlets producing 200 kW peak power, 17 kW average power, 6% bandwidth, an anode voltage of 26 kV, with a magnet weighing 16 kg. At S band, one of their tubes with 36 beams had a peak power of 600 kW, 12 kW average power, operated with 31 kV anode voltage, had a 6.5% bandwidth, and a weight without magnet of 25 kg.

An apparent extension of the multiple beam concept is to employ a sheet electron beam, which is as thin and as wide and has as much current as can be achieved consistent with other constraints. It has been considered for very high-power klystrons (150 MW peak power and periodic permanent magnetic, or PPM, focusing) designed for a very large linear accelerator. [12] It is claimed that the beam current density and the focusing magnetic field can be reduced, be made with fewer parts, might be more reliable, and can have lower acquisition and operating costs. One possible disadvantage is that sheet-beam klystrons might not be wideband.

The principle of the multiple-beam linear-beam tube has also been considered for the traveling wave tube,[9] but it is not obvious whether it has any significant advantages over the MBK.

Traveling Wave Tube (TWT). The TWT linear-beam tube is similar to the klystron in that the cathode, RF circuit, and collector are all separate from one another. There is, however, continuous interaction of the electron beam and the RF field over the entire length of the microwave propagating structure of the TWT as compared to the klystron where the interaction occurs only at the gaps of a relatively few resonant cavities. The TWT was originally conceived with a helix as the slow-wave RF structure, as in the illustration shown in Figure 10.2. The electron beam is similar to that of the klystron, and they both use the process of velocity modulation to cause the electron beam to be periodically bunched (density modulation). The electron beam passes through the RF interaction circuit. In the example shown in Figure 10.2, where a helix is shown as the slow-wave structure, the RF signal is slowed down by the helix so that its forward velocity is very nearly equal to that of the velocity of the electron beam. This near match of velocities is what causes the cumulative interaction that transfers dc energy from the electron beam to amplify the electromagnetic wave propagating on the helix. After delivering its energy to the RF field, the spent electrons are removed by the collector, usually a multistage depressed collector. An axial magnetic field keeps the electron beam from dispersing as it travels down the tube, just as in the klystron.

Figure 10.2 Representation of the principle parts of a traveling wave tube, showing a helix slow-wave circuit shown for simplicity



The helix TWT is capable of bandwidth in excess of an octave (2 to 1), which is much higher than other radar tubes. The TWT is often thought of as a very broadband tube, but the broad bandwidth of a helix TWT is not of great significance in radar applications since the helix TWT is limited in its peak power to a few kW. This means that the helix TWT is best used in CW or high duty cycle radar applications, if at all. Also, such broad band widths are seldom available for radar applications because of regulatory restrictions in the use of the electromagnetic spectrum. To achieve high power in a TWT, other types of slow-wave structures have to be employed, and these usually provide less bandwidth than the helix. Such structures are the coupled cavity [13] (of which the cloverleaf is an example), ring-bar, and the so-called ladder network. The bandwidth of a coupled-cavity TWT can be 10 to 15%. The ring-bar has broader bandwidth and higher efficiency than the coupled-cavity circuit, but it is not capable of as high a power as the coupled cavity. Thus, the bandwidth of a TWT decreases as its power increases. On the other hand, as mentioned previously, the bandwidth of a klystron increases with increasing power, so that the bandwidths of the TWT and the klystron are generally comparable for many high-power radar applications.

Both forward and backward waves may propagate along the microwave structure of a TWT, leading to a possibility of backward-wave oscillations. In Figure 10.2, attenuation is shown along the helix so as to prevent oscillation due to reflections at the output and the input of the structure. The attenuation may be distributed or lumped, but it is usually found in the middle third of the tube. Although oscillation can be prevented by distributing loss along the structure, it results in lower efficiency—something unattractive in high-power tubes. Instead, oscillations may be prevented by the use of discontinuities called severs, with one sever for every 15 to 30 dB of tube gain. At each sever, the power traveling in the reverse direction is dissipated in the sever loads without seriously affecting the power traveling in the forward direction. The sever loads may be placed external to the tube to reduce dissipation within the RF structure itself. The efficiency of a TWT is usually less than that of a klystron because of the loss due to the attenuation of the severs, as well as by the presence of relatively high RF power over an appreciable part of the entire structure. A technique for improving the efficiency of high-power TWTs is called *velocity tapering*. This technique consists of tapering the length of the last few sections of the slow-wave circuit to take into account the slowing down of the beam as the energy is extracted from it. Velocity tapering permits extracting more of the energy from the beam and significantly improves the power-bandwidth performance of the tube. [3] Nevertheless, high-power TWTs generally show an appreciable falloff of power output toward the band edges, so that the rated bandwidth depends very much on how much power falloff can be tolerated by the system.

If a TWT using a coupled-cavity circuit is cathode-pulsed (Section 10.7), there is an instant during the rise and fall of voltage when the beam velocity becomes synchronous with the cutoff frequency (the so-called π mode) of the microwave circuit, and the tube can generate oscillations. These oscillations at the leading and trailing edges of the RF output pulse have a characteristic appearance on a power-time presentation that has given them the name *rabbit ears*. Only in rare cases has it been possible to suppress these oscillations completely. However, since this particular oscillation depends on electron velocity, which in turn depends on beam voltage, the problem is avoided by the use of mod-anode or grid pulsing (Section 10.7). In this case, it is only necessary to be sure not to let the modulator begin pulsing the beam current during turn-on of the high-voltage power supply until the voltage is safely above the oscillation range, which is typically somewhere between 60 and 80% of full operating voltage.

A modification of the helix slow-wave structure is the ring-bar circuit, which can be used if the peak power is less than 100 to 200 kW. The Raytheon QKW-1671A is an example, with a peak power of 160 kW, 0.036 duty cycle, and 50 dB gain. It operates at L band from 1215 to 1400 MHz. The U.S. Air Force Cobra Dane, operating from 1175 to 1375 MHz, is a long range radar located in the Aleutian Islands that uses 96 ring-bar TWTs (QKW-1723), each with a peak power of 175 kW and average power of 10.5 kW.

The S band VA-125A TWT amplifier employs a cloverleaf coupled cavity microwave slow-wave structure. With the use of liquid cooling, it is capable of 3 MW peak power over a 300 MHz bandwidth. Its duty cycle is 0.002, with a gain of 33 dB, and a 2 μs pulse width. This TWT was originally designed to be used interchangeably with the popular VA-87 klystron, except that the VA-125 A TWT has a wider bandwidth than the VA-87 klystron. It also requires a greater power input signal because of its lower gain than the klystron. When high power is required, the klystron tends to be preferred over the TWT since it doesn't experience the stability problems of the TWT.

Gilmour [14] gives the mean time between failures (MTBF) for nine different types of coupled-cavity TWTs as varying from 17,800 hours to 2,200 hours, with an average of 7,000 hours for all nine classes of tubes. (He also says that TWTs for space application, which are of lower power than radar TWTs, have MTBFs of the order of one million hours.)

Depressed Collector. The efficiency of a TWT or a klystron can be improved by the use of a so-called*depressed collector*.[15,16] With a single collector, a significant fraction of the power input to the tube is dissipated as heat in the collector. If the voltage on the collector is reduced (depressed) below the body voltage, the velocity of the electrons striking the collector is reduced and so is the heat generated in the collector. Thus, the collector recovers some of the power in the spent electron beam. The use of multiple depressed collectors at intermediate voltages, rather than a single collector, allows catching each spent electron at a voltage near optimum. Up to ten collector sections have been used in some communication tubes, but three sections are more typical for high-power TWTs for radar systems. The several different voltages needed for the depressed collectors add complexity to the high-power voltage supply, but these voltages need not be as well regulated as the main-beam voltage. It is usually easier to design a depressed collector for a TWT than for a klystron since the spent electron beam of a TWT might have a 20% spread in velocity, but the klystron might have a velocity spread of almost 100%.[17] Because the efficiency in a conventional TWT is usually lower than that of a klystron, the increase in efficiency in the TWT provided by a depressed collector has a greater relative effect than with a klystron.

Variants of the Klystron and the TWT. It was mentioned that the bandwidth of a klystron increases as its power is increased. The bandwidth can also be increased by combining the best features of the klystron and the traveling wave tube to obtain better bandwidth, efficiency, and gain flatness than either the conventional klystron or the TWT. In these tubes, the basic structure is that of a klystron, but instead of a number of single cavities being used, the single cavity is replaced by a more complex multiple cavity. Three such variants are the *Twystron, extended interaction klystron*, and the *clustered cavity klystron*. Most high-performance radar klystrons tend to employ the more intricate cavity structure because of the better performance it provides.

Comparison of Various Linear-Beam Tube Structures. Figure 10.3 illustrates the basic structure of the RF circuits that characterize the various types of linear-beam tubes.

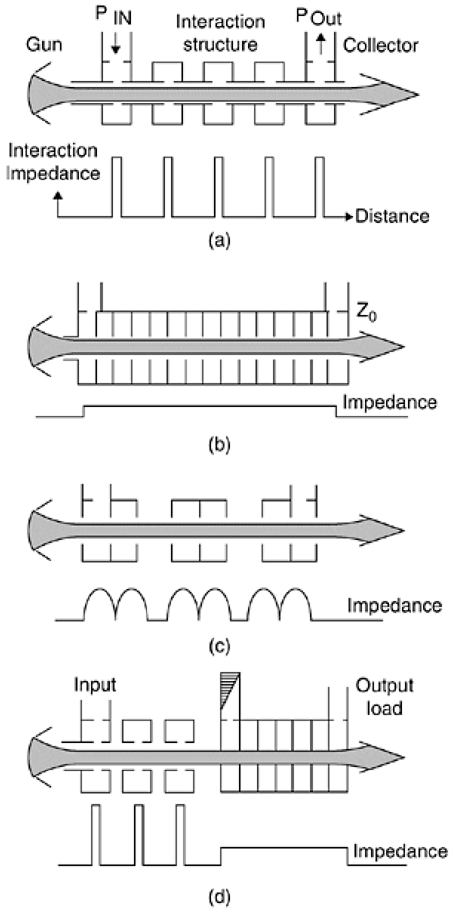
Twystron. The bandwidth of a conventional klystron is limited primarily by the bandwidth of the output resonant cavity. If a coupled cavity slow-wave circuit, as is used in the TWT, is substituted for the output resonant cavity of a klystron (Figure 10.3*d*), the bandwidth of the klystron can be increased significantly, and there is a slight increase in efficiency. This requires that the intermediate cavities and the input cavity of such a tube be stagger-tuned to accommodate the increased bandwidth offered by the output circuit. Because this type of tube is part klystron and part TWT, it was named *Twystron*. The VA-145 S-band Twystron has a bandwidth of 14% with a 35% efficiency, 41 dB gain at midband, peak power of 3.5 MW, and average power of 7 kW.[19]

Extended Interaction Klystron (EIK). In the EIK, the single-gap resonant cavities of the klystron are replaced by a resonated slow-wave TWT-like circuit that contains two or more interaction gaps (Figure 10.3*c*). Such cavities can be used for the prior cavities as well as the output cavity. This allows wider bandwidth and greater power than the conventional klystron amplifier. Staprans et al.[2,18] state that the high-power VA-812C EIK operated over a frequency range from 400 to 450 MHz (12% bandwidth), with a peak power of 8 MW and an average power of 30 kW, and an efficiency of 40%.

EIK devices have been of interest for millimeter-wave applications. According to the Communications & Power Industries (CPI) brochure, its VKB 2475 millimeter-wave EIK when operating at a center frequency of 94.5 GHz with a 1 GHz bandwidth, has a peak power of 1.2 kW, average power of 150 W, about 10% duty cycle, gain of 47 dB, pulse width of 20 μs, and is liquid cooled. It has much lower power than a gyroklystron (discussed later) at this frequency, but its 18 cm by 10 cm (diameter) size is considerably smaller and it costs considerably less than a gyroklystron.

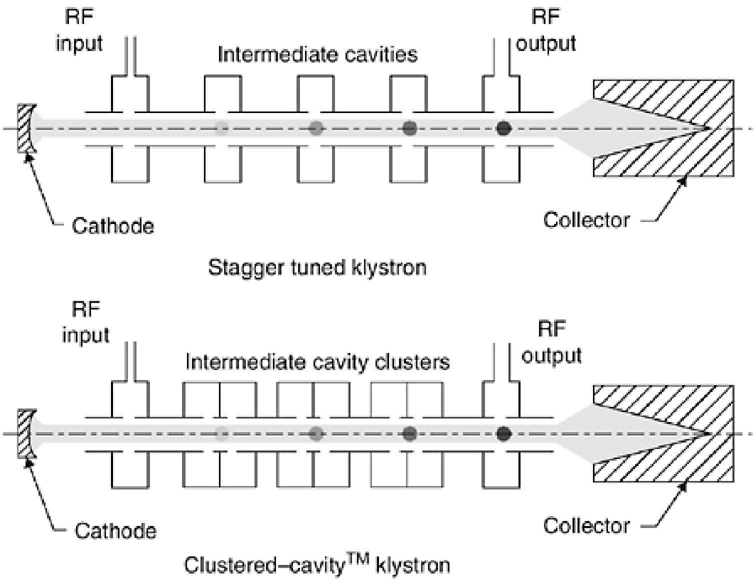
A similar EIK, also built by CPI, has been used in the NASA CloudSat spaceborne radar that provides the vertical profile of clouds for understanding cloud effects on both the weather and climate.[20] It operates at a center frequency of 94 GHz with a 250 MHz bandwidth, 1.5 kW peak power, 3.3 μs pulse duration, 4300 Hz prf, and an efficiency of 32%. It is conduction cooled. Each cavity is a short piece of resonant slow-wave structure based on ladder geometry. The tube weighs 6.2 kg and can operate over a temperature range from −15 to +60°C. It was predicted that this EIK would be capable of two years of continuous operation with a 92% confidence level. Two EIKs were employed in CloudSat (one prime, one redundant) so as to achieve a 99% confidence of meeting the two-year life requirement.

Figure 10.3 ***Basic structure of several types of linear beam tubes: (a) klystron, (b) coupled-cavity TWT, (c) extended interaction klystron, and (d) Twystron (after A. Staprans et al. 18 © IEEE 1973)***



Clustered-Cavity Klystrons. This is a good example of the technique of grouping cavities to improve the operation of a klystron. The individual intermediate cavities of a multicavity klystron are each replaced by a cluster of two or three artificially loaded low-Q cavities with Qs of one half to one third of the single cavity they replace. [21] Figure 10.4 compares schematically the basic difference between the conventional stagger-tuned klystron and the clustered-cavity klystron. It has been said for a given gain-bandwidth product, this form of structure can produce a tube of much shorter length so that there can be substantial savings in magnet weight and power. Symons, [22] the inventor of the clustered-cavity klystron, states that one of these wide bandwidth tubes can be used to replace the two narrower-band klystrons in the AWACS radar. When each of the two narrow-band tubes is replaced by a wideband clustered-cavity tube, redundant operation can be provided with higher reliability and without a large weight penalty because either of these clustered-cavity klystrons provide full operational capability similar to the redundancy commonly employed in FAA air-traffic control radars.

Figure 10.4 ***Comparison of the structures of a conventional stagger-tuned klystron (top) and clustered-cavity klystron (bottom) 16 (Courtesy of the IEEE)***



Microwave Power Module (MPM). [23, 24] A novel variant of the linear-beam tube is the*microwave power module*, which is an amplifier that employs a solid-state microwave integrated-circuit amplifier to drive a moderate-power helix traveling wave tube, along with an integrated circuit power conditioner, all in a lightweight package. It can provide high efficiency, wide instantaneous bandwidth, low noise, and average power levels from several tens to several hundreds of watts. It is said to be smaller and lighter than comparable TWT and solid-state power sources, and is capable of operating at high ambient temperatures. The gain of an MPM might be nominally 50 dB and is divided between the solid-state driver and the TWT power booster in the ratios from 20/30 to 30/20. The MPM seems best suited for the higher microwave frequencies, perhaps from 2 to 40 GHz.

A serious constraint of the MPM for radar applications is that the helix TWT limits its use to CW or high duty cycle transmissions (preferably greater than 50%). It also is of relatively modest power for many radar applications.

10.3. ***MAGNETRON***

Unlike linear-beam tubes that are normally operated as amplifiers, the magnetron is an oscillator. As example of a commonly used early magnetron was the 5J26, an L-band tube that was mechanically tunable from 1250 to 1350 MHz. It could operate with a peak power of 500 kW, a 1 us pulse width, and a pulse repetition frequency of 1000 Hz that provided an average power of 500 W. Its 40% efficiency was typical for magnetrons at that time. The compact size and efficient operation of the magnetron at microwave frequencies allowed radars in World War II to be small enough to fly in military aircraft and to be mobile for ground warfare. Magnetrons, however, seem to be limited to about a few kilowatts of average power, which can restrict their utility. They also have limitations in stability and, therefore, in the MTI improvement factor they can achieve, and they often have a shorter life than linear-beam tubes.

Because the magnetron is an oscillator rather than an amplifier, the starting phase of each pulse is random from pulse to pulse. This random change of phase can be accommodated in a MTI radar receiver by use of a coherent oscillator (coho) as the reference signal in the phase-detector stage of the receiver. On each pulse, the phase of the magnetron pulse sets the phase of the coho. In this manner, the received signal appears to be coherent pulse to pulse. This is sometimes called *coherent on receive*. The MTI improvement factor obtained with a magnetron and a coherent-on-receive operation usually is not as good as can be obtained with an MTI system that uses a power amplifier as the transmitter.

Automatic frequency control (AFC) is often employed to keep the receiver tuned to the frequency of the transmitter since the magnetron frequency can slowly drift with changes in ambient temperature and self-heating. The AFC can be applied to the magnetron itself to keep it operating on its assigned frequency, within the limits of the accuracy of the tuning mechanism.

A magnetron can be mechanically changed in frequency over a 5 to 10% frequency range and, in some cases, as much as 25%. Rapid mechanical tuning can be achieved with a slotted disk suspended above the anode cavities. When rotated, it alternately provides inductive and capacitive loading of the cavities to raise and lower the frequency. Such a rotary-tuned magnetron can provide very fast tuning rates. For example, at a rotation rate of 1800 rpm, a magnetron with 10 cavities can tune across a band 300 times per second.

Coaxial Magnetron. [25] A significant improvement in the power, efficiency, stability, and life of the original form of the magnetron occurred with the introduction of the coaxial magnetron. The key difference is the incorporation of a stabilizing cavity surrounding the conventional magnetron cavities, with the stabilizing cavity coupled to the magnetron cavities so as to provide better stabilization. The frequency of a coaxial magnetron can be changed by mechanically moving one of the end plates, called a *tuning piston*, of the stabilizing cavity. The tuning piston can be positioned mechanically from the outside of the vacuum by means of a vacuum bellows.

In the coaxial magnetron, the output of every other resonant cavity is coupled to the stabilizing cavity that surrounds the anode structure. The output power is then coupled from the stabilizing cavity.

π Mode of Operation. A magnetron, whether conventional or coaxial, can oscillate at a number of different, closely spaced frequencies due to various possible configurations of the RF field that can exist between the cathode and the resonant cavities.

These different RF field configurations, along with coupling among the cavity resonators of the magnetron, result in different modes of oscillation. The magnetron can shift, almost unpredictably, from one mode to another (which means the frequency shifts unpredictably) as the voltage changes or as the input impedance that the magnetron experiences changes. The shift from one mode to another, often called *moding*, is especially bad since it can occur when the radar antenna scans and views different environments. It is important to avoid moding.

The preferred magnetron mode of operation is the so-called *π mode* that occurs when the RF field configuration is such that the RF phase alternates 180° (π radians) between adjacent cavities. The advantage of the π mode is that its frequency can be more readily separated from the frequencies of the other possible modes. (An N-cavity magnetron can have $N/2$ possible modes. The π mode oscillates at a single frequency, but the other modes can oscillate at two different frequencies so that the magnetron can oscillate at $N-1$ different frequencies.)

Coaxial Magnetron Life. The power that can be produced by a magnetron depends on its size. A larger size means more resonators, which makes it more difficult to separate the various modes of oscillation in a conventional magnetron. The coaxial magnetron, however, with stabilization controlled by the outer cavity, permits stable operation with a larger number of cavities, and thus with greater power. The anode and cathode structures of a coaxial magnetron can also be bigger, which further allows operation at higher power. The larger structures permit more conservative design, with the result that it has longer life and better reliability than conventional magnetrons, as well as more stable operation. The operating life of a coaxial magnetron has been said [26] to be between 5,000 and 10,000 hours, which is a five- to twentyfold increase compared to conventional high-power magnetrons.

Limitations of Magnetrons. When the magnetron was first introduced, it provided a capability not available with the grid-controlled tubes used for early radars. As time passed, the demands for improved radar performance outran the capabilities available from the magnetron. Fortunately, other tube types were invented that overcame the limitations of the magnetron.

Although the magnetron has had important applications in the past, it has also had serious limitations that constrain its usefulness for radar. Its major limitations are its poor stability which limits the ability to detect moving targets in clutter, its relatively modest average power, and its signal cannot be readily modulated for pulse compression. These and others are discussed next.

The use of the doppler frequency shift to detect moving targets in the midst of large clutter echoes requires that the transmitter produce a stable signal with little extraneous noise. Because of their poor stability and noisy transmissions, magnetrons are limited in the amount of MTI Improvement Factor they can achieve to about 30 or perhaps 40 dB. Many radar applications require greater MTI Improvement Factors. Some radars also require the use of pulse-compression waveforms to obtain the resolution of a short pulse with the energy of a long pulse. It is difficult to phase or frequency modulate the waveform of a magnetron, as is needed for pulse compression. Thus, power amplifiers are almost always used for pulse compression applications. Magnetrons are not stable enough to be suitable for very long pulses (e.g., 100 μs), and starting jitter limits their use at very short pulse widths (e.g., 0.1 μs), especially at high power and at the lower frequency bands. Its maximum average power is of the order of several kilowatts, which is less than that required for some military applications.

Since the magnetron is an oscillator with a random starting phase on each pulse, it cannot be used to eliminate second-time-around clutter echoes—as can an amplifier transmitter. Similarly, combining the power outputs of multiple magnetrons has not been attractive. Magnetrons can produce considerable electromagnetic interference across a bandwidth much wider than the signal bandwidth (coaxial magnetrons are somewhat better in this respect). Also, magnetrons do not have precise frequency control nor are they able to perform precise frequency jumping.

In spite of its many unfavorable characteristics, the magnetron is a tube that can be considered for less demanding radar tasks. For a long time, it was the transmitter of choice for use in the civil marine radar, one of the most widely used radars, as briefly discussed next.

Civil Marine Radar Magnetrons. [27] The magnetron has been well-suited for application in civil marine radars used on small pleasure boats or large commercial ships. Its success has been due in part to the radar needing only small transmitter power, and the radar does not require doppler processing to separate moving targets from large fixed clutter echoes. Thus, many of the problems that occur with magnetrons when used in other applications are not found is this application. Also important is that the civil marine radar business is very competitive because of the large worldwide need for such radars. This has resulted in the development of low-cost, highly reliable magnetrons for this important radar application.

These magnetrons generate peak powers from 3 to 75 kW and have relatively low average powers of a few watts to a few tens of watts. An example of a magnetron for a civil marine radar is the MG5241 manufactured by EEY of Chelmsford, England. It is an 18 cavity X-band magnetron that operates at a fixed frequency within the band from 9380 to 9440 MHz with a peak power of 12.5 kW and an efficiency of 43%. It operates with an anode voltage of 5.8 kV and an anode current of 5.0 amps. Typically, its pulse width might be 1.0 μs with a duty cycle of 0.001. The manufacturer claims an expected typical life of over 10,000 hours and guarantees a minimum life of 3,000 hours.

It might also be mentioned that the magnetron has had outstanding success as the power source for the microwave oven. Over the years, it has developed into a very low cost and highly reliable generator of microwave power that is well-suited for this application.

10.4. *CROSSED-FIELD AMPLIFIERS*[28]

The crossed-field amplifier, or CFA, like the magnetron, has a magnetic field that is orthogonal to the electric field, but it is an amplifier rather than an oscillator. [29] It is similar in appearance to a magnetron except that the RF circuit is interrupted to provide the input and output connections as needed for an amplifier. CFAs might have an efficiency from 40 to 60%, use a lower voltage than linear-beam tubes, are lighter in weight and smaller in size, and have been found from UHF to K band. However, they have relatively low gain and their stability and noise are not as good as found in linear-beam tubes, so their application for MTI radar has been limited. Because of the CFAs low gain, the crossed-field amplifier transmitter needs more than one stage of RF amplification, each with its own power supply, modulator, and controls. All these stages must be stable to achieve good MTI performance.

Because the CFA has relatively low gain, it is sometimes used only in one or two of the highest-power stages of an amplifier chain, where it may offer an advantage in efficiency, operating voltage, size and/or weight compared to other tubes. The output-stage CFA might be preceded by a medium-power TWT that provides most of the gain of the total amplifier chain. (When comparing the CFA with the linear-beam tube, the entire transmitter system needs to be compared and not just the tube itself.) The CFA has also been considered as a means to boost the power output of previously existing radar systems that employed magnetrons. There have been both backward-wave and forward wave CFAs. The backward-wave CFA is also known as the *Amplitron*.

It is possible to pulse some CFAs, which have cold cathodes, to employ what is called*DC operation*, where the transmitter is turned on and off to generate a pulse waveform without the need for a high-power modulator. In dc operation the high voltage is continuously present between anode and cathode, and the current is turned on by applying the RF drive and turned off by pulsing the control electrode. (The control electrode consists of a segment of the cathode structure in the drift region.) To prevent the tube from starting without RF drive, the cathode must be kept cool enough to prevent thermionic emission. The control electrode needs only a short, medium-power pulse, typically one-third of the anode voltage and one-third of the anode peak current. Since the control electrode is insulated and since some energy is dissipated on the control electrode, it can be difficult to cool. This can limit the maximum pulse repetition frequency that can be used. In spite of it requiring no modulator, dc operation has seldom been used because of its many limitations. [30]

Crossed-field amplifiers have been used in radars in the past, but they have significant disadvantages, as was described in the second edition of this *Radar Handbook*, that make it less likely they will be widely used in the future.

10.5. *GYROTROINIS*[31,32,33]

It has been noted previously that the power handling capability of the microwave power tubes discussed thus far in this chapter decreases as the frequency is increased. This results because the resonant structures of the slow-wave microwave circuitry of these tubes become smaller with increasing frequency. The smaller the device the more difficult it is to dissipate the heat that is generated. Thus, the power output decreases approximately inversely as the square of the radar frequency.

The gyrotron RF power generator, however, does not have this limitation because it does not employ slow-wave resonant microwave structures. These devices employ a fast-wave structure, such as a smooth circular tube,[*] one where the phase velocity of the electromagnetic wave is greater than the velocity of light. (With a slow-wave device, the phase velocity is less than the velocity of light.) The diameter of the gyrotron circuit can be many wavelengths, and the electron beam need not be placed close to delicate RF structures. Because a fast-wave structure rather than a slow-wave structure is used, they do not have the size limitations of other microwave power sources as the frequency is increased. Thus, they can generate greater power at the higher frequencies than can other RF power sources, something especially attractive at millimeter wavelengths.

The magnetic field in a gyrotron serves a different function from the magnetic field in a slow-wave device. In the slow-wave device, the magnetic field keeps the electronic beam collimated. In the fast-wave device, however, the magnetic field determines the frequency; but the frequency of a conventional slow-wave device is determined by the circuit dimensions. An electron in an applied axial magnetic field B_o will rotate at what is called the *electron cyclotron frequency*, which is given by $\omega_c = eB_o/m\gamma$, where e = electron charge, m = electron rest mass, and γ is the relativistic factor, which is $[1+(e/mc^2)V_o]$, where c = velocity of light and V_o = beam voltage. The beam voltage and the corresponding electron velocity in a gyrotron are high enough to cause relativistic effects. The electrons follow helical paths around the magnetic field lines when in the presence of an electromagnetic wave with a transverse component of electric field. Electrons that lose energy to the electromagnetic wave become lighter and accumulate phase lead and then catch up with the electrons that gain energy and become heavier and accumulate phase lag. Thus, electrons become phase-bunched in their cyclotron orbits as a result of the relativistic mass change of the electrons. The gyrotron bunching operation also can be obtained at harmonics of the cyclotron frequency, but there can be problems with higher circuit losses and competition with modes operating at lower harmonics so that most high-power gyrotrons operate at the fundamental frequency or its second harmonic. [33]

Because the frequency of a gyrotron is determined by the magnetic field and not by the size of the fast-wave structure, the structure can be large, and it is then possible to generate quite high power at millimeter-wave frequencies. The large magnetic fields needed for millimeter-wave gyrotrons often have to be generated by superconducting magnets.

The gyrotron with a single cavity operates as an oscillator. It is sometimes called a *gyro-osdilator* to differentiate it from a *gyro-amplifier* that utilizes several resonant cavities or a traveling wave circuit to operate as an amplifier. The gyro-amplifier that employs several resonant cavities is called a *gyroklystron*, and when a traveling-wave circuit is used, it is called a *gyro-traveling-wave-tube*, or, more commonly, *gyro-TWT*. There is also a *gyrotwystron* with the resonant output cavity replaced by a TWT circuit so as to achieve greater bandwidth than can be obtained with a resonant cavity. Although gyro-oscillators have been capable of greater power than gyro-amplifiers, the gyro-amplifier has usually been preferred for radar applications for the same reason the amplifier has been preferred at microwave frequencies, especially when doppler processing is important.

An example of a high power gyroklystron for radar applications is the VGB-8194[34, 35] that was used in the experimental W-band radar known as *Warloc* at the U.S. Naval Research Laboratory. It had five cavities, operated over a 700 MHz bandwidth centered at 94.2 GHz with an average power of 10.2 kW, a peak power of 102 kW, 10% duty cycle, and 31% efficiency with a 55 kV, 6 A electron beam. It used a super-conducting magnet with a closed-cycle cooling system (so that no liquid cryogens were required). It provided a magnetic field of 36.6 kG. The five-cavity gyroklystron could achieve a bandwidth of 1050 MHz at an average power of 4 kW. The radar used a 6 ft diameter antenna that provided a beamwidth of 0.1°. This W-band Warloc was installed in a van and was used for various experiments. The Warloc radar was about three orders of magnitude more capable than most previous radars used for millimeter-wave radar. This experimental Warloc radar was employed to demonstrate at W band the ISAR imaging of moving targets, cloud structure, low-angle operation, and unusual atmospheric research including what have been called “air spikes.”

The above discussion was mainly about the gyrotron amplifier. The gyrotron has also been operated as an oscillator to produce very high power, but the oscillator version has not been as popular as the amplifier for radar applications. This might be due to the amplifier being better able to produce the desired radar waveforms.

10.6. *TRANSMITTER SPECTRUM CONTROL*

The increasing demand for electromagnetic spectrum for both civilian and military applications has accentuated the need to control the spectrum of radar transmitters to avoid interference with users of the electromagnetic spectrum operating at other frequencies. The aspects of concern here are those that affect RF tube selection and achievement of minimum spectrum occupancy by the transmitters discussed previously in this chapter.

Reduction of Spurious Outputs. RF tube spurious outputs may be grouped into three kinds: harmonics, adjacent-band, and in-band.

All RF tubes produce some harmonic output. In general, little can be done in tube design to reduce harmonic outputs, but it is feasible to filter out harmonics (30 to 60 dB reduction) with high-power filters.

Adjacent-band spurious output can also occur in some cathode-pulsed TWTs and CFAs. Adjacent-band spurious output is affected by tube and modulator selection, but it can be filtered by a high-power microwave filter if necessary.

All RF tubes produce some in-band background noise level. In a 1-MHz bandwidth, this noise might be 50 to 60 dB down in conventional CFAs, 70 to 80 dB down in the low-noise-high-gain CFA, and 90 dB down or better in linear-beam tubes. In-band spurious cannot normally be improved with filters because it occurs within the same frequency range as the desired signal spectrum. Attempts to use noise degeneration to reduce the inherent RF tube noise levels are subject to limitations. In-band spurious signals can also result from power supply and modulator instabilities.

Reduction of Spectrum Amplitude Exceeding (sin *x*)/*x*. The spectrum of a perfectly rectangular pulse has the familiar $(\sin x)/x$ form, where x is $\pi(f_o - f)\,\tau$, f_o is the radar carrier frequency, and τ is the pulse width. If $1/\tau$ is called the nominal bandwidth of the signal, the envelope of the spectrum peaks falls off at the rate of 6 dB per octave of bandwidth, and this reduction will continue until the envelope reaches the inherent noise output level of the transmitter. This rate of spectrum falloff is too slow to meet most system requirements. Nevertheless, without special care the actual spectrum envelope might be even worse than this, depending on tube characteristics, as a result of phase modulation during the finite rise and fall of practical modulator and RF drive pulse shapes. In these cases, either the leading and trailing edges must be appropriately tailored, or else (in linear-beam tubes) the RF drive may be withheld during the rise and fall time. Although this may slightly reduce apparent efficiency, it should be noted that energy outside the approximately $1/\tau$ generated during rise and fall with the RF drive present is not utilized by the receiver anyway.

Improvement by Means of Shaped Pulses. Since the energy in the spectrum beyond plus or minus $1/\tau$ from f_o is not used by the receiver, it is desirable for electromagnetic compatibility purposes to avoid transmitting energy beyond those limits. This objective may be approached by using a pulse shape different from the convenient and conventional rectangular pulse. [36] Highly shaped pulses have not been used often in radar systems because of the loss of efficiency that results. (These limitations, however, do not apply when using the grid-controlled tubes known as the *Constant Efficiency Amplifier* or the *Inductive-Output Tube*, as discussed later in Section 10.7.)

Another approach to spectrum improvement is to shape the rise and fall of a rectangular pulse. [37] This attenuates the spectrum of frequencies far from f_o, while the flat-topped portion of the pulse retains the high transmitter efficiency for most of the pulse duration. Since a rectangular pulse has the best transmitter efficiency but has high spectral energy at frequencies far from the center frequency, whereas a highly shaped pulse has less far-out spectral energy but poor transmitter efficiency, the fraction of the pulse length to be used for the shaped rise and fall is a crucial decision.

Although the improvement attainable in practice is limited by phase modulation in the transmitter during the rise and fall, [38, 39] significant improvements can be obtained. In a linear-beam-tube transmitter with properly shaped RF drive, for example, the spectrum width at 60 dB down can usually be narrowed by about an order of magnitude at a cost of about 1 dB in transmitter efficiency.

Amplifier chain radar systems, whether tube or solid state, often use some shaping of the edges of the transmitted RF pulse to reduce the RF spectrum width. This can be done by simply slowing the rise and fall times of the exciter signal to the transmitter, and this approach generally has been adequate to satisfy Military Standards and related system requirements.

Spectral Noise in Doppler Radars. The doppler frequency shift is widely used to detect moving target echo signals in the presence of large clutter echoes. However, if the radar transmitter generates noise or its pulse waveform has significant spectral energy at the doppler frequencies expected from moving targets, this unwanted noise or spectra will degrade the detection of desired targets. The transmitter noise is reflected back from the clutter and enters the receiver and is sometimes called "transmitted clutter." [40] Some types of microwave tubes are more of a problem than others. Extraneous noise in a microwave amplifier tube at the frequencies expected from doppler-shifted target echoes can be produced by ion oscillations. According to A. A. Acker, [40] "these are periodic instabilities that can occur in the electron beam at video frequencies, resulting in signals other than the carrier frequency, causing severe problems to doppler radar performance." Acker also states that ion oscillations require a finite time to develop so that if a tube is operated with less than a 10 μs pulse width, ion noise is usually not of concern.

Advances in digital technology have allowed a method to reduce intra-pulse transmitter noise and power supply instabilities that affect radar performance by the presence of strong clutter echoes. The technique, [41] known as *Transmitter Noise Compensation (TNC)*, captures and processes an accurate replica of each transmitted pulse. By means of pulse-to-pulse comparisons, the measured transmitter errors are used to derive a digital filter that compensates for the transmitter noise that arrives in the receiver digital signal processor. TNC compensates for intra-pulse transmitter noise as well as power supply instabilities. Although TNC works only in a single unambiguous range interval, it is said that it should be able to operate with some medium PRF radars if significant clutter is not likely to extend over more than one PRF interval.

An experimental implementation using data collected on an operational radar with a CFA transmitter showed that "the TNC technique can improve radar detection of targets in clutter by 15 dB or more."

10.7. *GRID-CONTROLLED TUBES*

The grid-controlled tube is a modern version of the classical triode or tetrode vacuum tube that dates back to the early years of the 20th century. These devices employ a cathode to generate electrons, one (for a triode) or two (for a tetrode) control grids, and an anode to collect the electrons. A small voltage applied to the control grid acts to control the number of electrons traveling from cathode to anode. The process by which the electron density of the electron stream is modulated by the signal on the control grid to produce amplification is called *density modulation*. In the latter half of the 20th century, grid-controlled tubes were successfully employed in such important radar applications as HF over-the-horizon radar, VHF and UHF aircraft surveillance radars, and satellite surveillance radars. Grid-controlled tubes are capable of high power, wide bandwidth, good efficiency, and inherent long life, but they are of low or moderate gain. Their chief limitation is that they are not capable of operating at higher frequencies, but they are capable up to frequencies approaching 1 GHz. Grid-controlled tubes have been operated at UHF and higher frequencies by using microwave techniques in their construction, as was done in the Coaxitron. They can also be made to operate with constant efficiency when shaping of the pulse amplitude is used to reduce interference caused by its far-out spectrum, something not as practical to do with other types of microwave tubes.

Coaxitron. The performance of conventional grid-control tubes at the higher frequencies is limited by the time it takes for the electrons to transit from the cathode to the anode of the tube. This transit time must be small compared to the period of the RF signal to be amplified. To minimize the undesired transit-time effects, the complete RF input and output circuit and the electrical interaction system can be placed within the vacuum envelope. Such a grid-controlled tube is called a *Coaxitron*. [42] In one embodiment of the Coaxitron, the electron-interaction structure consisted of a cylindrical array of 48 essentially independent grounded-grid unit triodes.

The so-called A15193F Coaxitron, described in Vingst et al.,[42] operated over a frequency range from 406 to 450 MHz with a peak power of 1.25 MW, a pulse width of 13 μs, a duty cycle of 0.0039, an average power of just under 5 kW, and a plate efficiency of 47%. The Coaxitron has been successfully employed for UHF radars, including airborne.

Constant Efficiency Amplifier (CEA). It has been said [43] that “a constant-efficiency amplifier has been a goal for transmitter engineers ever since Lee DeForest and Ambrose Fleming invented the first electronic amplifiers.” This goal seems to have been achieved by the CEA grid-controlled tube.

It is customary to think of the shape of a conventional radar pulse as being rectangular. It is seldom, however, perfectly rectangular with very short rise and fall times because such a waveform has a very large bandwidth, as one can observe from its Fourier transform. Even if a large bandwidth were available to support a rectangular pulse, a large bandwidth would likely cause interference to other radars and other electromagnetic systems. For this reason, government frequency allocation agencies usually require that the frequency spectrum from a radar not contain large energy at other frequencies. This is becoming more important as the occupancy of the electromagnetic spectrum is increasingly crowded with transmitters. The classical way to reduce the far-out spectrum from a radar transmitter is to shape, or taper, its waveform, such as by using a trapezoidal shape, a gaussian-like pulse shape, a truncated gaussian, perhaps a cosine on a pedestal, or other type of nonrectangular shape. The problem with using conventional transmitters such as discussed in this chapter is that when using a shaped waveform some loss in efficiency results. Thus, it is seldom that a radar designer would want to use a highly shaped pulse waveform in order to reduce the spectrum radiated outside of the radar’s normal operating signal bandwidth. The CEA, however, is an RF power source that does not have its efficiency decreased when a nonrectangular, or shaped, waveform is used. The CEA has been widely used for commercial TV transmitters that have highly modulated, nonconstant amplitude waveforms.

The CEA is based on a grid-controlled tube known as an *Inductive Output Tube*, or IOT. (The CEA is similar to something called a Klystrode [44] except that the CEA employs the IOT with a multistage depressed collector similar to that used in klystrons and TWTs. [37]) In the IOT, the wire grid of a grid-controlled tube is replaced with an aperture that does not intercept the electrons, and it has a coaxial magnetic field that confines the electron stream as in a klystron or a TWT. Although an RF cavity is used in an IOT, the beam is density modulated, or bunched, with a grid similar to how it is modulated in a triode or tetrode grid-controlled tube. This makes it smaller and lighter than a comparable klystron. The density modulated electrons thus form bunches, and RF energy is extracted by passing the beam through the resonant cavity. The CEA has been widely used for UHF-TV transmitters, a highly competitive industry concerned with cost. It has been said that in UHF-TV, the use of a CEA reduces the required prime power by one-half compared to a conventional tube transmitter [45] and by one-third of the prime power of a silicon-carbide solid-state transmitter. [46] The CEA achieves these efficiencies since there is no loss of efficiency when using shaped pulse waveforms, as there is with other microwave tubes. This is an important reason for its use for UHF-TV with its time-varying ing-amplitude waveform. It also should be an advantage for radar applications that require shaped waveforms at frequencies up to 1000 MHz, when it is required to reduce the far-out spectral energy.

A CEA, such as manufactured by L-3 Communications, can operate within the UHF-TV band from 470 to 806 MHz with an 8 MHz bandwidth (the spectral width of a TV channel), 130 kW peak power at 60% efficiency, and an average power of 6 kW or greater. The single input cavity can be made to tune over the entire band with low VSWR.

Thus, the constant efficiency amplifier is a grid-controlled tube, operating as class-AB, that consists of an inductive-output tube with a multistage depressed collector. It is a linear amplifier whose prime power can be proportional to the output power, providing constant efficiency over a wide range of output powers. The CEA seems to be the preferred tube for UHF-TV transmitters, rather than other types of grid-controlled tubes, solid-state, or klystrons. It would seem that the CEA ought to be of interest for radar applications at frequencies as high as 1000 MHz when highly shaped pulses need to be used.

Application of Grid-Controlled Tubes. There has been important application of the grid-controlled tube for radars in the past at HF, VHF, and UHR It is still of value for applications in these frequency regions and should be considered as a candidate when designing a radar to operate at the lower frequencies. The constant efficiency amplifier should be of interest because of its higher efficiency when shaped waveforms are needed for control of the radiated spectrum.

10.8. *MODULATORS*

This section briefly reviews the *modulator*, sometimes called the *pulser*, which is the device that turns the transmitter tube on and off to generate the desired pulse waveform. Those desiring more information might examine Chapter 9 in L. Sivan's book on transmitters, [47] the chapter by T. A. Weil in the second edition of *Radar Handbook*, [48] the Conference Records of the International Power Modulator Symposia, and the Conference Proceedings of the IEEE Pulse Power Conferences.

The type of tube determines, to some extent, the type of modulator. A modulator basically consists of an energy storage device, which may be a capacitance or a pulse forming network, and a switch for triggering the dc pulse. The switch in the past might have been a vacuum tube, thyratron, ignitron, silicon-controlled rectifier (SCR), reverse verse-switching rectifier, spark gap, or magnetic. However, the solid-state switch seems to be the switching mechanism that should be considered initially when designing a transmitter modulator. Modulators can be classed as either low power or high power, depending on how the tube is modulated.

If the tube has a grid, a small and relatively inexpensive type of modulator can be used, but grids usually are not feasible with high power tubes. A widely used switching element for low-power modulators is the MOSFET transistor. [47]

Low-power modulators can be used with tubes that employ a modulating anode, as does the linear-beam amplifier. The modulating anode in a linear-beam tube is part of the electron gun and is separated from the body of the tube. The voltage of the modulating anode is varied over a large range in order to vary the electron-beam current, but the power needed to drive the modulating anode is small because the current intercepted by the modulating anode is very small.

Very high-power tubes cannot use a modulating anode because the control electrode might not be able to handle the power. When this occurs, a high-power modulator, called a *cathode pulser* might have to be used to switch the tube on and off. Cathode pulsers must switch the full beam voltage and current simultaneously, which involves high instantaneous powers. They must control the full beam power of the RF tube, either directly or through a coupling circuit. The energy storage device might be made up of capacitors, inductors, or some combination of the two as in pulse-forming networks. The energy in the energy storage device is discharged by a very capable switch.

The *line-type modulator* uses a delay line or a pulse-forming network (PFN) as the energy storage element. A switch initiates the discharge of the energy stored in the PFN. The shape and duration of the pulse are determined by the passive elements of the PFN. The switch has no control over the pulse shape, other than to initiate it. The pulse ends when the PFN has discharged sufficiently. A disadvantage of this action is that the trailing edge of the pulse is usually not sharp since it depends on the discharge characteristics of the PFN. It has been widely used in the past for magnetron pulsing.

In an *active-switch modulator*, the switch has to be turned off as well as turned on. Originally, the switch was a vacuum tube and the modulator was called a hard-tube modulator to distinguish it from the gas-tube switch often used in a line-type modulator. Since other than vacuum tubes can be used as the switch in an active-switch modulator, the "hard-tube" designation (meaning a vacuum tube) might not always apply. Unlike the line-type modulator, the switch in the active-switch modulator controls both the beginning and end of the pulse. Since the energy storage device is a capacitor, the pulse can droop, something that can be prevented by extracting only a small fraction of the stored energy from the capacitor. This requires a large capacitance, which may be obtained with a collection of capacitors called a *capacitor bank*. The active-switch modulator permits greater flexibility and precision than the line-type modulator. It can provide excellent pulse shape, varying pulse durations, and pulse repetition frequencies, including mixed pulse lengths and bursts of pulses with close pulse spacings.

Microwave tubes and their high-voltage switches can sometimes produce an unwanted arc discharge that effectively places a short circuit across the power supply and/or modulator delivering power to the tube. Since 50 J of energy can usually cause damage to an RF tube (or the switching device) and since the capacitor bank for an active-switch modulator must often store far more than 50 J (to prevent excessive droop), some means must be provided to divert the stored energy when an arc discharge occurs. Such a device is the *crowbar*, so called because it is equivalent to placing a heavy conductor (like a crowbar) directly across the power supply to divert the energy and thus prevent the energy from discharging through the tube and causing serious damage. A crowbar is, therefore, needed for a high-power active-switch modulator because of the large amount of energy stored in its capacitor bank. On the other hand, crowbars are not usually needed with line-type modulators, which store less energy in their pulse-forming network.

Certain crossed-field amplifiers can be pulsed by means of a control electrode, located in the tube's drift region, without a separate full-power pulse modulator. [49] This is called *dc operation*. Even though dc operation avoids a high power modulator, it has seldom been used because it requires a much larger capacitor bank to limit droop, an arc in the tube requires a crowbar that interrupts operation for a few seconds instead of only for a single pulse, and the adjacent radars might inject enough RF power into the radar antenna and back to the transmitter to turn on a dc operated CFA at the wrong times. There has been at least one example in the past where a major radar system originally designed with CFAs based on dc operation had to have its dc operated CFAs replaced during the middle of its development with CFAs that used conventional pulse modulators.

At the beginning of the 21th century, the *solid-state modulator* was developed and began to be used for radar transmitters as either cathode pulsed or modulating anode pulsed modulators, as well as grid pulsed. Solid-state modulators offer improved transmitter performance by allowing a wide variation in parameters (pulse width, pulse repetition frequency, pulse agility, and pulse-to-pulse consistency). They also provide cost savings that result from the inherent reliability of these switch modules compared to conventional switch tubes, and the elimination of numerous auxiliary components needed for the operation of switch tubes. [50, 51] Lower operating costs and smaller cooling requirements occur because of their higher conversion efficiency. They are also said to have higher reliability with longer component life. The ability of the solid-state switch to open quickly (less than one microsecond) when a fault is detected eliminates the need for a crowbar. The energy-storage device does not discharge during an arc, so when the fault has cleared, the transmitter can resume operation in microseconds.

A solid-state cathode modulator can provide pulse widths varying from 50 ns to "dc" on a pulse-to-pulse basis and can support pulse repetition frequencies up to 400 kHz. [52] The high voltage solid-state switches are built from modules that might contain from 4 to 20 individual transistors connected in series to provide the required transmitter cathode voltage. Rise times can be as low as 30 ns.

10.9. *WHICH RF POWER SOURCE TO USE?*

There is no good, simple answer to this question, but in this section we shall attempt to discuss some of the various issues that might be involved.

This chapter has briefly described the various vacuum tubes that have been used or considered for radar applications, and the next chapter discusses the solid-state transmitter, which has also been widely used in radar. A question that naturally arises is which RF power source should be used for some particular radar application. Radar system design usually involves making choices among the various possibilities available. When trying to determine which RF power source to use, a choice can be made by doing a separate system design with each RF power source that seems promising. The decision as to which to use can be based on how well each system design performs the desired task according to some pre-established criteria. This, unfortunately, is seldom done. It is suspected that sometimes the decision as to which RF power source to use is determined by what the radar system designer thinks the buyer (or customer) of the radar desires. Sometimes the buyer will actually specify the type of transmitter to be delivered. Manufacturing a product based on what the buyer thinks he or she wants may be a good marketing strategy for many products, but in something like a radar, it might be better for a customer to clearly specify what performance is wanted and then leave the decision as to what RF power source should be used to the radar system designer. It is usually better if the radar design can be determined by the radar system designer and not by the manufacturer's marketing department. The goals of the radar designer and the marketing department are not always the same. It is appreciated, however, that sometimes the marketing manager's opinion has to prevail if the company is to remain in business.

A number of different RF power sources have been considered that, at one time or other, have been employed in radar. Not all might be popular or desired at some particular time but most should be considered, even if briefly, by the radar system designer when trying to determine a new radar system design or an upgrade of some existing system. Opinions about the utility of the various vacuum tube transmitters mentioned here will be briefly given next, with the suggestion to the reader to keep in mind that circumstances can change and these opinions can change as well. These opinions are not "written in stone," and are not likely to be universally agreed to by all those who work in radar. But that is the nature of any engineering endeavor.

Brief Opinions About the Utility of Various Radar Vacuum Tubes. The types of RF power sources are mentioned below in no particular order.

Grid-Controlled Tube. Although some might think these should have disappeared along with the old radio vacuum tube, there have been many HF, VHF, and UHF radars that successfully operated with grid-control tubes. Often with such radars, it would cost more to replace them with solid-state transmitters, and there might be little gained by doing so. The grid-controlled tube known as the constant efficiency amplifier (CEA)

and its predecessors (the IOT and the Klystrode) are the only RF power sources that can operate efficiently when amplitude shaped waveforms are desired for minimizing out-of-band interference to other radars. Thus, the CEA probably should be a candidate when considering any new UHF radar system, as well as radars at lower frequencies, especially if mutual interference is a potential problem.

Magnetron. It was mentioned that the magnetron was what made microwave radar possible in the 1940s. The magnetron is still a valid candidate for small, non-doppler radars such as civil marine radars, although such radars also have been manufactured with solid-state transmitters. It is not likely that magnetrons will be used in high performance radars, especially those that require average powers more than one or two kilowatts or where MTI improvement factors have to be greater than 30 to 40 dB. For example, during the procurement of the Nexrad doppler weather radar in the mid-1980s, the magnetron was considered, but it could not meet the clutter cancellation specifications, which is why Nexrad employs a klystron. In the past, some long-range Air Traffic Control Air Route Surveillance Radars used a magnetron, but the klystron seems to be the preferred choice for this application.

Crossed-Field Amplifier. Although these tubes were employed for some major radar applications because they have good efficiency, require relatively low voltage, and have wide bandwidth (about 10%), they are less likely to be used because they are noisy (which affects their doppler-processing performance), they are of relatively low gain (which requires the transmitter to have multiple stages), and because the klystron is usually a better overall choice.

Klystron. The original klystrons employed resonant cavities that restricted their bandwidth. The bandwidth of a klystron, however, increases as its power increases. Resonant cavities were later replaced by wider-band circuits, which were related to the type of circuits used in TWTs. Such klystrons are known as the Clustered Cavity Klystron, Extended Interaction Klystron, and the Twystron. When considering a transmitter for high-performance radar, these variants of the klystron are likely to be highly favored for many applications. The klystron has good stability and low noise so as to enable larger MTI improvement factors to be obtained when using the doppler shift to detect moving targets in clutter. At high power, high voltages have to be used and protection from X-rays generated by the high voltage must be employed. However, the MBK (multiple-beam klystron) version of the klystron can be used to achieve high power with lower voltage.

Traveling Wave Tube. As mentioned, the TWT and the klystron can have comparable bandwidths when the tube produces high power. The performance of a TWT is similar to that of a wideband klystron, except that it might not be as stable as the klystron and have slightly less gain. The microwave power module (MPM), which is a combination of helical TWT and solid-state device, has not had significant application in radar.

Gyrotrons. If very high power is needed at millimeter-wave frequencies, the gyrotron amplifier or oscillator is the only RF power source available. For low-power radar applications at millimeter waves, the EIK can be used.

Solid-State Amplifiers for Radar Transmitters. Solid-state transmitters and vacuum tube transmitters have significant differences, yet they are both employed in radar. Some of these differences are mentioned in Section 11.1 of Chapter 11 "Solid-State Transmitters." Briefly, proponents of solid state might say that they do not need a hot cathode as does a vacuum tube, do not require high voltages or magnets, do not produce X-ray radiations as some vacuum tubes do, have "graceful degradation," and that maintainability is its key asset. On the other hand, proponents of vacuum tubes might say that radars using solid-state transmitters have limited peak power and thus need to operate with a long pulse and a high duty cycle, which require the use of pulse compression. The long pulse can mask or eclipse target echoes at short range so that an additional short pulse transmission is needed to unmask the eclipsed echoes at short ranges. When Sensitivity Time Control (which has a varying receiver gain with range) is used with a long pulse and pulse compression, distortion can result in the compressed pulse. It has also been said that solid-state transmitters are often less efficient, they might be heavier, and their cost might be greater than an equivalent vacuum tube radar system. The above have all been said at one time or another, but there is not universal agreement about the importance of these characteristics for all radar applications.

The radar engineer should not simply compare the particular differences between a solid-state transmitter and a vacuum tube transmitter when determining what type of RF power source to use in any particular application. The choice between the two should be made by comparing a radar system designed to effectively use solid state and a radar system designed to effectively use vacuum tubes. Assuming the solid state and vacuum tube radars are designed to provide identical performance for the desired application, then the choice should be based on comparing cost, size, weight, reliability, maintainability, and any other system requirement that is important for decision making. Unfortunately, this is not always done. Buyers of radars should be encouraged not to insist that the radar designer use some particular technology because it is considered the fashionable thing to do at the time. They might not always be getting the best radar for the particular application.

There have been at least three ways to apply solid-state transmitters to high-performance radars: (1) as a replacement for a vacuum tube transmitter in an already existing radar; (2) as the transmitter for a new radar design; and (3) as an active aperture phased array radar.

An example of replacing an existing vacuum tube transmitter with a solid-state transmitter is the U.S. Navy's AN/SPS-40, a relatively modest capability UHF radar for air surveillance. [53] This radar was chosen for having its vacuum tube transmitter replaced with a solid-state transmitter using transistor amplifiers because it already used a long pulse waveform with a high duty cycle and pulse compression, which is what solid-state radars usually require. The solid-state transmitter was put into production and installed in existing radars. It did the job it was supposed to do, but it is not obvious that the solid-state transmitter had a net advantage over the tube transmitter. The solid-state transmitter was supposed to occupy the same floor space as the vacuum tube transmitter, but it occupied about the same floor space as the entire AN/SPS-40 radar, which used a vacuum tube. Also the solid-state transmitter cost more than the tube version. One highly significant advantage of the solid-state version of the SPS-40, however, was that it could include spare solid-state modules as part of the transmitter itself, so that time to repair was reduced.

An example of the second approach to achieving a solid-state radar transmitter is the ASR-12 airport surveillance radar. In the mid-1980s, the ASR-9 air surveillance radar at S band was developed by Northrop Grumman (then Westinghouse) for use at major airports to control local air traffic. [54] It was an excellent radar that used a well-tested klystron amplifier vacuum tube, and it was installed throughout the United States. (The same tube is used in the Nexrad doppler weather radar.) However, in the late 1990s solid-state technology had advanced sufficiently so that Northrop Grumman developed the ASR-12, also at S band, using a solid-state transmitter. Its overall radar performance was similar to the ASR-9, but it was not just a replacement of the transmitter but a new design to use solid-state transmitters effectively. It also took important advantage of advances in digital receivers and digital processing that occurred since the development of the ASR-9 to significantly improve what could be accomplished with this radar. [55] As mentioned, solid-state transmitters require the use of long pulses. The ASR-12 employed a 55 μs pulse duration at a peak power of 21 kW. This means that targets out to a range of about 5 nmi would be masked, or eclipsed, by the long pulse and might not be detected. To detect targets at ranges masked by the long pulse, a second (short) pulse 1 us in duration, and at a different frequency from the long pulse, was transmitted almost immediately after the long pulse. It detects targets within the range from 0.5 nmi or less to a range of about 5.5 nmi. The long pulse employs nonlinear FM pulse compression with a 55:1 pulse compression ratio to achieve a range resolution of less than 1/8 nmi as required for an air-traffic control radar. Typical time-sidelobes with the nonlinear FM waveform were 58 dB below the peak response. It might be noted that Cole et al. [55] state that in order "to ensure continued availability of the power transistors required to produce the power amplifier panels, Northrop Grumman has developed an in-house manufacturing capability for high-power S-band transistors."

The third approach to employing solid-state transmitters is the active aperture phased array radar. At each element of a phased array radar antenna is a solid-state module, known as a *T/R module*, that contains a transmitter, receiver, and duplexer. The vacuum tube is not usually competitive for this application. In Chapter 5, "Multifunctional Radar Systems for Fighter Aircraft," the active aperture radar is called an *Active Electronically Scanned Antenna* (AESA). The subsection entitled "Active Electronic Scanned Array (AESA)" (in Section 5.1) describes quite well the military airborne application of solid-state radar, and enumerates its advantages and why it is important. There it is stated that "one of the principal advantages of an AESA is the ability to manage both power and spatial coverage on a short-term basis (10s of ms)." It is also said that "bandwidth of several GHz on transmit" is required, and this is within the capability of solid-state transmitters. The reader is referred to Section 5.1, Chapter 11, and Section 13.10 for further information about this important application of solid-state.

Although any of the RF power sources mentioned here could be used in future radar systems, it seems likely that the linear-beam amplifier, particularly one of the variants of the klystron, might be the first RF power source to consider for a high performance microwave radar that employs a mechanically steered antenna or a conventional phased array radar that does not employ the active aperture. For active aperture phased array radars, it is likely that the solid-state transistor amplifier will be the choice.

10.9. ***REFERENCES***

1 M. I. Skolnik, Introduction to Radar Systems, New York: McGraw-Hill 2001, p. 88.

2 A. S. Gilmour, Jr., Microwave Tubes, Norwood, MA: Artech House, 1986.

3 W. J. Dodds, T. Moreno, and W. J. McBride, Jr., "Methods for increasing the bandwidth of high power microwave amplifiers," IRE WESCON Com. Rec. 1, pt. 3, 1957, pp. 101–110.

4 R. J. Barker et al., Modern Microwave and Millimeter-Wave Power Electronics, New York: IEEE Press and Willey Interscience, 2005, p. 108.

5 A. S. Gilmour, Jr., Principles of Traveling Wave Tubes, Boston, MA: Artech House, 1994, Sec. 18.4.

6 R. S. Symons, "Tubes: Still vital after all theses years," IEEE Spectrum, vol. 35, pp. 52–63, April 1998.

7 R. M. Phillips and D. W. Sprehn, “High-power klystrons for the next linear collider,”Proc. IEEE, vol. 87, pp. 738–751, May 1999.

8 R. H. Abrams, B. Levush, A. A. Mondelli, and R. K. Parker, “Vacuum electronics for the 21st century,” IEEE Microwave Magazine, pp. 61–72, September 2001.

9 G. S. Nusinovich, B. Levush, and D. Abe: “A review of the development of multiple-beam klystrons and TWTs,” Naval Research Laboratory, Washington, DC, MR/6840–03–8673, March 17, 2003.

10 R. H. Abrams, B. Levush, A. A. Mondelli, and R. K. Parker, “Vacuum electronics for the 21st century,” IEEE Microwave Magazine, pp. 61–72, September 2001.

11 A. N. Korolyov, E. A. Gelvich, Y. V. Zhary, A. D. Zakurdayev, and V. I. Poognin, “Multiple-beam klystron amplifiers: performance parameters and development trends,” IEEE Trans., vol. PS-32, pp. 1109–1118, June 2004.

12 R. J. Barker et al., Modern Microwave and Millimeter-Wave Power Electronics, New York: IEEE Press and Willey Interscience, 2005, Sec. 3.5.3.

13 W. H. Yocom, “High power traveling wave tubes: Their characteristics and some applications,”Microwave J., vol. 8, pp. 73–78, July 1965.

14 A. S. Gilmour, Jr., Principles of Traveling Wave Tubes, Boston, MA: Artech House, 1994, Sec. 18.4.

15 H. G. Kosmahl, “Modern multistage depressed collectors—A Review,”Proc. IEEE, vol. 70, pp. 1325–1334, November 1982.

16 A. S. Gilmour, Jr., Microwave Tubes, Norwood, MA: Artech House, 1986, Sec. 12.2.

17 M. J. Smith and G. Phillips, Power Klystrons Today, New York: John Wiley, 1995, Sec. 7.2.3.

18 A. E. Staprans, W. McCune, and J. A. Ruetz, “High-power linear-beam tubes,” Proc. IEEE, vol. 61, pp. 299–330, March 1973.

19 A. S. Gilmour, Jr., Microwave Tubes, Norwood, MA: Artech House, 1986, Sec. 11.3.

20 A. Roitman, D. Berry, and B. Steer, “State-of-the-art W-band extended interaction klystron for the CloudSat program,”IEEE Trans., vol. ED-52, pp. 895–898, May 2005.

21 R. S. Symons and J. R. M. Vaughan, “The linear theory of the clustered cavity klystron,” IEEE Trans., vol. PS-22, pp. 713–718, October 1994.

22 R. S. Symons, “Tubes: Still vital after all these years,” IEEE Spectrum, vol. 35, pp. 52–63, April 1998.

23 R. H. Abrams, Jr., “The microwave power module: A ‘supercomponent” for radar transmitters,”Record of the 1994 IEEE National Radar Conf., Atlanta, GA, pp. 1–6.

24 C. R. Smith, C. M. Armstrong, and J. Duthie, “The microwave power module: A versatile building block for high-power transmitters,” Proc. IEEE, vol. 87, pp. 717–737, May 1999.

25 M. I. Skolnik, Introduction to Radar Systems, 3rd Ed., New York: McGraw-Hill, 2001, Sec. 10.4.

26 N. Butler, “The microwave tube reliability problem,” Microwave J., vol. 16, pp. 41–42, March 1973.

27 P. D. L. Williams, Civil marine radar, London: Institution of Electrical Engineers, 1999, Sec. 10.3.

28 M. I. Skolnik, Introduction to Radar Systems, 3rd Ed., New York: McGraw-Hill Companies, 2001, Sec. 10.5.

29 A. S. Gilmour, Jr., Microwave Tubes, Norwood, MA: Artech House, 1986, Sec. 13.3.

30 L. L. Clampitt, “S-Band amplifier chain,” Raytheon Company, Waltham. MA, presented at NATO Conf. Microwave Techniques, Paris, March 5, 1962.

31 V. L. Granatstein and I. Alexoff, High Power Microwave Sources, Boston: Artech House, 1987.

32 A. S. Gilmour, Jr., Microwave Tubes, Norwood, MA: Artech House, 1986, Chap. 14.

33 K. L. Felch et al., “Characteristics and applications of fast-wave gyrodevices,” Proc. IEEE, vol. 87, pp. 752–781, May 1999.

34 M. Blank et al., “Development and demonstration of high-average power W-band gyro-amplifiers for radar applications,” IEEE Trans. vol. PS-30, pp. 865–875, June 2002.

35 G. J. Linde et al. (private communication), “Warloc: A high-power coherent 94 GHz radar.”

36 J. P. Murray, “Electromagnetic compatibility,” Chap. 29 in Radar Handbook, 1st Ed., 1970, pp. 29.18 to 29.23.

37 T. A. Weil, “Efficient spectrum control for pulsed radar transmitters,” Chap. 27 in Radar Technology, E. Brookner (ed.), Norwood, MA: Artech House, 1977.

38 J. P. Murray, “Electromagnetic capability,” Chap. 29 in Radar Handbook, 1st Ed., M. Skolnik (ed.), New York: McGraw-Hill, 1970.

39 E. Brookner and R.J. Bonneau, “Spectra of rounded trapezoidal pulses having an AM/PM modulation and its application to out-of-band radiation,” Microwave J., vol. 16, pp. 49–51, December 1983.

40 A. A. Acker, “Eliminating transmitted clutter in doppler radar systems,” Microwave J., vol. 18, No. 11, pp. 47–50, November 1975.

41 M. T. Ngo, V. Gregers-Hansen, and H. R. Ward, “Transmitter noise compensation—A signal processing technique for improving clutter suppression,” Proc. 2006 IEEE Conference on Radar, 24–27 April 2006, pp. 668–672.

42 T. E. Vingst, D. R. Carter, J. A. Eshleman, and J. M. Pawlikowski, “High-power gridded tubes—1972,” Proc. IEEE, vol. 61, pp. 357–381, March 1973.

43 R. S. Symons, “Tubes: Still vital after all these years,” IEEE Spectrum, vol. 35, pp. 52–63, April 1998.

44 V. L. Granatstein, R. K. Parker, and C. M. Armstrong, “Vacuum electronics at the dawn of the twenty-first century,”Proc. IEEE, vol. 87, pp. 702–718, May 1999.

45 R. S. Symons, “The constant efficiency amplifier,” NAB Broadcast Engr. Conf. Proc., 1977, pp. 523–530.

46 R. S. Symons et al., “The constant efficiency amplifier—A progress report,” presented at NAB Broadcast Engr. Conf. Proc., 1998.

47 L. Sivan, “The modulator,” Chap. 9 in Microwave Tube Transmitters, London: Chapman & Hall, 1994.

48 T. A. Weil, “Transmitters,” Chap. 4 in Radar Handbook, 2nd Ed., New York: McGraw-Hill, 1990, Sec. 4.8, “Pulse modulators.”

49 T. A. Weil, “Transmitters,” Chap. 4 in Radar Handbook, 2nd Ed., New York: McGraw-Hill 1990, pp. 4.13 to 4.14.

50 M. P. J. Gaudreau et al., “Solid state radar modulators,” presented at 24th International Power Modulator Symposium, June 2000. (Available from Diversified Technologies, Inc., www.divtecs.com.)

51 M. Gaudreau et al., “Solid-state upgrade for the COBRA JUDY S-band phased array radar,”presented at 2006 IEEE Radar Conference. (Available from DTI Internet site www.divtecs.com.)

52 M. Gaudreau et al., “High performance, solid-state high voltage radar modulators,”presented at 2005 Pulsed Power Conference. (Available from DTI Internet site www.divtecs.com.)

53 K. J. Lee, C. Corson, and G. Mols, “A 250 kW solid-state AN/SPS-40 radar transmitter,” Microwave J, vol. 26, pp. 93–105, July 1983.

54 J. W. Taylor, Jr. and G. Brunnis, “Design of a new airport surveillance radar (ASR-9),” Proc. IEEE, vol. 73, pp. 284–289, February 1985.

55 E. L. Cole et al., “ASR-12: A next generation solid state air traffic control radar,” Proc. for RADARCON 98, 1998 IEEE Radar Conference, 12–14 May 1998, pp. 9–14.

[*] In the United States, the device that generates the RF power is called a *tube*, but in the United Kingdom, it is called a *valve*. A book on microwave power sources [4] suggests that these devices be called *microwave vacuum electronic devices (MVED).* In this chapter, however, the name *tube* will be retained.

[*] In electrical engineering, RF stands for radio frequency, but in radar, it is often used to mean the radar frequency.

[*] *Tube* is used here as being a "hollow elongated cylinder."