CHAPTER 10

Radar Transmitters

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Chapter Outline

10.1 INTRODUCTION

The radar transmitter subsystem generates the radiofrequency (RF) energy required for the illumination of a remotely situated target of interest. Targets may include aircraft, ships, missiles and even weather phenomena such as rain, snow, and clouds. The radar transmitters described in this chapter includes three basic elements: (1) a radiofrequency oscillator or power amplifier, (PA); (2) a modulator (either analog or digital); and (3) a power supply that provides the high voltages (HVs) and currents typically required in modern radar transmitters. Depending on the specific application, the peak powers generated by the radar transmitter can range from milliwatts to gigawatts. The carrier frequency can range from 3 to 30 MHz (high-frequency [HF] over-the-horizon [OTH] radars) to frequencies as high as 94 GHz (millimeter wave [MMW] radars). However, the majority of today's civilian and military search-and-track radar systems operate in the frequency range from 300 MHz to 12 GHz and typically generate an average power ranging from tens to hundreds of kilowatts. Both thermionic tube-type transmitters and solid-state transmitters are used, depending on the application.

10.1.1 The Radar Transmitter as Part of the Overall Radar System

10.1.1.1 Basic Pulse Radar

Figure 10-1 is a block diagram of a typical pulsed radar [1]. The subunit identified as the RF amplifier in practice can be either a high-power oscillator, such as a *magnetron*, or a high-power amplifier, such as the *traveling-wave tube* (TWT) or multicavity *klystron*. The characteristics of these and related high-power microwave vacuum tubes are presented in Section 10.3.

The first radar transmitters date back to World War II and used pulsed magnetrons [2]. These systems radiated a simple pulse of microwave energy and measured the time delay to the target and back (range) and the angular position of the antenna at which the detection was made (angle). The magnetron oscillator, often attributed to World War II developments, was demonstrated as early as 1928 by Professor Hidetsugu Yagi of Japan when he used a magnetron to generate RF at frequencies as high as 2.5 GHz [3]. In fact, all presently used high-power thermionic radar tubes are based on fundamental physics known well over 70 years ago. With the development of new materials and advanced manufacturing techniques, the newer high-power radar tubes (discussed in Section 10.3) exhibit much more bandwidth, higher peak power, and greater reliability than their predecessors. The modulator block shown in Figure 10-1 essentially turns the high-power oscillator or amplifier on and off at some predetermined rate termed the pulse repetition frequency (PRF; see Section 10.4).

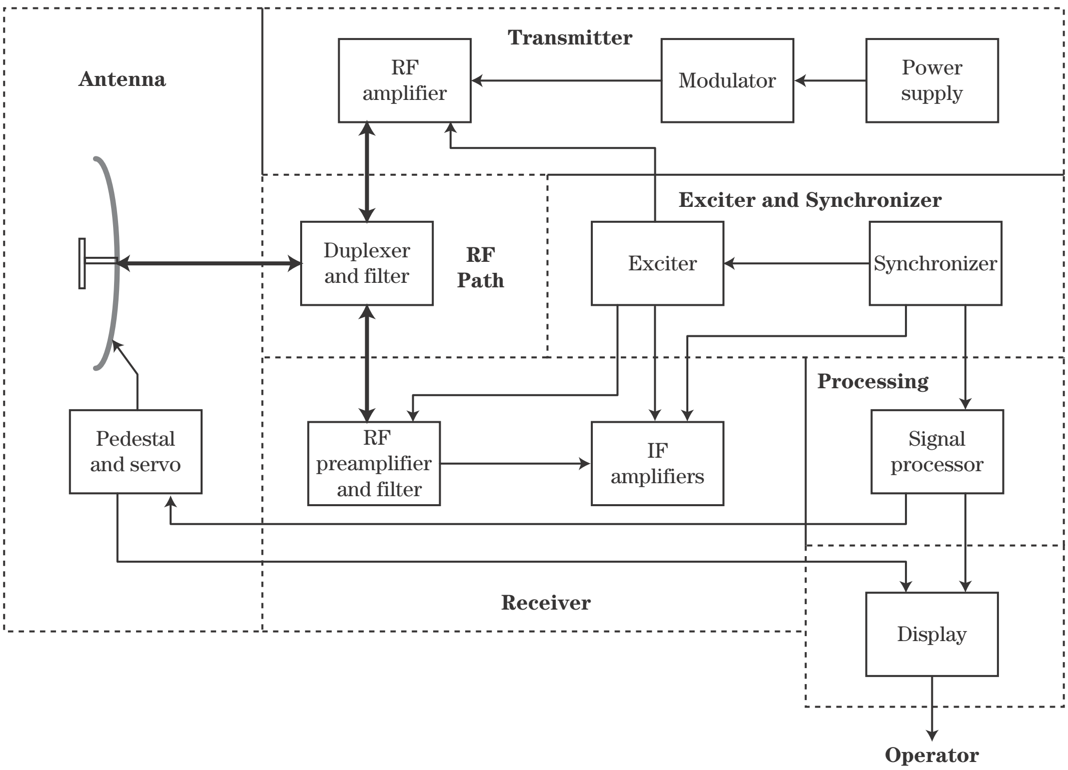


FIGURE 10-1 ■ Block diagram of typical pulsed radar. (From [1]. With permission.)

The last module of the pulsed radar transmitter in Figure 10-1 is the high-voltage power supply. The power supply typically provides thousands of volts at very high peak currents with negligible ripple while maintaining a high degree of stability and reliability. More details are described in Section 10.5.

10.1.1.2 Phased Array Radar

There are many instances where a pulsed radar with a single dish antenna is not the best way to collect the required data. Such is the case with the OTH skywave long-range missile tracking radar systems that operate in the 3 to 30 MHz HF band [4]. This application, as well as others, requires a different approach to generating the required radar signals and beam pattern. That approach is the modern phased array pulse radar.

Figure 10-2 depicts the block diagram of a typical phased array radar [1]. A brief examination makes it immediately apparent that many elements of the basic pulsed radar also exist within the phased array pulsed radar concept. The principle difference is that the phased array system, instead of using a dish antenna, incorporates an antenna aperture consisting of a large number of computer-controlled elemental antennas. Typically, these elemental antennas are spaced a wavelength or less apart to minimize unintended main lobes called *grating lobes* (see Section 9.7.3).

The pointing of individual antenna elements, or sometimes subarrays of a cluster of elements, is achieved by using computer control of digital RF phase shifters. Note by comparing Figures 10-1 and 10-2 that the transmitter subsystems could be the same in either case. The only difference is that in the case of the phased array, the high-power oscillator or amplifier output is uniformly divided and distributed to each of the computer phase-controlled antenna elements or subarrays by means of a matrix of RF power

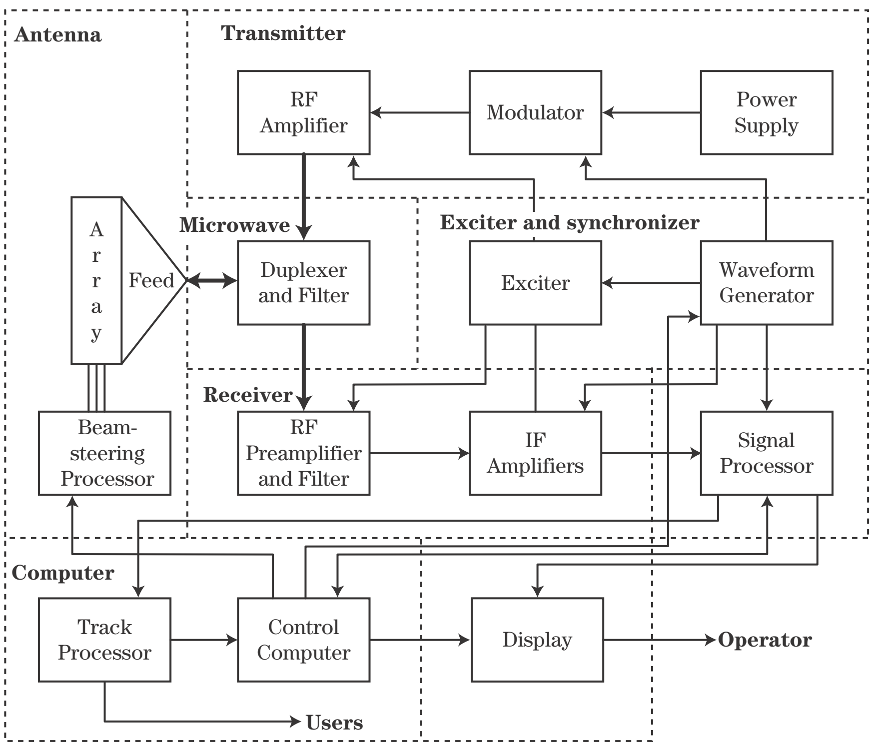


FIGURE 10-2 ■ Block diagram of a typical phased array radar. (From [1]. With permission.)

dividers. Pointing of the antenna in azimuth and elevation angle is achieved by means of the computer-directed phase shifts at each element or subarray.

The phased array concept just described is termed a *passive phased array* since the individual antenna elements do not incorporate any RF generation function. A major disadvantage of a passive phased array radar is that the RF losses in the power-dividing hardware can be large. One way of overcoming this disadvantage is to obtain the high levels of RF power needed by placing active lower-power solid-state or thermionic tube transmitting sources at each of the elements or subarrays. The total radiated power is the sum of the radiation from the aggregate of elements. This implementation is termed an *active phased array*.

Antenna pointing is again achieved using computer-controlled RF phase shifters. Often, solid-state power amplifiers are used at each element, in which case the individual radar modulators and associated direct current (DC) power supplies for each element or subarray can operate at fairly low voltages, an advantage when considering voltage breakdown issues. Also associated with each antenna element is the solid-state transmit/receive (T/R) module, which assures separation of the transmitted signal from the received radar echo. In addition to potential efficiency improvements over the passive phased array, active arrays offer the benefit of graceful degradation. When just a single high-power radar transmitter tube is used the radar becomes totally inoperative if the tube fails. In contrast, in the active phased array radar many individual low power RF transmitters can fail without totally shutting down radar operations. Solid-state power amplifiers are discussed in Section 10.3.3.1.

10.1.2 Radar Transmitter Parameters

The average radiated power, P_{av}, of a radar system in combination with the effective antenna aperture, A_e, establishes the maximum operating range, R_{max}, of a given radar [5]. That is, the maximum range is proportional to $(P_{av}A_e)^{1/4}$ (see Chapter 2). The product $P_{av}A_e$ is known as the *power-aperture product* and is a measure of performance for search radars. (A related measure is the *power-aperture-gain* product (PAG) which is often used as a measure of tracking or measurement performance.) Thus, maximum radar range can be increased by increasing either antenna size or radar transmitter net average power output. As discussed previously, this net average RF power can be derived from a single high-power tube or, as in the case of the active phased array, from the spatial summation of the output of many low to moderate power transmitters. Much of the discussion of transmitter parameters that follows is modeled after the discussions in Skolnik [5] and Curry [6].

A key specification of any radar transmitter is the RF power generated. For pulse-type radars this is usually specified by peak RF power, P_p, and average RF power, P_{av}, generated. The average power of a pulsed radar equals the peak power times the *duty cycle*, which is the fraction of the total time that the transmitter is on. That is,

$$P_{av} = P_p \tau PRF = P_p \cdot dc \text{ (watts)} \tag{10.1}$$

where

P_p = peak power (watts).
τ = maximum pulse duration (seconds).
PRF = pulse repetition frequency (hertz).
dc = duty cycle.

The duty cycles for klystron amplifiers, TWTs, and magnetrons are limited by tube element heat dissipation factors and typically range from 1% to 30%, although it is possible to obtain these devices in CW (100%) variants, depending upon the application.

The average transmitted power is limited by such factors as available prime power, heat removal from the transmitter, and computer scheduling limitations. The definition of transmitter efficiency, η_t, is given by

$$\eta_t = \frac{P_{av}}{P_{DC}} \tag{10.2}$$

where

P_{DC} = DC prime power (watts)

Typical transmitter efficiencies range from 15% to 35%.

Overall radar efficiency, η_r, is the ratio of RF power actually radiated by the antenna to DC prime power input. That is,

$$\eta_r = \frac{P_{av}}{P_{DC} L_m L_\Omega} \tag{10.3}$$

where

L_m = transmitter to antenna loss factor > 1.0
L_Ω = antenna ohmic loss factor > 1.0

Overall radar efficiencies may run from 5% to 25% or more, depending on the type of transmitter. Next, detailed transmitter configurations and the impact of the transmitter on the electromagnetic (EM) environment are discussed.

10.2 TRANSMITTER CONFIGURATIONS

There are many ways to characterize radar systems, and hence the transmitter used in them. Depending on the concerns of the designer or the end user, no one approach captures the wide variety of compromises and decisions that must be made in the final transmitter design. One way to characterize them is by end use. For example, a designer of a search radar in an air traffic control system will seek to optimize detection range, accuracy in Doppler determination, speed in covering the designated search volume, and rejection of clutter within that search volume. In this case a transmitter with a high average power and a medium to high PRF will be required. On the other hand, the designer of an instrumentation grade radar for a target measurement system on a measurement range or in an anechoic chamber would consider such issues as signal coherency for imaging purposes or high-range resolution for determining the location of scattering sources to be of great importance. In this case a solid-state transmitter may provide adequate power, and a low PRF may be all that is required.

Another way to characterize radar transmitters is by the power level required for operation. For a typical handheld police radar, the average power output is measured in tens of milliwatts. At the other end of the power spectrum, the U.S. Air Force's Space Surveillance System AN/FPS-85 radar uses a transmitter with a peak power greater than 30 MW. The two ends of this power spectrum call for very different approaches in generating the necessary power required for proper operation. A radar that emits an average power in the

milliwatt to watt range can be constructed using only solid-state construction techniques, and the upper limit of output power is approaching tens of kilowatts of average power. However, radars radiating an average power in the range of hundreds of kilowatts or more will require vacuum tube sources to reach those power levels for the foreseeable future.

Finally, when considering the way the output power of the radar is generated, transmitters can be subdivided into two broad categories. The power source either directly generates the radar signal, or else it amplifies a lower-level signal generated in the exciter subsystem (see Chapter 12). In the former case, an oscillator is used, while in the latter case a power amplifier is used.

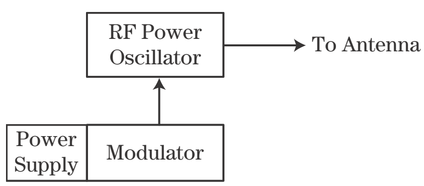
There are several basic configurations for a radar transmitter. There are many variations of these basic types, but the two most common types of transmitters are the free-running oscillator and the amplifier. Magnetrons and several types of solid-state oscillators are typically used in free-running oscillator transmitters, while TWTs, klystrons, and solid-state amplifiers are used in amplifier configurations. In a phased array transmitter, the amplifiers in the transmitter may be distributed across the face of the array and their outputs combined in space rather than combined at a single feed point as, for instance, with a dish antenna.

Before embarking on a discussion of the hardware of these different transmitter types, it is useful to review the concept of coherent versus noncoherent radar operation, which was introduced in Chapter 1 and is also discussed in Chapters 8 and 12. In a noncoherent system, the phase of the transmitted pulse relative to a reference oscillator is not known (random), so there is no significance to the phase of the received pulse relative to that same reference. Transmitters that use free-running oscillators tend to be noncoherent, with some exceptions discussed as follows.

In a coherent system, the transmit signal is derived from an ensemble of stable oscillators, so the phase of the transmitted signal is known. A key attribute of a coherent radar is the ability to maintain over time that known phase relationship between transmitted and received waveforms, which implies that the transmitter has the ability to amplify and replicate the waveform to be transmitted with minimal phase distortion, either across the pulse or from pulse to pulse. This allows for measurement of the effect of the target on the received signal phase and thus of Doppler frequency shift effects, indicative of target radial velocity relative to the radar. Coherent systems are more complicated from both hardware and signal processing perspectives, but they also generate more information about the target. These issues will be discussed in more detail later in this chapter.

Figure 10-3 presents a simplified diagram showing a simple transmitter using a free-running oscillator as the transmitter source and signal source for the radar, with the signal turned on and off at a given PRF by the modulator. A pulsed transmitter using a magnetron is shown, but the source could also be continuous wave (CW) or pulsed, solid state, or tube. A common example of a CW radar using an oscillator as the source is the infamous police speed-timing radar, which uses a solid-state source (usually a Gunn oscillator). Many maritime navigation radars use pulsed solid-state sources or, for longer-range systems,

FIGURE 10-3 ■ Free-running oscillator-based transmitter.



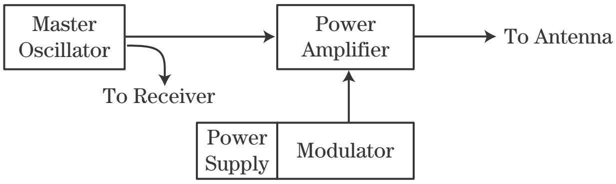


FIGURE 10-4 Master oscillator/power amplifier transmitter.

pulsed magnetrons. This type of radar is somewhat simplistic when compared with more advanced coherent radars but is also much cheaper to implement. For cost reasons, this type of architecture is prevalent in high-volume, lower-performance consumer applications as opposed to low-volume, high-performance military applications.

Transmitters based on a free-running oscillator are usually operated in a noncoherent fashion but can be operated in a quasi-coherent mode in some cases. Consider a pulsed magnetron that starts each pulse at a random phase. A CW oscillator can be phase-locked to a sample of the magnetron output, resulting in what is called a *coherent-on-receive* system. Alternatively, a signal can be injected into the output port of a free-running oscillator to *injection-lock* or *injection-prime* the device [7]. This helps the device to start at a phase that is coherent with the injected signal, which can then be related to the received signal phase, resulting again in a quasi-coherent system.

Figure 10-4 shows a simplified diagram of a coherent radar transmitter using a pulsed power amplifier. Again, the source can be a tube or a solid-state amplifier. In some cases, more than one stage of power amplification is needed, depending on the gain available from a single stage. For instance, *crossed-field amplifiers* (CFAs) exhibit rather low gain per device, on the order of 10 dB to 15 dB, whereas klystrons and TWTs exhibit gains in the 35 dB to 50 dB range. In addition, the output amplifier stage could consist of a parallel combination of amplifiers to boost the output level. This configuration is commonly called the *master oscillator-power amplifier* or MOPA configuration for obvious reasons. The signal generator can range from a single-frequency oscillator to a complex, tunable, wide-bandwidth digital waveform generator under control of the radar control software. Modern systems typically use a digital waveform generator to take advantage of advances in computer processing power and the ability to change waveforms (e.g., frequencies, bandwidths, pulse widths, modulation codes) to maximize either detection or tracking performance, especially in the presence of countermeasures.

The preceding diagrams focused on simple transmitters connected to a single-feed antenna such as a conventional dish antenna. Especially in the military arena, many newer radars under development are phased arrays. Transmitters for active phased array radars are, almost by definition, of the coherent master oscillator/power amplifier type. This is because the conventional phased array antenna steers its beam via the phase relationship between radiating elements across the array face; therefore, precision is needed in knowing the phase of the signal on both transmit and receive at each element relative to some reference point in the array.

There are several ways to characterize a phased array antenna system. One approach to characterization is based on whether the array architecture uses a *passive array* or an *active-aperture array*. An active-aperture array contains an active power amplifier as well as a phase shifter at each element; a passive array contains only a phase shifter at the element. The other approach is to characterize the array by the way the energy is distributed to the radiating elements. An understanding of the array feed is fundamental in transmitter design for phased array systems because there is an intimate relationship between the RF

power source and the RF distribution system. Achieving required power levels, efficiencies, bandwidths, operational reliabilities, and so forth can be accomplished only by properly matching the transmitter output to the feed system. There are many possible transmitter configurations for a phased array radar. The following paragraphs review possible feed approaches and then tie them to various approaches to generating the required RF energy for the proper operation of the phased array radar system.

In any type of phased array, the RF energy has to be distributed to the radiating elements that comprise the array. This energy is guided to the elements via a feed system or RF manifold. This feed manifold uses one of two major approaches: distributing the energy either via a guided, or constrained, approach or via a radiated or space-fed approach [8,9]. Constrained feeds use a transmission system such as a waveguide to transport the energy to the radiating element. Constrained feeds are usually classified as either series feeds (Figure 10-5a), where the radiating elements are in a series configuration with the feed system, or shunt feeds, where the radiating elements are fed in parallel via the feed system.

Series feed systems can be further subdivided into resonant feeds, which exhibit a higher efficiency at the cost of narrower bandwidths, or traveling wave feeds, which trade off a lower efficiency to achieve a broader bandwidth. A good example of a constrained series feed is the waveguide-based linear array. Linear arrays based on microstrip patches are also possible, but there are potential limitations in the array's operation due to the characteristics of microstrip structures.

Parallel feed systems can be subdivided into *corporate feeds* (Figure 10-5b) or *distributed feeds* (Figure 10-5c). Corporate feeds depend on successive power divisions as the RF energy moves through the feed network, until each radiating element is excited. Although the power division ratio at each junction is usually by a factor of two, it can range from two to five, depending on the number of elements to be fed and the type of power divider to be used. In distributed feed systems, each radiating element of a group of elements is connected to its own T/R module. Corporate feeds, as illustrated in Figure 10-5b, are known as passive arrays, as all the energy is provided by the radar transmitter. On the other hand, distributed feeds, as illustrated in Figure 10-5c, are also known as active arrays since active power sources, be they amplifiers or T/R modules, are located within the array structure and feed either individual elements or subarrays.

A *space-fed feed* system uses a feed antenna to excite the main phased array much like exciting a lens antenna system with one or more antennas. One form of the space-fed array system is the direct feed or in-line space-fed array (Figure 10-5d), where the radiation drives an array of phase shifters that feed the eventual radiating elements. The Patriot air defense radar uses this approach. The other form of the space fed array is the reflect array (Figure 10-5e), where the energy from the primary feed antenna illuminates a reflecting surface made up of array elements with a phase shifter behind them. While there are some advantages of this configuration over the in-line configuration (primarily the fact that the phase shifters, bias, and control circuitry are conveniently located behind the reflecting array elements), there is also the disadvantage of aperture blockage due to the primary feed antenna being located in front of the array.

Having reviewed the most common approaches to feeding phased array systems, the following observations can be made concerning the interaction between RF sources and the way energy is fed to the array elements. For instance, the corporate fed array of Figure 10-5b has several advantages, including a simple design approach and a reduced acquisition cost, since the RF power source is often a major cost driver for the radar transmitter and a single amplifier can be used for the source. On the other hand, using

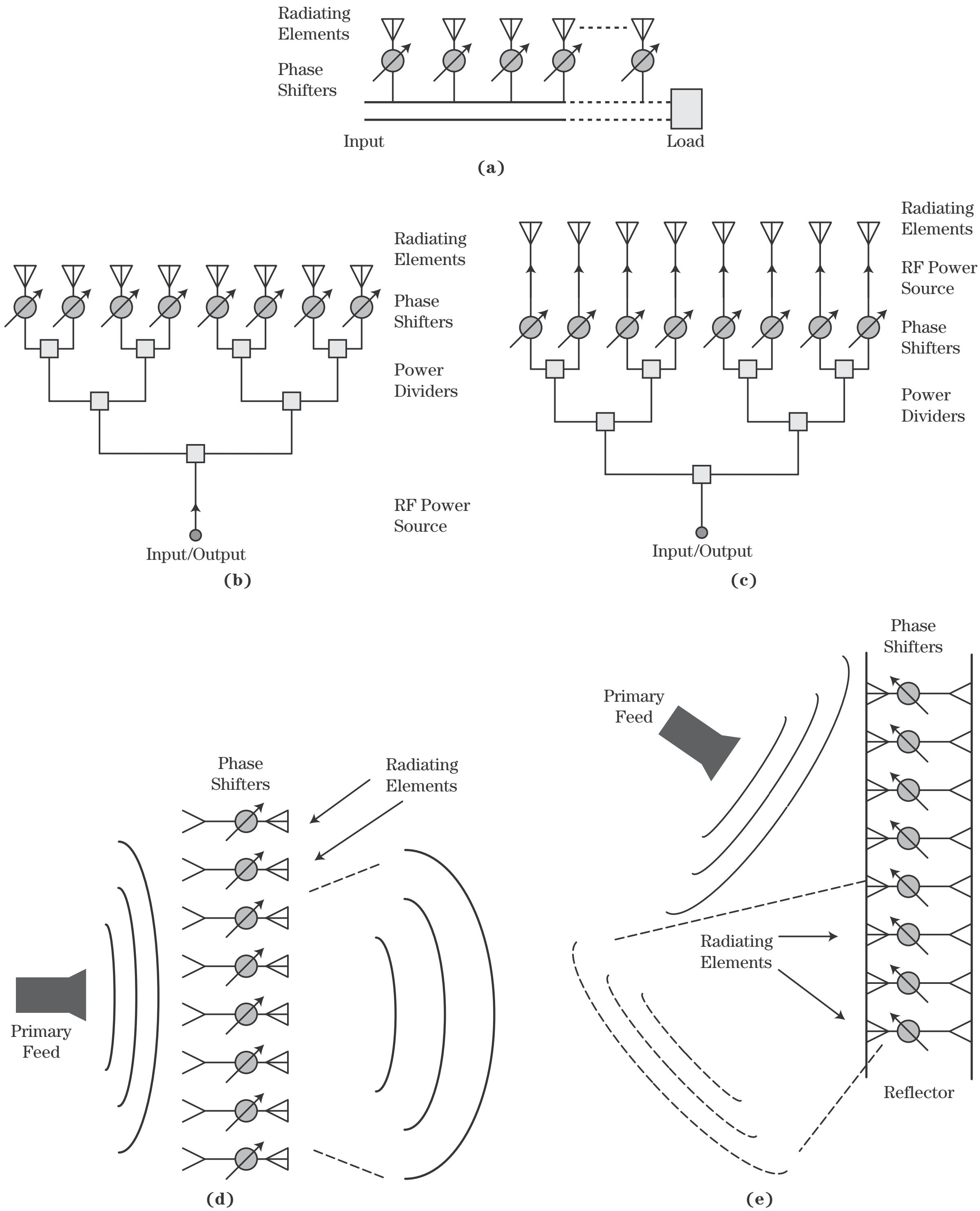


FIGURE 10-5 ■ Examples of phased array feed types. (a) Constrained series feed. (b) Constrained corporate feed. (c) Constrained distributed feed. (d) In-line space-fed array. (e) Reflect space-fed array.

a corporate feed with a single RF source means that all radar transmitter functionality will be lost if the source fails, reducing system reliability and eliminating the possibility of a graceful degradation of the radar system. One way to mitigate this situation is to replace some of the power dividers in Figure 10-5b with RF sources, resulting in a series of subarrays, each with its own power source. This is the approach used in the Cobra Dane early warning radar in Alaska, which uses 96 high-power TWTs, each feeding a single subarray [10]. This architecture allows for much greater overall reliability and graceful degradation, since the radar can still operate after losing one transmit subarray and the failed subarray can still be used in receive mode. There will be a small impact to sensitivity and perhaps an appreciable change in sidelobe levels, but the system can still operate in a degraded manner. Typical sources used for this configuration are medium- to high-power TWTs and some solid-state amplifiers.

Another approach is to feed the elements directly as indicated in Figure 10-5c, using an active array approach. Not only does this approach support a graceful degradation of the transmitter radar beam when individual elements fail, but it also has the added benefit that low-power phase shifters can be used prior to the power amplifier. This can greatly minimize ohmic losses on both transmit and receive, since on receive the phase shifter can be placed after the receiver's low-noise amplifier (LNA). Generally, solid-state amplifiers are used in the T/R modules at the element level. Solid-state active-aperture arrays will be covered in greater detail in the next section on power sources and amplifiers. Finally, it should also be pointed out that it is important to minimize the transmit losses. This can be accomplished by using a space-fed feed instead of a corporate feed, including its accompanying microwave plumbing and power dividers.

10.3 POWER SOURCES AND AMPLIFIERS

A key decision in the transmitter design process is the selection of the type of power source to be used. Even if the architecture is predetermined, some decisions still need to be made. For instance, if the radar is to be an active-aperture solid-state type, it is still necessary to perform detailed design of the *transmit/receive module* as well as select the type of solid-state technology to be used (e.g., silicon [Si], gallium arsenide [GaAs], gallium nitride [GaN]). If the transmitter is specified to generate high average power, than an amplifier based on vacuum tube technology will be required. To make appropriate design trade-offs an understanding of the relative advantages and disadvantages of the various power sources available is needed.

For the discussion that follows, power sources will be classified into two groups: oscillators and amplifiers. The choice of which approach to take in transmitter design will be determined by the properties of the sources that make up the specific group. Within each group, there are both solid-state and tube devices as well as high- and low-power possibilities. One of the key parameters that will influence which approach to use is whether the system will be coherent. As stated earlier, noncoherent radar systems tend to be built around oscillator-based sources, whereas coherent systems tend to be based on amplifier sources.

In the subsections that follow, a basic description will be provided of the tubes and devices available to the transmitter designer for generating RF power. For more detailed information on each of these devices, the reader is directed to Gilmour's texts [2,11] as well as to the excellent survey text by Barker et al. [12].

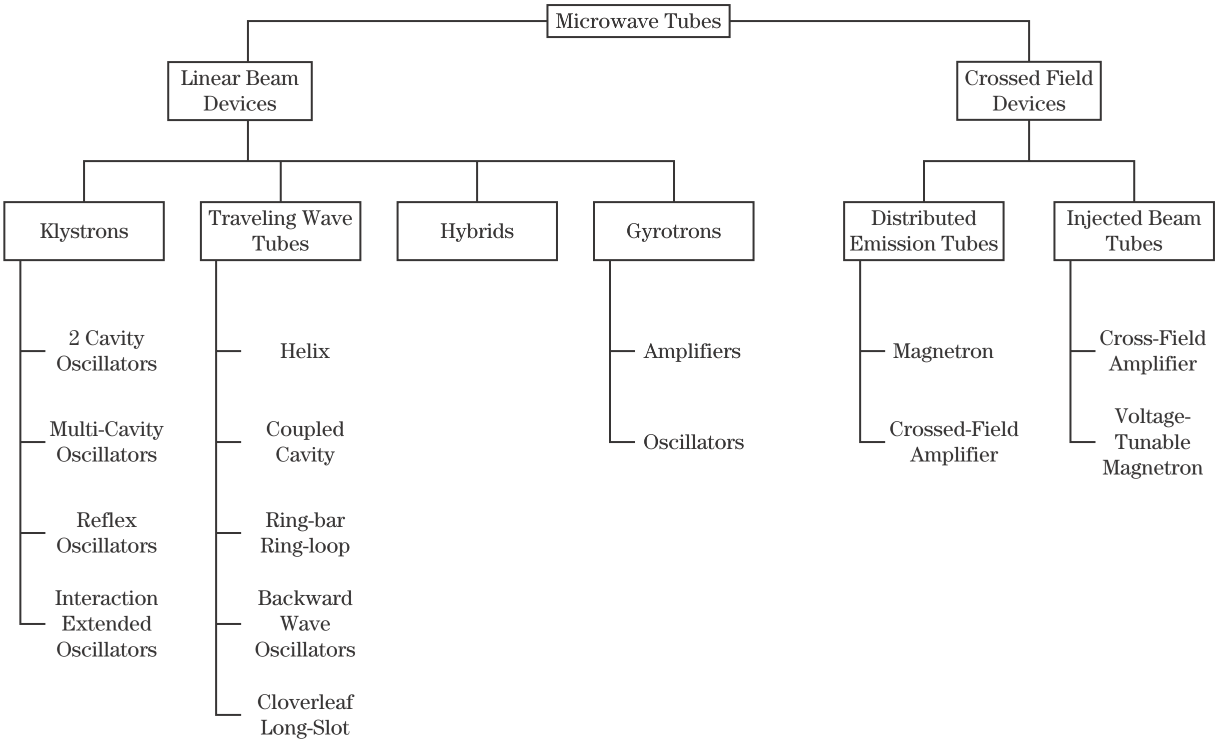


FIGURE 10-6 ■ Microwave tube family.

Figure 10-6 shows the relationship between the common tubes that are used or have been used in radar transmitters as either oscillators or power amplifiers. As can be seen by the figure, there are two main types of microwave tubes: *linear beam tubes* and *crossed-field tubes*, each with its advantages and disadvantages.

As the name implies, in a linear beam tube the electron beam and the circuit elements with which it interacts are arranged linearly. A simple schematic of a notional linear beam tube is shown in Figure 10-7. In a linear beam tube a voltage is applied to the anode, which accelerates the electrons given off by the cathode. The resultant electron beam has a kinetic energy determined by the anode voltage. A portion of the kinetic energy contained in the electron beam is converted to microwave energy as RF waves input into

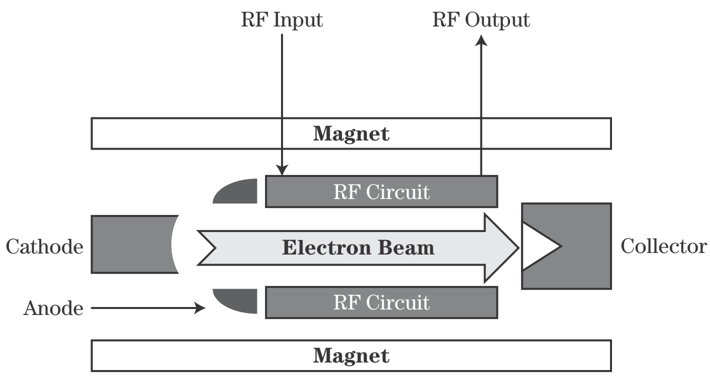


FIGURE 10-7 ■ Schematic diagram of a generic linear beam tube.

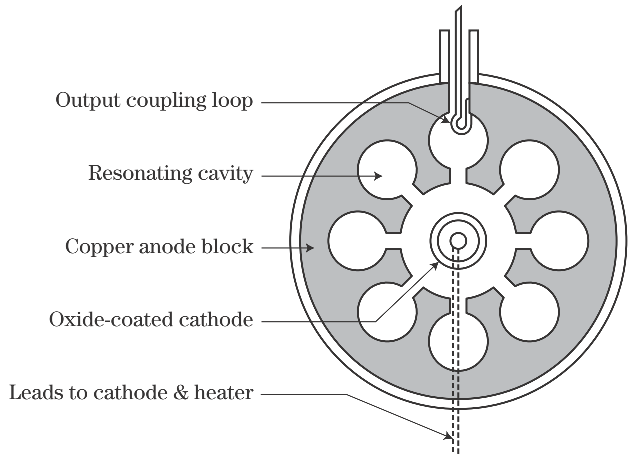


FIGURE 10-8 ■ Cross section of a magnetron tube.

the tube interact with the electron beam. The microwave energy is extracted at the RF output port, and the remainder of the electron beam is dissipated as heat from the tube or is returned to the power supply circuit at the collector. Because the electrons in the electron beam have a tendency to repel each other, a magnetic field, provided either by permanent magnets or an electromagnet, is used to focus the electrons into a beam going from cathode to collector.

Crossed-field tubes differ both in appearance and operation from linear beam tubes. The major difference is that the interaction between the electrons generated at the cathode and the anode requires a magnetic field at right angles to the applied electric field. The original device in the crossed-field tube family is the magnetron. Figure 10-8 shows a cross section of a magnetron tube. As can be seen from the drawing, a magnetron is basically a diode, with a cathode and anode. However, in this case the anode consists of a series of resonant cavities placed symmetrically around the cathode. Figure 10-9 shows a cutaway drawing of a complete magnetron assembly, showing the permanent magnet,

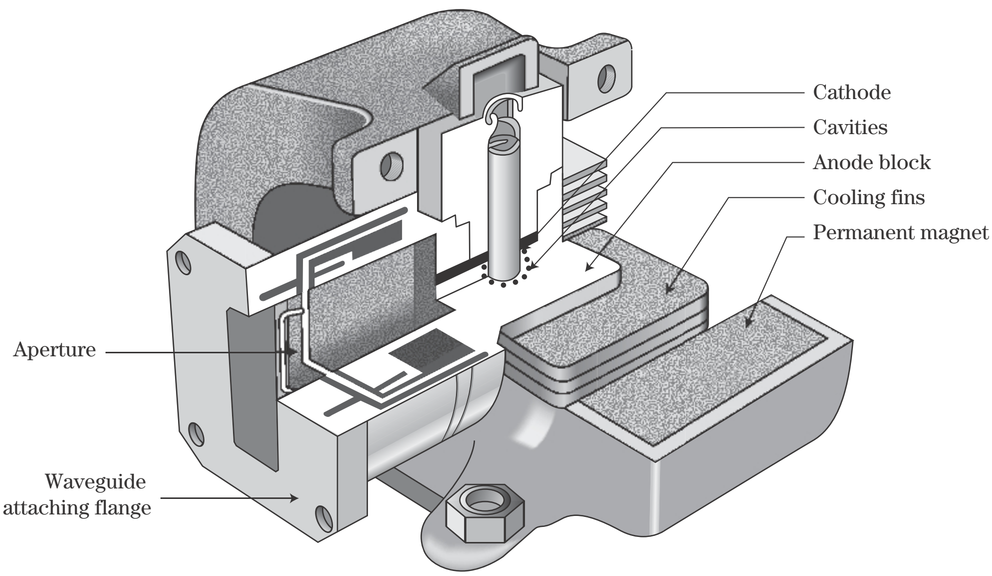


FIGURE 10-9 ■ Cutaway drawing of a typical magnetron.

which generates the focusing field, as well as the cooling fins attached to the anode block to dissipate the heat generated by the tube's operation, and the output aperture which couples the RF energy to the microwave plumbing going to the antenna.

With this general introduction to the tubes used in oscillators and high-power amplifiers, the specific tubes used in the typical radar configurations will be examined next. In addition, the basic solid-state devices used in lower-power configurations will be briefly considered as well as ways to achieve at least moderate power levels using power combining techniques.

10.3.1 Oscillators

Oscillator devices are typically used in lower-cost and hence generally lower-performance applications. These devices are easier to fabricate, are built around less expensive components, and are therefore cheaper than their stable amplifier counterparts. The primary tube oscillator for radar is the magnetron, while solid-state oscillator examples include the *Gunn* and *IMPATT diodes*.

10.3.1.1 Magnetron Oscillators

Magnetron tube oscillators, which originated prior to World War II, were the first high-power microwave radar sources developed [2]. They are crossed-field devices in that the electric and magnetic fields present in the device are orthogonal. Magnetrons are particularly useful as pulsed oscillators in simple, low-cost, lightweight radar systems.

Figure 10-10 is a photograph of a typical X-band pulsed magnetron. The large horseshoe-shaped frame is a permanent magnet that induces a magnetic field across the internal microwave cavity. When a large (20 kV) voltage pulse is applied to the electrodes at the top of the stem, an electric field is created orthogonal to the magnetic field, creating

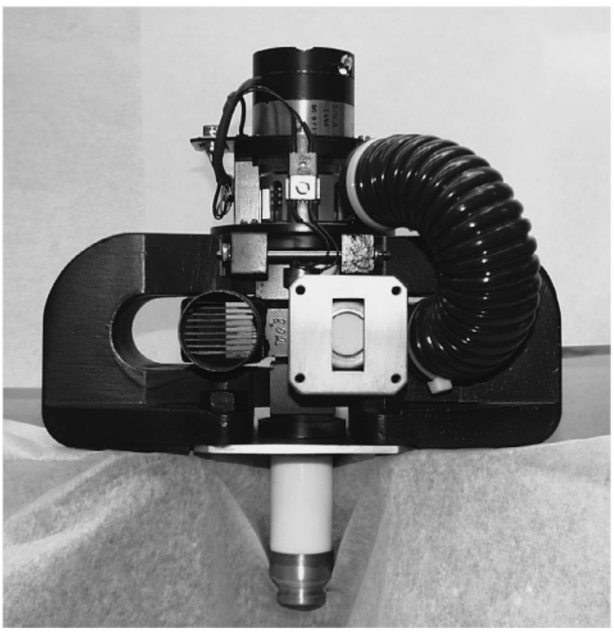


FIGURE 10-10 ■ X-band magnetron. (Photo courtesy of CPI. With permission.)

the required electromagnetic field. The frequency of oscillation depends on the mechanical characteristics of the internal cavity.

As discussed earlier, when a magnetron is used in a pulsed radar, there is no fixed relationship between the starting phase on one pulse relative to the next pulse, and hence the radar is termed noncoherent. However, injection locking can be used to allow a magnetron-based transmitter to emulate coherent operation. In injection locking, a signal is injected into the output of the magnetron prior to pulsing the tube. This microwave signal causes the energy buildup within the tube to concentrate at the frequency of the injected signal and also to be in phase with it. If the injected signal is coherent with the local oscillator (LO) of the receiver—perhaps offset from the LO by the intermediate frequency (IF)—the resulting transmitted signal is also coherent with the receiver LO, and hence the resulting radar system can measure the relative phase on receive, providing coherent operation. The degree of coherency is generally not as good as with an actual coherent amplifier chain, but such transmitters can be substantially cheaper than fully coherent systems such as TWT transmitters.

Magnetrons suffer from several undesirable operating characteristics: moding, arcing, missing pulses, and frequency pushing and pulling [13]. Many of these problems are related to how a magnetron generates microwave energy: the oscillations begin as noise, and the resonant structure of the device then forces the oscillations into a very narrow frequency band. *Moding* occurs when the tube oscillates at more than one frequency, or mode. This problem tends to be more prevalent if the rate of rise of the modulator voltage pulse is very fast. Modulator pulse shape control can help prevent moding. Since the buildup of oscillations from noise is a random process, statistically there will be instances where the pulse does not form, resulting in missed pulses. Finally, akin to phase pushing in linear beam amplifiers, the oscillation frequency is dependent on the cathode-to-anode voltage so that undesired voltage variations result in undesired frequency variations. Output load variations can affect the resonant cavity and so can also affect the operating frequency.

10.3.1.2 Gyrotron Oscillators

Gyrotrons are high-powered vacuum tubes that emit millimeter-wave beams by bunching electrons with cyclotron motion in a strong magnetic field. Output frequencies range from 20 to 250 GHz, covering wavelengths from 15 mm to less than 1 mm, with some tubes approaching the terahertz gap. Typical output powers range from tens of kilowatts to 1–2 megawatts. Gyrotrons can be designed for pulsed or continuous operation and can be used in either oscillator or amplifier applications. Although gyrotrons are more commonly used in fusion research and industrial heating applications, they have been used in radar systems that operate at millimeter wave frequencies. The Naval Research Laboratory has recently developed a high-power, coherent radar system at W-band using a gyroklystron amplifier tube with an average output power of 10 kW and a peak power of 100 kW [14]. This represents a 20-fold increase over previous systems. Although gyrotrons represent the best approach to achieving high output powers at millimeter wavelengths, much work remains to be done before gyrotrons will be commonly used in radar applications.

10.3.1.3 Solid-State Oscillators

The solid-state sources used in oscillator-based radars are primarily based on two devices: Gunn oscillators and impact ionization avalanche transit time (IMPATT) diodes. Gunn oscillators operate based on the principle of differential negative resistance within a bulk

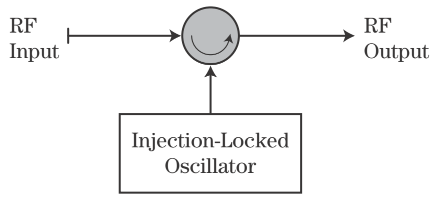


FIGURE 10-11 ■ Injection-locked amplifier.

semiconductor material, such as GaAs or indium phosphide (InP) [7]. Gunn diode oscillators are low-noise sources but are capable of only low-output power levels—tens to hundreds of milliwatts. They are useful as radar local oscillators or as the output source of low-power transmitters such as short-range frequency modulated continuous wave (FMCW) radars or altimeters. Gunn diode oscillators are available well into the MMW frequency regime.

IMPATT diode oscillators, in contrast with the Gunn diode oscillator, are fairly noisy but are capable of higher output powers, reaching into the tens of watts. They can be power-combined for even higher powers and are therefore more common as power sources. They are available up to MMW frequencies. They can also be injection-locked for amplifier operation [7] as illustrated in Figure 10-11. An RF signal is input into one port of a circulator as shown and then enters the output of the diode oscillator circuit. The signal interacts with the diode oscillator, locking the oscillation frequency to that of the input signal. The resulting output is then transferred to the load through the third port of the circulator. A reasonable MMW power amplifier can be constructed from injection-locking a power-combined set of IMPATT diodes.

10.3.2 Tube Amplifiers

The case where the radar transmitter is designed using a power amplifier to achieve the required output power for proper operation is considered next. There are many different kinds of radar transmitter amplifiers, and it is important to understand their basic differences. As with radar oscillators, tube amplifiers can be designed using either linear beam tubes or crossed-field tubes.

10.3.2.1 Linear Beam Tubes: Klystrons

Klystrons are linear beam tubes, which means the interaction between the RF field and the electron beam occurs longitudinally along the length of the tube. The klystron was the first microwave tube invented to overcome the transit-time effects that early triode and tetrode tubes experienced when used at higher frequencies. Klystron tubes are the most efficient of the linear beam tubes, are capable of the highest peak and average powers, and can be used over an extremely broad frequency range, from low ultra high frequency (UHF) (200 MHz) to W-band (100 GHz) [12]. Klystrons essentially consist of a series combination of high-Q cavities through which an electron beam passes, exchanging energy with an RF wave inserted into the input cavity. The RF is coupled from cavity to cavity via the electron beam itself, until it is amplified and extracted in the output cavity as shown schematically in Figure 10-12.

Each cavity is a resonant circuit at a particular frequency. Tuning the cavities in different ways changes the overall characteristics of the amplifier. A given design can be tuned to give broader bandwidth at reduced gain or higher gain at reduced bandwidth. The

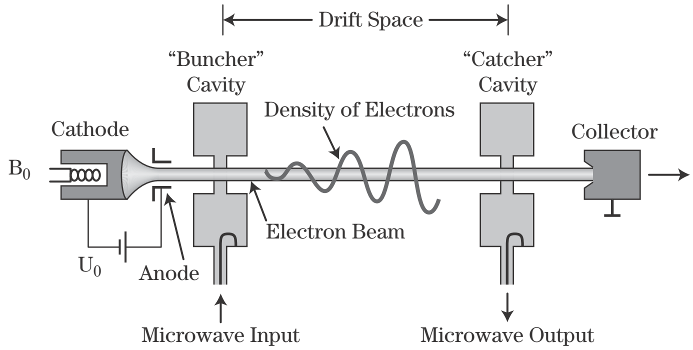


FIGURE 10-12 ■ Schematic view of a two-cavity klystron tube.

center frequency can be changed by mechanically adjusting the cavity characteristics via the tuning adjustment (typically on the side of the tube). Figure 10-13 is a photograph of a number of different klystron tubes.

The fact that the klystron uses high-Q cavities results in very low additive phase noise in the amplifier. Klystrons tend to have significant gain (40–60 dB) and good efficiency (40–60%) but suffer from inherently narrow bandwidth capability (about 1–10%) when compared with other tube types. Hence, for applications requiring a high-power source with low phase noise but not much bandwidth, the klystron is usually the proper choice.

Low-power klystrons such as reflex klystron oscillators have long been replaced by solid-state devices. However, they are unlikely to be replaced by solid-state devices at MMW frequencies any time soon. Solid-state devices cannot yet economically produce the several tens of watts of average power achieved by klystrons in those bands.

10.3.2.2 Linear Beam Tubes: Traveling Wave Tubes

Like the klystron, the traveling-wave tube is a linear beam device. Other than the magnetron used in microwave ovens, the TWT is the most commonly used microwave tube, serving in such diverse applications as the final stage amplifier in satellite communication systems, as wide bandwidth, high power, high gain, high efficiency power sources for electronic countermeasure (ECM) systems, and the driver for crossed-field amplifiers in high-power radar systems. Traveling-wave tubes are also a major component in many

FIGURE 10-13 ■ A variety of klystron tubes. (Photo courtesy of CPI. With permission.)

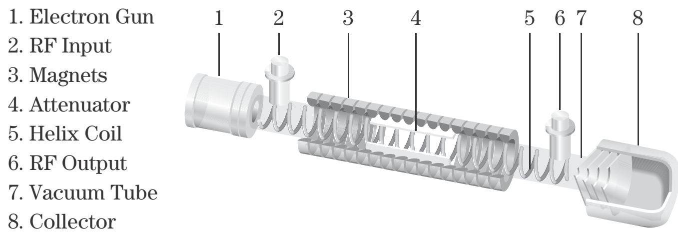


FIGURE 10-14 ■ Functional diagram of a traveling wave tube.

microwave power modules (MPMs), which combine some of the desirable attributes of solid-state devices with the power output of tubes. While many different RF circuits have been developed to use in TWTs, the two most common are the helix approach, which is well suited for broadband operations, and the coupled cavity approach, which is best for high power applications.

Figure 10-14 is a functional diagram of a TWT showing its major components. An electron gun (1) emits a beam of electrons that passes through a slow-wave structure such as a helix (5) or coupled cavity. RF energy is injected into the tube via an input port (2) and removed via an output port (6). The velocity of the electron beam is set by the cathode-to-body voltage. The slow-wave circuit slows up the longitudinal component of the velocity of the RF signal so that it travels roughly in synchronism with the electron beam. Magnets (3) are used to keep the electron beam focused as it travels down the tube. As the beam and the signal traverse the length of the tube (7), the interaction causes velocity modulation and bunching of the electrons. The bunched beam causes induced currents to flow on the RF circuit, which then causes further bunching of the electron beam. Through this regenerative process, energy is transferred from the beam to the RF signal, and amplification of the RF signal occurs. The electron beam then strikes the collector (8), which dissipates the thermal energy contained in the beam. To reduce the impedance mismatches that will occur at the RF ports, and to decrease the backward wave that can flow in the tube, it is common to use an attenuator (4) to reduce these effects. Figure 10-15 shows the various current flows that are involved in TWT operation.

Beam control is accomplished by pulsing a modulating anode or grid. Some older high-power tubes are cathode-pulsed. Grid-controlled tubes allow for beam control with lower voltages than any other means, providing for very fast rise and fall times for short pulse operation and for high-PRF operation for pulse-Doppler radars. Grids tend to intercept a small amount of beam current, which can limit the power capability of the tube. Modulating anode- or cathode-pulsed tubes do not suffer this limitation. However, their peak or average

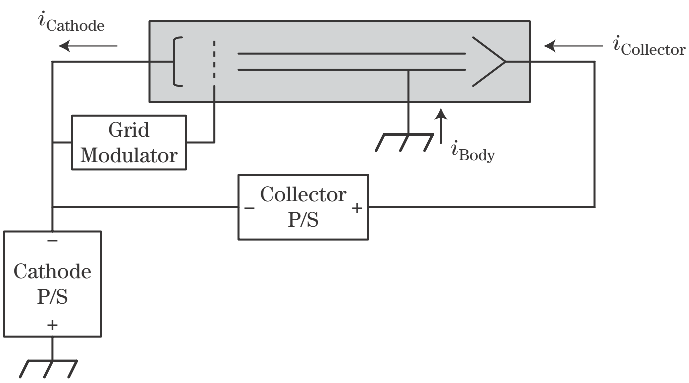


FIGURE 10-15 ■ Current flows associated with traveling-wave tubes.

powers are limited by other factors, such as RF circuit or collector heat dissipation. An excellent beginning reference for detailed information on the design and operation of TWTs is Gilmour's text [11].

10.3.2.3 Cross-Field Tubes: Crossed-Field Amplifier

The crossed-field amplifier (CFA) is similar to the magnetron in that the electric and magnetic fields are perpendicular to each other. CFAs are characterized by relatively low gain, typically 10 dB to 17 dB, and relatively high additive phase noise, especially when compared with klystrons or TWTs. The low gain is a disadvantage when generating high power levels, as it requires increased drive levels and hence more expensive driver amplifier stages. For this reason, TWTs are often used to drive CFAs. For a given amount of average output power, however, the CFA is very cost-effective, especially when considering the relatively simple power supply/modulator system required to operate it. As an example, CFAs are used in the U.S. Navy AN/SPY-1 phased array radar. Like the gyrotron, the CFA can also be used as an oscillator, although this is not a common application in current radar systems.

In summary, because of their output power, frequency range, and, in the case of TWTs, broad bandwidth characteristics, vacuum tubes will be used for the foreseeable future in high-power radar applications. For comparison purposes, the characteristics of the various tubes previously discussed are collected in Table 10-1, extracted from a U.S. Department of Defense (DoD) report on the status of the vacuum tube industry as of the late 1990s [15].

10.3.3 Solid-State Sources

There has been a strong push to replace vacuum tube-based RF sources with solid-state devices because of the many perceived advantages, including reliability and maintainability, modularity, and potentially performance. While there are many applications where solid-state devices meet all the system requirements for a radar transmitter, there are many applications where solid-state devices cannot yet compete with vacuum tube devices in terms of output power, efficiency, and cost. In fact, it can safely be predicted for the foreseeable future that solid-state devices will not be able to replace tubes in many radar applications as well as in such related fields as electronic warfare equipment, that require hundreds of kilowatts of average power. However, this does not mean that solid-state amplifiers and power modules built around solid-state devices do not have a role to play in radar technology. In fact, many applications, ranging from the radar guns used by law enforcement agencies to the radar systems being integrated into automotive systems as safety features, are best addressed using solid-state technology. The transmitter designer must be aware of the actual advantages and disadvantages of solid-state devices versus vacuum electronic devices and be able to select the best technology as appropriate.

10.3.3.1 Solid-State Amplifiers

Phased array antennas are increasingly being used in radar systems due to their many advantages. At the same time, there is a trend toward using *monolithic microwave integrated circuits* (MMICs) based on GaAs technology. According to Brookner [16], the majority of phased array antenna element PAs are fabricated using GaAs MMICs using a metal semiconductor field-effect transistor (MESFET) process, although these devices are being superseded by pseudomorphic high-electron mobility transistor (PHEMT) technology.

TABLE 10-1 ■ Compilation of Characteristics of Common Vacuum Devices

Tube Type	Frequency / Bandwidth	Power Out (Typical)	Attributes / Drawbacks	Applications
Klystron	0.1–300 GHz 5–10%	10 kW CW ** 10 MW Pulse	High Power 40–60% Efficient Low Noise Narrow Bandwidth	Radar Television Industrial Heating Satellite Uplinks Medical Therapy Science
Traveling Wave Tube (Helix)	1–90 GHz Wide Bandwidth 2–3 Octaves*	20 W CW 20 kW Pulse	Broad Bandwidth Power Handling Limitations Efficiency	Electronic Warfare Communications Commercial Broadcasting Industrial Applications
Coupled-Cavity TWT	1–200 GHz 10–20%	300 W CW 250 kW Pulse	Average Power Capability Complex & Expensive Slow Wave Structure	Airborne Radar Satellite Communications AEGIS FC Illuminator
Magnetron	1–90 GHz N/A	100 W CW 10 MW Pulse	Simple–Inexpensive Rugged Noisy	Radar/Medical Industrial Heating
Crossed-Field Amplifier	1-30 GHz 10–20%	1000 W CW 5 MW Pulse	Compact Size 30–40% Efficient Complex and Expensive Slow Wave Structure	Transportable Radars Shipboard Radar Seeker Radar Industrial Heating
Gyrotron	30–200 GHz 10% Max	0.2–3 MW Pulse	High Power at High Frequencies High Voltage Required	High-Frequency Radar Fusion Accelerators Industrial Heating

*One octave is the range defined where the highest frequency is twice the lowest (e.g., 2–4, 4–8).
**DOE's APT klystrons will run at 1 MW CW.
Source: From [15] (with permission).

In addition to GaAs, other compound semiconductors are being used in PAs for phased array antenna systems, including GaN and silicon carbide (SiC) in both discrete and MMIC form [17].

Specific device technology is undergoing constant change and improvement. Here, only the general trends in solid-state amplifiers and transmitters are discussed, providing comparisons between tubes and solid-state devices. Compared with tubes, solid-state devices posses the following advantages:

- No hot cathode is required for electron generation. Thus, there is no delay for device warm-up and no power required for a cathode heater.
- Solid-state amplifiers operate at much lower voltages. Because of this, power supply voltages are on the order of tens of volts instead of kilovolts. This has several advantages, including smaller and less expensive components and a smaller power

supply size, since large spacing between components is not required to prevent voltage breakdown and arcing between power supply components and the components do not require encapsulation for high voltage potting. Also, the lower voltage eliminates or minimizes the generation of x-rays, which are a potential health hazard in high-voltage vacuum tubes.

- Transmitters designed with solid-state devices may exhibit improved *mean time between failures* (MTBF) compared with tube transmitters. However, this assumes that the solid-state transmitter is properly matched to the surrounding subsystems and can handle the high peak-to-average power ratio that is typically present in high-power transmitters.
- Solid-state transmitters can be designed with wide bandwidths, exceeding the 10–20% bandwidths typically achievable with high-power tubes and instead reaching bandwidths up to 50%. However, to date no solid-state amplifier can achieve the 2–3 octave bandwidths of the TWT at equivalent power levels.
- Modules based on solid-state devices can exhibit a large degree of flexibility in the implementation of amplifier designs. In the next section the impact of this flexibility on the design of transmit/receive modules will be examined.

However, it should be pointed out that transmitters based on solid-state devices have their own drawbacks. For instance, a solid-state transmitter may operate with a high duty cycle, which means it will generate long pulses that require the use of pulse compression. Long pulses also result in a long minimum range, which means targets at shorter ranges might be masked by the long pulses.

Solid-state amplifiers for use in transmitters are often characterized by their class of operation. Amplifiers can operate in any of the following classes: Class A, B, AB, C, D, E, F, G, or H. Classes A, B, AB, and C are used in analog amplifier circuits where linear operation is required, while Classes D, E, F, G, and H are used in switching-mode amplifiers.

For analog amplifier circuits the class of operation is defined by the way the transistor is biased. For instance, Class A amplifying devices operate over the whole of the input cycle such that the output signal is an exact scaled-up replica of the input with no clipping. Class A amplifiers are the usual means of implementing small-signal amplifiers. They are not very efficient; a theoretical maximum of 50% is obtainable with inductive output coupling and only 25% with capacitive coupling. In a Class A circuit, the amplifying element is biased so the device is always conducting to some extent and is operated over the most linear portion of its characteristic curve. Because the device is always conducting, even if there is no input at all, power is drawn from the power supply. This is the chief reason for its inefficiency.

Contrast this with the Class C amplifier, which conducts less than 50% of the input signal. The distortion at the output is high, but efficiencies up to 90% are possible. The most common application for Class C amplifiers is in RF transmitters, where the distortion can be greatly reduced by using tuned loads on the amplifier stage. The input signal is used to roughly switch the amplifying device on and off, which causes pulses of current to flow through a tuned circuit. Collector current is drawn only when the input voltage exceeds the reverse bias across the input and the output voltage is developed across the tuned load. Thus, there is no power dissipation in the amplifier when the transmitter is switched off during receive mode.

Class D, E, F, G, and H amplifiers are switching amplifier configurations with high efficiencies that also require specialized filtering of the signal harmonics to maximize the amplifier efficiency. These can be very complicated hardware implementations and are usually warranted only if the incremental improvement in efficiency brings a significant benefit to the transmitter system.

Many different circuit configurations can be employed to implement these various classes. A detailed discussion of those configurations is beyond the scope of this chapter. The interested reader is referred to one of the many texts available on the design of RF amplifiers, including books by Krauss et al. [18], Cripps [19], and Grebennekov [20] or the articles by Raab, et al. [21] or Gao [22]. There is also an excellent chapter on solid-state transmitters by Borkowski in the third edition of the *Radar Handbook* [23].

10.3.3.2 Solid-State Transmitter/Receiver Modules

Solid-state T/R modules have received much investment and hence research and development attention over the last 20 years. Many new military radar development programs are using solid-state technology as opposed to tubes. Solid-state T/R modules are a broad category by themselves, since there are many different technologies, applications, and configurations. A typical T/R module architecture is shown in Figure 10-16. Each module generally employs an attenuator for control of receive gain and receive antenna sidelobes (via tapering across the aperture) and a low-power phase shifter for beam steering control. Several amplifiers can be power-combined to increase the power per element at the expense of increased cooling and prime power requirements. A circulator is typically used to provide a good match between the amplifiers and the antenna element, since the voltage standing wave ratio (VSWR) at the element can vary greatly as a function of scan angle. A receiver protector of some sort (e.g., a diode switch or diode limiter) is usually employed to prevent burnout and damage of the sensitive low-noise amplifier input.

Modules using high-peak power (over 100 W) silicon amplifiers for low duty cycle waveforms at UHF are used in radars such as the PAVE PAWS missile warning radar. In contrast, space-based radar applications, due to severe prime power limitations, require only milliwatts of power per module, typically operate at much higher frequencies, and tend to use GaAs devices. Most solid-state radars are somewhere in between these extremes, although to date GaAs has seen the most use in solid-state systems operating above

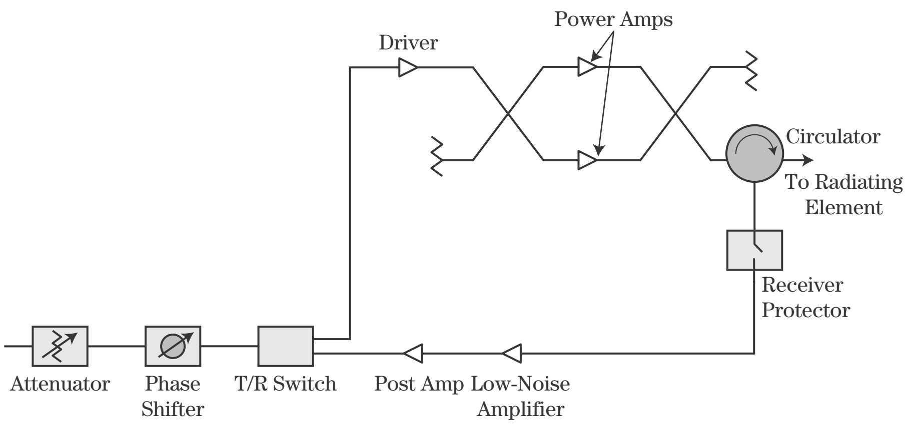


FIGURE 10-16 ■ Example T/R module architecture.

S-band. Current T/R modules using GaAs technology can have output powers in the tens of watts range. Newer materials currently under development such as gallium nitride are of interest for even higher-power amplifiers. GaN has 5–10 times the power density of GaAs and can operate at higher voltages due to higher breakdown capability.

10.3.3.3 Solid-State Active-Aperture Arrays

Solid-state active-aperture arrays can be separated into high-power density and low-power density arrays. Figure 10-17 shows a plot of aperture area and power illustrating lines of constant power aperture, a key parameter for search radars, and lines of constant power-aperture squared, a key parameter for tracking radars (see Chapter 2). Low-power density arrays are those arrays with very low power per element. These types of arrays maintain sensitivity on a target by increasing aperture size and hence transmit and receive gain while minimizing output power, which is usually done to reduce prime power, cooling requirements, and cost. Such arrays have been investigated recently for space applications as well as for ground-based applications.

High-power density arrays try to increase the amount of output power that can be generated and cooled at each element in an effort to reduce array size, for instance to reduce the footprint for storage or transport. Such arrays require much more prime power and cooling than do low-power density arrays of equivalent power-aperture-gain (PAG) product. Of course, if the volume available for the antenna is limited, then increased radar sensitivity must be obtained via increased transmitter power and reduced noise temperature.

One of the attractive features of a low-power density array is that for the same level of sensitivity, a properly designed array can be built that requires much less prime power than a high-power density array of equivalent performance. The savings in terms of the cost of the power itself is not usually the main advantage. For tactical military applications, reducing prime power requirements can mean reduced logistics requirements because of reduced fuel consumption by diesel-powered generators. Another advantage for low-power density active-aperture arrays is that the reduction in prime power results in a reduction of waste heat at the array face (where most of the waste heat is generated). This can help improve reliability of the electronics in the array as well as decrease cooling requirements at the array face, easing the thermal and mechanical engineering challenges.

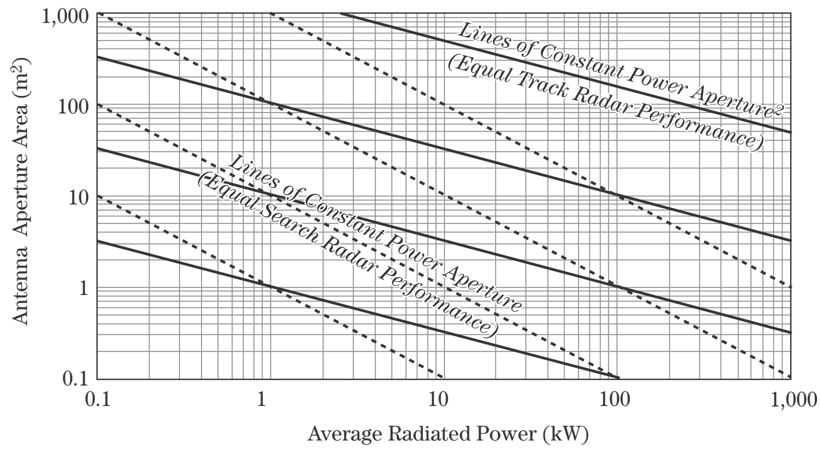


FIGURE 10-17 ■ Aperture area and radiated power for constant PA and PA^2.

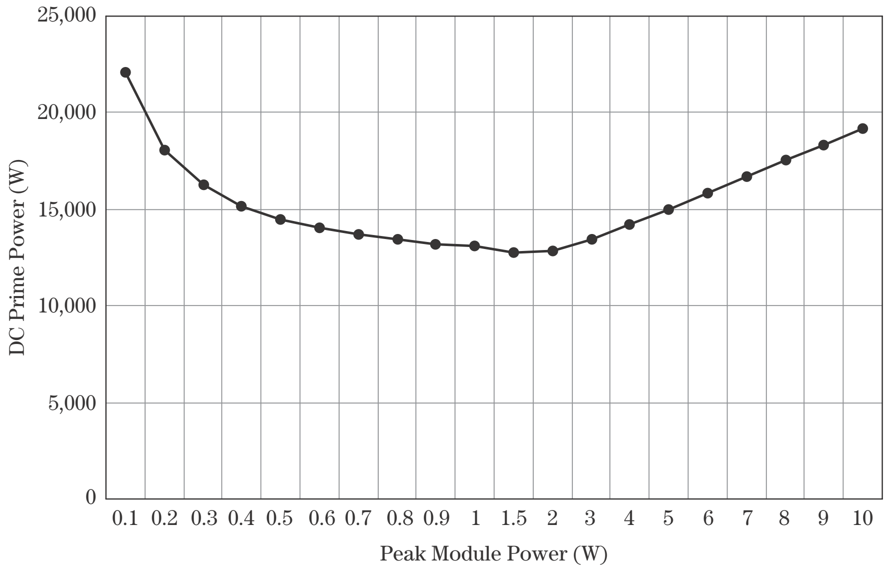


FIGURE 10-18 Example phased array radar prime power requirement as a function of peak module power for a given level of power-aperture-gain product.

The variation in array prime power required as a function of peak module power is shown in the example in Figure 10-18. This example assumes a single-pulse radar PAG requirement of 90 dBWm^2; a power amplifier power-added efficiency of 33% in the transmit mode over the peak output power range of interest; prime power consumption of 1 W in the receive mode; background DC power of 0.5 W in the transmit mode (in addition to the final power amplifier DC power requirements); and a 10% transmit duty cycle. The figure then plots the average DC prime power required to operate the T/R modules for an array that meets the PAG requirement.

At extremely low module transmit power levels, the array prime power requirements are dominated by the receive-side power required by the large number of elements needed. As the peak module power increases, the array size and hence the number of elements decreases. It can be seen from the figure that there is a fairly broad minimum in the relationship, such that module output powers in the range of 0.7 W to 3 W result in reasonably low levels of prime power for this example. This range will vary as the array and module parameters change. However, as the peak module power continues to increase, the prime power required rises again as the radar sensitivity is being attained increasingly through power (P) rather than by area (A) and gain (G). This exercise neglects issues associated with power-aperture product (a key performance metric for the search mode) and any physical size constraints. Modern techniques such as beam spoiling on transmit (broadening the beam by defocusing the array) coupled with multiple simultaneous receive beams can be used to improve the search performance of a narrow-beam, large-aperture radar.

10.3.4 Microwave Power Modules

Microwave power modules combine the best attributes of both solid-state sources and tubes, particularly helix TWTs, in an attempt to create a more compact transmitter than is possible using either technology alone. In its most basic form, an MPM consists of three major components: (1) a solid-state amplifier driver; (2) an integrated power conditioner;

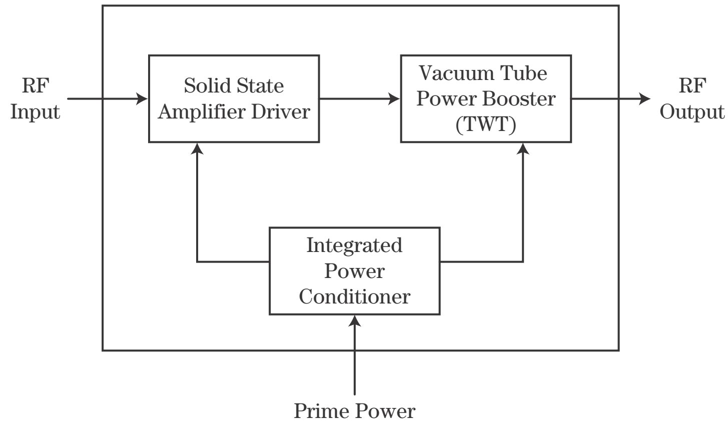


FIGURE 10-19 ■ Simple MPM block diagram.

and (3) a vacuum tube-based power booster. A simple block diagram of an MPM is shown in Figure 10-19.

MPMs take advantage of the fact that the physical length of a TWT is a function of the gain required from the RF circuit; if that gain can be minimized, the tube can be made physically smaller, assuming that the device does not generate or dissipate so much power that its mass is dominated by heat sinks. Thus, instead of requiring a 50 dB gain TWT, a solid-state driver is used to provide the first 25 dB or so of gain (where power levels are reasonably low), and the TWT is then used for the final 25 dB or so of gain where the power levels are high. Since the solid-state device can generate reasonable powers at wide bandwidths and the TWT is inherently wideband, the MPM is also capable of wide bandwidths. Typical output powers are on the order of 100 W CW for octave-bandwidth devices from S-band through K-band. Figure 10-20 shows an example MPM. The module also contains the low-voltage power supply circuitry for the solid-state amplifier as well as the high-voltage power supply for the TWT. Although MPMs have traditionally found more applications in electronic warfare (EW) systems, they are becoming more common as components of radar systems, especially on unmanned aerial vehicles (UAVs), where minimum weight and volume are key requirements. Additional information concerning MPMs is available in the paper by Smith et al. [24].

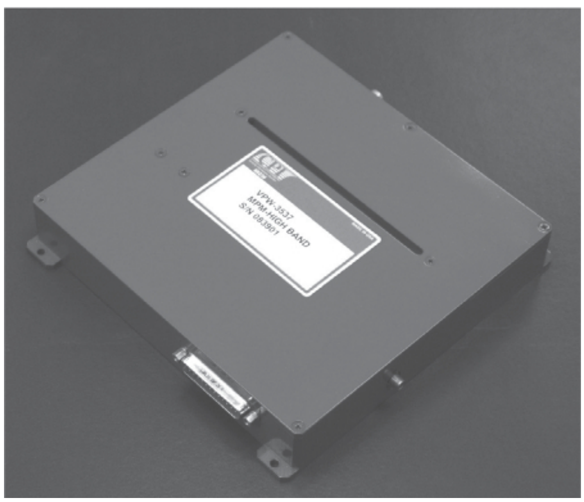


FIGURE 10-20 ■ Microwave power module (MPM). (Photo courtesy of CPI. With permission.)

10.4 MODULATORS

A CW radio wave carries no information. Modulation of the radio wave in radar is necessary to convey intelligence, just as is modulation in radio communications. In high-power (kilowatts to megawatts), long-range detection and tracking radars, pulse modulation in some form is the norm. Although not discussed in this section it should be mentioned that certain radar transmitters make use of frequency modulation (FM). This category includes low power (i.e., milliwatts to watts) FMCW radars, which are often associated with altimeters, proximity fuzes, and traffic surveillance. Also, many high-resolution, high-power radars employ a concept called linear FM *pulse compression* in which the transmitter frequency is linearly swept throughout the pulse duration (see Chapter 20).

The following subsections discuss some of the basic concepts associated with line-type pulse modulators and active-switch pulse modulators [5]. Modern microwave power vacuum tube technology is now commonly referred to as *vacuum electron device* (VED) technology [25]. VEDs include magnetrons, klystrons, TWTs, and crossed-field amplifiers. The type of VED determines, to some extent, the type of modulator required. If the VED has a control grid or modulating anode, a low-power modulator can be used. A widely used switching element of low-power modulators is the MOSFET transistor [5]. In addition to VEDs, *solid-state power amplifiers* (SSPAs) are often used in *active electronically scanned array* (AESA) radar systems. In the latter case, low-voltage, high-current-distributed solid-state pulse modulators are indicated.

10.4.1 Line-Type Modulators

Some of the earliest pulse radar modulators used were the so-called *line-type modulators* where energy is stored in a transmission line or its equivalent, a *pulse-forming network* (PFN). The PFN simulates a transmission line by means of lumped constants consisting of many low-loss inductors and capacitors. Figure 10-21 shows the PFN being charged by a high-voltage power supply through a charging diode and discharged through a triggered switch. The switch can be a vacuum tube (typically a gas-filled triode called a thyratron in older circuits) or a stacked series of solid-state switches in more modern systems. The resultant pulse is transferred to the transmitting device (e.g., a magnetron or klystron) through a pulse transformer. Pulse transformers are used because of their impedance-matching properties and because they allow isolation between primary and secondary circuits. To operate effectively with narrow pulses, specially designed pulse transformers are required. Pulse transformers have ferromagnetic cores, are closely coupled, and have relatively few turns in each winding.

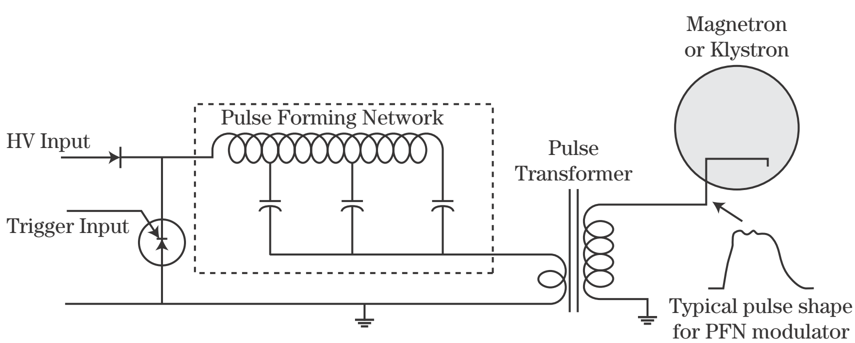


FIGURE 10-21 ■ Simplified diagram of a PFN modulator.

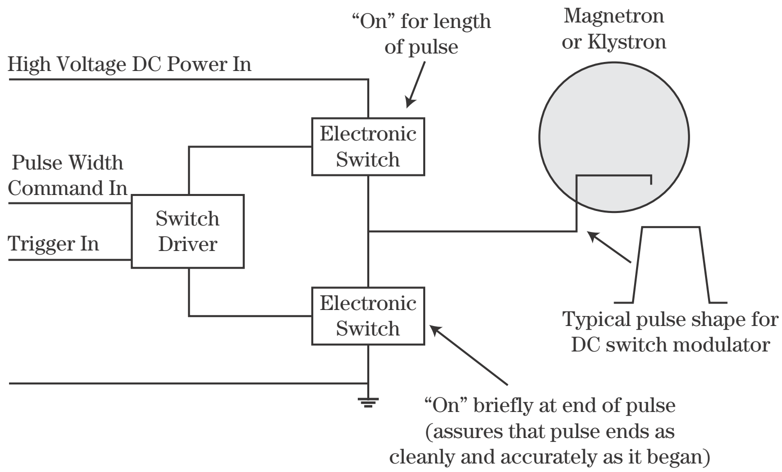


FIGURE 10-22 ■ Simplified diagram of an active switch modulator.

The switching rate sets the radar PRF while the pulse shape and duration are determined by the PFN characteristics. The switch has no effect on the pulse shape. The pulse ends when the PFN has discharged to a level that the transmitting tube is cut off. Line-type modulators tend to be less expensive than active-switch modulators (refer to Section 10.4.2) and are commonly used to operate pulsed magnetrons. One major disadvantage of this type of modulator is that the trailing edge of the pulse is usually not well defined since it depends on the discharge characteristics of the PFN. Other drawbacks to this configuration are less pulse generating flexibility and less pulse precision when compared with other types of modulators.

10.4.2 Active-Switch Modulators

Figure 10-22 is a simplified diagram of an *active-switch modulator* where the pulse 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 thyratron switch often used in line-type modulators.

The "hard-tube" designation has been replaced by the more generalized term "active-switch" to allow for the use of both solid-state as well as vacuum tube switches [5]. With the advent of high-voltage, high-current solid-state switch devices such as field-effect transistors and *silicon-controlled rectifiers* (SCRs), active-switch modulators are realizable without the use of vacuum tubes. In many cases such solid-state devices must be stacked in series to handle the high voltages involved. Care must be taken in the design of series-stacked devices when switching high voltages to ensure equal voltage sharing among the devices during turn-on and turn-off transients. In a high-power radar transmitter the voltage swing across the on/off switches often exceed tens of kilovolts (kV). As shown in Figure 10-22, the switches of an active-switch modulator control both the beginning and end of the pulse. This is in contrast to the PFN modulator described previously where the pulse shape and duration is primarily determined by PFN characteristics. The active-switch modulator permits greater flexibility and precision than the line-type modulator. It provides excellent pulse shape with varying pulse durations and pulse repetition frequencies. It also provides the opportunity of using closely spaced coded bursts of pulses. A more recent outgrowth of the active-switch solid-state modulator is the solid-state cathode

switch modulator [26], which can provide pulses as narrow as 50 nanoseconds at PRFs up to 400 kHz [5].

10.5 POWER SUPPLIES

The power supplies associated with any particular radar system provide the prime DC power to operate all radar system electronics. For the basic radar transmitter employing such devices as magnetrons, klystrons, and TWTs, a high-voltage power supply is required. High-voltage (HV) power supplies for all applications (not just radar) require special attention to factors such as HV insulation of wires, use of components properly rated for HV, prevention of arc-over due to ionization, and overload protective circuitry. In basic radar the HV supply must also meet the extra requirement to supply very high currents under pulsed conditions. In contrast, the power supplies for solid-state amplifiers such as associated with AESAs are relatively low-voltage, high-current DC supplies.

10.5.1 High-Voltage Power Supplies

High-power transmitter tubes (i.e., VEDs) require very high voltages for operation, generally in the range of 10 kV to 50 kV. Even so called lower-power VED transmitters can require from 4 kV to 6 kV. Since the tube may only be 20% to 40% efficient, the high-voltage power supply must produce 2.5 to 5 times the average and peak power output of the transmitter. For most applications, the high voltage supplied to the VED must be highly regulated and have extremely low ripple content to minimize phase and amplitude distortions in the RF output pulse.

Figure 10-23 illustrates a typical high-voltage power supply and shows many of the required elements of the circuit. The input alternating current (AC) voltage is preregulated, either via a variable transformer or by a high-frequency switching regulator. The resulting

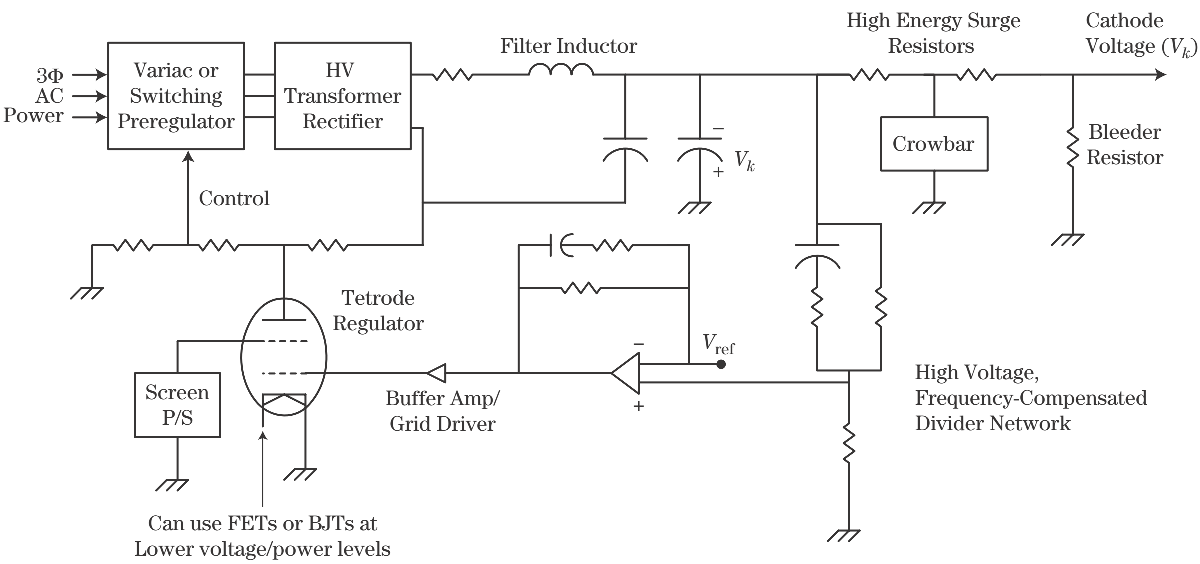
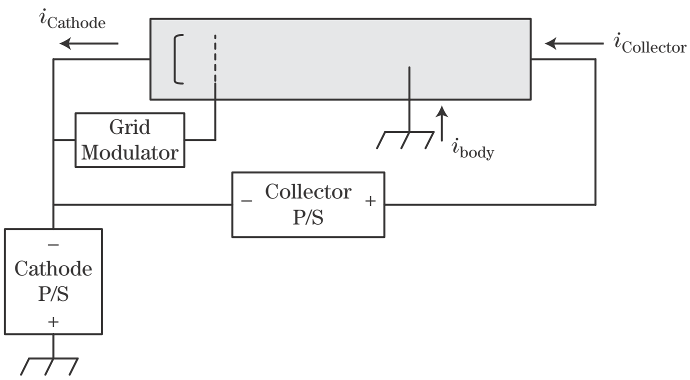


FIGURE 10-23 ■ Typical high voltage power supply for a radar transmitter.

FIGURE 10-24 ■ Traveling-wave tube power supply circuitry.



voltage is then either supplied directly to the tube or, if tighter regulation is needed, is applied between the tube and a series regulator. The series regulator can be either a pass tube such as a triode or tetrode or a solid-state device such as an FET, if lower voltage swings can be maintained at the drain terminal. The standard input line frequencies are 60 Hz and 400 Hz.

Prototype multi-phase high voltage power conditioning systems using input line frequencies of 20 kHz while generating up to 140 kV or 11 megawatt pulses to drive high power accelerator klystrons have been demonstrated at the Los Alamos National Laboratory [27]. The high voltage transformers operating at 20 kHz are only 1% of the size and weight of the 60 Hz versions!

Many TWTs require so-called *depressed collector* operation, which entails the collector voltage being depressed below ground. Some TWTs have multiple collectors that require several different voltages. Such tubes are costly but exhibit much higher power efficiency than conventional TWTs. Figure 10-24 shows a block diagram of a TWT with a single depressed collector and its associated power supplies.

As an example, assume the following values in Figure 10-24: $V_{cathode} = 30$ kV, $V_{collector} = 10$ kV, $I_{collector} = 0.9$ A, $I_{helix} = 0.1$ A, and RF output = 5 kW. Without collector depression, the input DC power would be 30 kV × 1 A or 30 kW. The efficiency would then be 5/30, or 17%. With collector depression, the input DC power would be 30 kV × 0.1 A + 10 kV × 0.9 A, or 3 kW + 9 kW = 12 kW. The efficiency would then be 5/12, or 42%, a substantial improvement. Collector depression reduces thermal dissipation at the tube collector element and reduces the amount of power that must be processed, filtered, and delivered by the high-voltage power supply subsystem.

Almost without exception, high-power microwave tubes and their accompanying high-voltage switches occasionally arc over, essentially placing a short circuit across the modulator (and hence the high-voltage power supply). Since the resulting discharge of 50 joules (or more) will usually damage an RF tube (VED) or switching device, some means must be provided to divert the stored energy when an arc discharge occurs. Such a protective circuit is a called a *crowbar* since it is equivalent to placing a heavy conductor (like a crowbar) directly across the power supply to divert the energy and prevent its discharge through the tube or switching device.

10.5.2 Power Supplies for Solid-State Amplifiers

Solid-state amplifiers are associated with AESA radars such as the X-band U.S. Navy AN/SPY-3, which was designed to meet all horizon search and fire control requirements

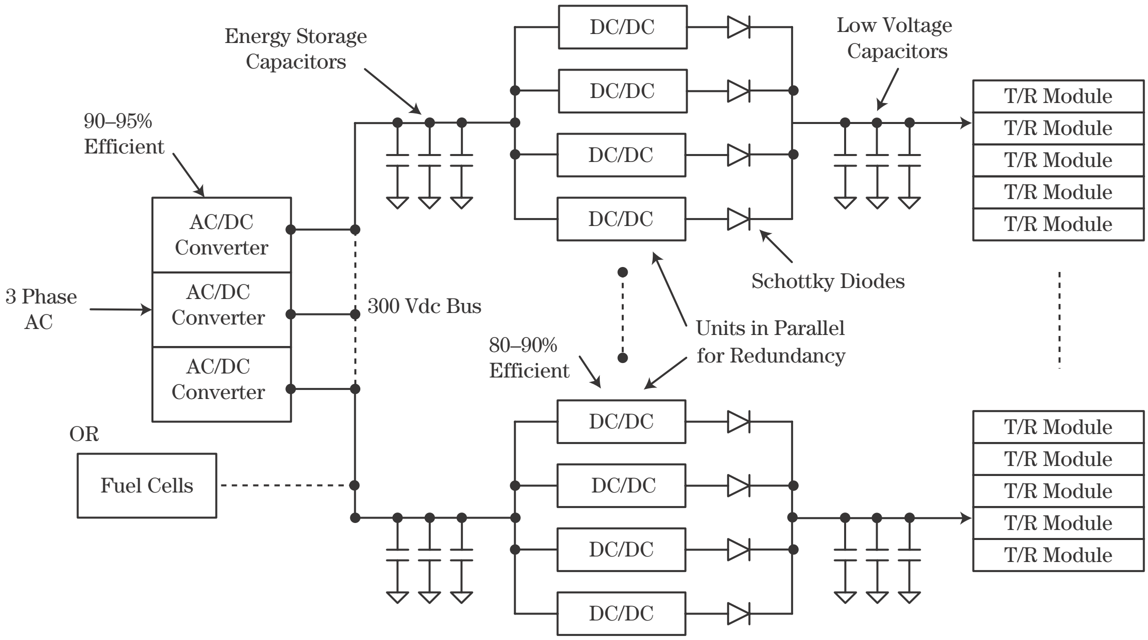


FIGURE 10-25 ■ An active aperture power supply configuration.

for the Navy. It uses three fixed arrays, each containing approximately 5,000 active elements. The aggregate of the DC power supplies for solid-state amplifiers associated with thousands of active elements must produce high currents (100s of amperes) at low voltages (5 to 10 volts). Since the transmitters of an AESA type system are distributed over the array, then the power supply system should be distributed as well. For large phased arrays, power distribution at higher voltages than required by the individual solid-state amplifiers can minimize heat generation due to ohmic losses. For example, GaAs type microwave transmitter modules typically require DC input voltages in the range of 5–10 VDC. It would be advantageous to produce these low voltages at a subarray level near the individual solid-state amplifiers by means of local DC/DC converters operating with inputs at hundreds of volts. Figure 10-25 illustrates a potential active aperture power supply configuration.

10.6 TRANSMITTER IMPACTS ON THE ELECTROMAGNETIC ENVIRONMENT

Because of the large power levels typically associated with high-power radar systems, it is incumbent upon the designer of radar transmitters to ensure not only that the RF energy generated has the proper waveform and power levels but also that the radiated energy occupies that portion of the EM spectrum allocated to it. Additionally, because the spectrum must be shared with other radar systems within the band, the transmitted radiation should occupy only that amount of the band required to operate properly and not cause interference with other radar systems or any other electronic systems that operate within or adjacent to the designated bands for radar. High-power transmission also presents other

potential negative impacts on the equipment and personnel that are in the environment located around radar transmitters.

10.6.1 Transmitter Design and Spectrum Issues

When designing the hardware that makes up a radar system, the designer attempts to balance competing requirements to maximize detection range, resolution, and system reliability while trying to minimize, for example, noise, size, weight, volume, and power requirements. Much study and effort has gone into developing design principles that meet these conflicting hardware and system requirements. An equally important area of radar engineering that has not received as much attention by radar designers is the area of spectrum management and engineering. The purpose of *spectrum management* is to coordinate and control the usage of the electromagnetic spectrum between and within countries. This encompasses a multitude of activities, including the following:

- Coordination, organization, and optimization of the use of the RF spectrum.
- Allocation of spectrum among various users.
- Controlling and licensing the operation of radio and radar systems within the spectrum.
- Controlling, avoiding, and solving interference problems between radiators and receivers,
- Advancing and incorporating new technology that impacts spectrum users.

Spectrum engineering is the complement to spectrum management. It seeks to design and develop equipment and create practices and procedures that maximize the efficient use of the EM spectrum while allowing the RF system to carry out its required functions within its frequency allocation. This means radiating the minimum amount of RF energy and using the minimum amount of spectrum that will allow the system to carry out its task, while not interfering with other equipment that lawfully operates within the same frequency band allocated to the radiating RF system.

It is relatively easy to make a determination as to how efficient the radar hardware is. There are several well-established measures of radar efficiency, including the efficiency of the radar system and the efficiency of the transmitter. This is not the case when determining the efficiency of spectrum usage. In the United States the National Telecommunications and Information Administration (NTIA) has undertaken a study of ways of measuring spectrum efficiency (SE) with the tasks of (1) developing metrics to define SE for the various radio services, (2) developing methods to implement such a metric, and (3) producing recommendations on ways to enhance SE. Until the NTIA finishes this task, the best guidance available to the radar engineer is the Radar Spectrum Engineering Criteria (RSEC) [28]. The purpose of the RSEC is to regulate the amount of bandwidth a radar is permitted to use, based on its modulation type. Additionally, it specifies a spectral roll-off requirement and a limit on spurious emissions, depending on the category a given radar falls within. Currently all primary radars are classified in one of five categories, Group A through E. Broadly speaking, Group A contains low-power (less than 1 kW peak power) radars; Group B contains medium-power (1 kw to 100 kW) radars; Groups D and E are certain special frequencies or applications; and Group C is everything else. Radars that fall within Group A are currently exempt from any RSEC specifications. Radars that fall within Groups B through E must meet the appropriate criteria for their group.

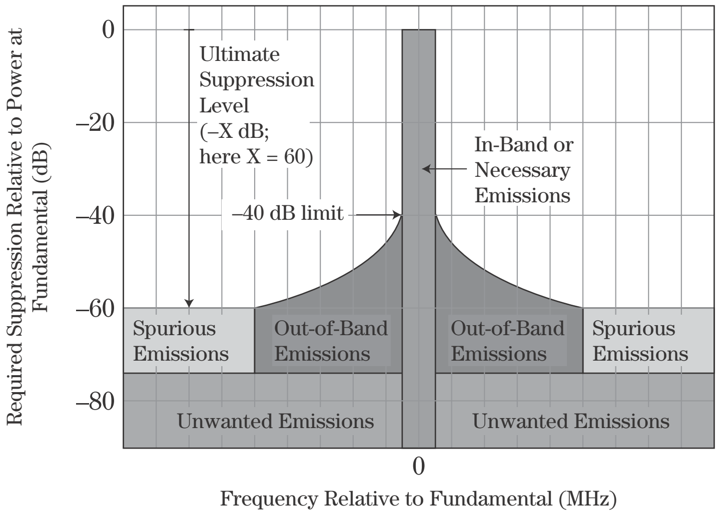


FIGURE 10-26 ■ Various signal domains considered by the RSEC.

The RSEC approach is generally to ensure that a radar's emissions fit within a spectral "mask" that is defined with respect to the radar's fundamental frequency of operation and peak power. The various types of emissions that are considered by the RSEC are illustrated in Figure 10-26, and a generic emissions mask that sets the upper bound on the radar spectral emissions is shown in Figure 10-27. Figure 10-28 shows a measured emission and the appropriate mask for checking compliance with the RSEC. Examining the figure shows that at about 3050 MHz the system exceeds the allowable emission limits.

Radar technology has advanced considerably since the RSEC was last modified in 1977. While the RSEC has bandwidth equations for pulsed, FM pulsed, phase coded, and FMCW radars, many other types of radars have no standard criteria. Thus, radars employing more than a single emitter—including phased array radars, variable PRF radars, radars whose modulation changes on a pulse-to-pulse basis, and other special types of radars—require a case-by-case examination to certify them as being compliant with spectrum engineering criteria. For the engineer tasked with designing a new radar system, the

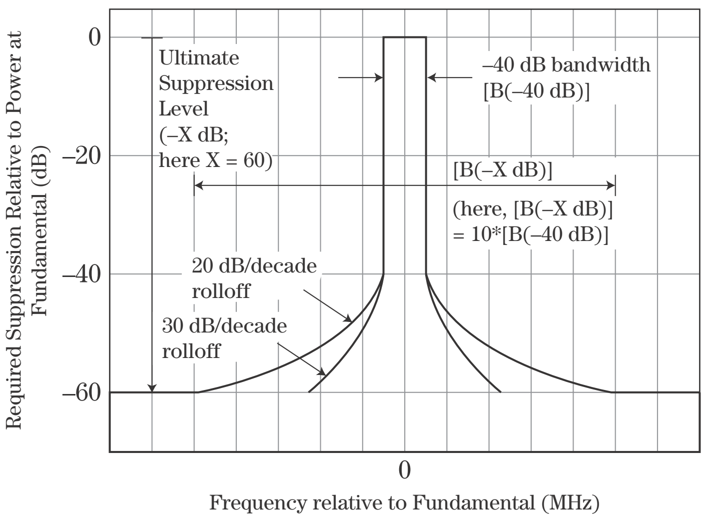


FIGURE 10-27 ■ Generic RSEC emissions box.

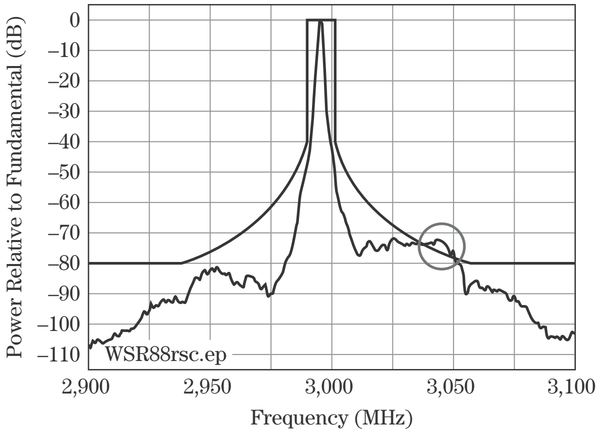


FIGURE 10-28 ■ Figure shows a measured emission within the RSEC box. At about 3050 MHz the system exceeds the allowable limits for the subject group.

best way to avoid operational problems related to spectrum issues is to work closely with the NTIA in the earliest stages of design to guarantee that the planned design approach is consistent with current regulations. This is especially important with the current effort to incorporate more waveform design and diversity into newer radar systems.

Another approach to using the spectrum more efficiently and minimizing interference to other radiating systems within a band is to consider making the radar "smarter." One way to do this is to make the radar adaptive, or to use a knowledge-based approach to transmitting the radar signals. The basic idea of this approach, also known as *cognitive radar*, is to monitor the electromagnetic environment that the radar will be operating in and to choose those portions of the band not currently occupied by other emitters or sources of interference, potentially modifying either the frequency or modulation scheme employed by the transmitter to avoid interfering with other users of the band. While this requires a much more complex transmitter design, it may be the only way to use existing radar bands efficiently. Knowledge-based radar is an active area of research. Good sources for initial study in this area are [29,30].

10.6.2 Transmitter Impacts on Spectral Purity

Transmitter impacts on radar spectral purity can be categorized as either time-varying or nontime-varying. Errors that are repeatable from pulse to pulse are considered nontime-varying. Errors that are not repeatable from pulse to pulse are considered time-varying. Time-varying errors are more serious because it is difficult to calibrate them out. In addition, they affect multipulse processes such as moving target indication (MTI) and pulse Doppler, whereas nontime-varying errors do not. It is interesting to note that the nontime-varying *unintentional modulation of pulse* (UMOP) [31] is often used as a "signature" by U.S. defense systems to identify and track foreign radars.

Transmitter output phase and amplitude are generally sensitive to the voltages applied to the power amplifier or oscillator. This is the case for both solid-state and tube-type devices. Transmitter phase and amplitude specifications in turn establish requirements on power supply voltage droop, regulation, and ripple to maintain the required spectral purity. Power supply-induced errors are usually time-varying unless the power supply frequency of operation (i.e., switching frequency or AC line frequency) is synchronized to the radar PRF or some multiple thereof.

Another source of spectral error is the nonlinear phase characteristic of transmitters, which results in frequency dispersion that in turn degrades the range sidelobes [32] associated with pulse compression systems. These effects tend to be nontime-varying as a function of waveform bandwidth for a given center frequency providing that temperature can be maintained constant. Since these effects are repeatable, they can be measured and characterized and for the most part can be calibrated or processed out. Another example of nontime-varying error is solid-state amplifier phase and amplitude sensitivity to junction temperature. These errors can vary across a pulse or from pulse to pulse depending on the waveform, but the effects can be predicted, or at least measured, and should be repeatable.

10.6.2.1 Time-Varying Errors

Within the transmitter, power supply ripple induces phase and amplitude ripple at the amplifier output due to amplifier phase/amplitude *pushing factors* [33]. Pushing factors are measures of how sensitive a device is to voltage variations at one of its electrodes. In earlier radars *frequency pulling* of magnetrons was often caused by RF load variations. This problem has been solved by means of improved RF isolation through the use of microwave circulators. Power supply ripple can cause pulse-to-pulse phase/amplitude errors, which result in Doppler sidebands that degrade coherent radar performance. High-frequency ripple can cause intrapulse modulations that can adversely affect linear frequency modulated (LFM) or chirp systems and degrade range sidelobe performance.

For example, a sinusoidal power supply ripple at 100 kHz will result in a pair of spectral sidebands that are offset from the carrier by 100 kHz. The power in these sidebands depends on the amount of voltage ripple and the phase sensitivity of the device in degrees/volt as well as amplitude modulation (AM) sensitivity in dB/V. Typical values of phase sensitivity for FETs are 1–2 deg/V (drain voltage) and 100–200 deg/V (gate voltage). The spurious sideband amplitude in decibels relative to the desired carrier (dBc) can be estimated as $20\log_{10}(\Delta\phi_{peak}/2)$, where $\Delta\phi_{peak}$ is the peak phase deviation in radians [34]. The phase deviation is calculated by multiplying the peak voltage ripple by the phase sensitivity. Note that switching power supplies do not produce ideal sinusoidal ripple waveforms, so the spectral content is complex and spread across multiple offset observed Doppler frequencies.

Figure 10-29 illustrates the effects of intrapulse ripple on the pulse-compressed receiver output for the echo from a single point target. Figure 10-29a shows the compressed ideal return with no modulation error. Figure 10-29b shows the same return with 10 degrees root mean square (rms) sinusoidal phase error, with three cycles of error across the transmitted pulse. Figure 10-29c shows the same return but with a lesser error of 2 degrees rms sinusoidal phase error, again with three cycles of error across the transmitted pulse. In this figure it is seen that the error-induced time sidelobes are three compressed range cells away from the main response. Figure 10-29d is similar to Figure 10-29b except that the 10 degree rms error waveform is now random instead of sinusoidal. The random error tends to spread out the peak time sidelobes, whereas the total integrated sidelobe floor remains the same as that in Figure 10-29b.

For several reasons, solid-state active arrays exhibit less main-beam additive spurious modulation than tube transmitters. One reason is that solid-state power amplifiers have lower noise figures. Also, if each element of an AESA has an individual transmitter amplifier and the additive noise from each amplifier is independent element to element, the resulting modulation component is suppressed by the inverse of the number of elements. (An exception would be for error components common to each element, due to common

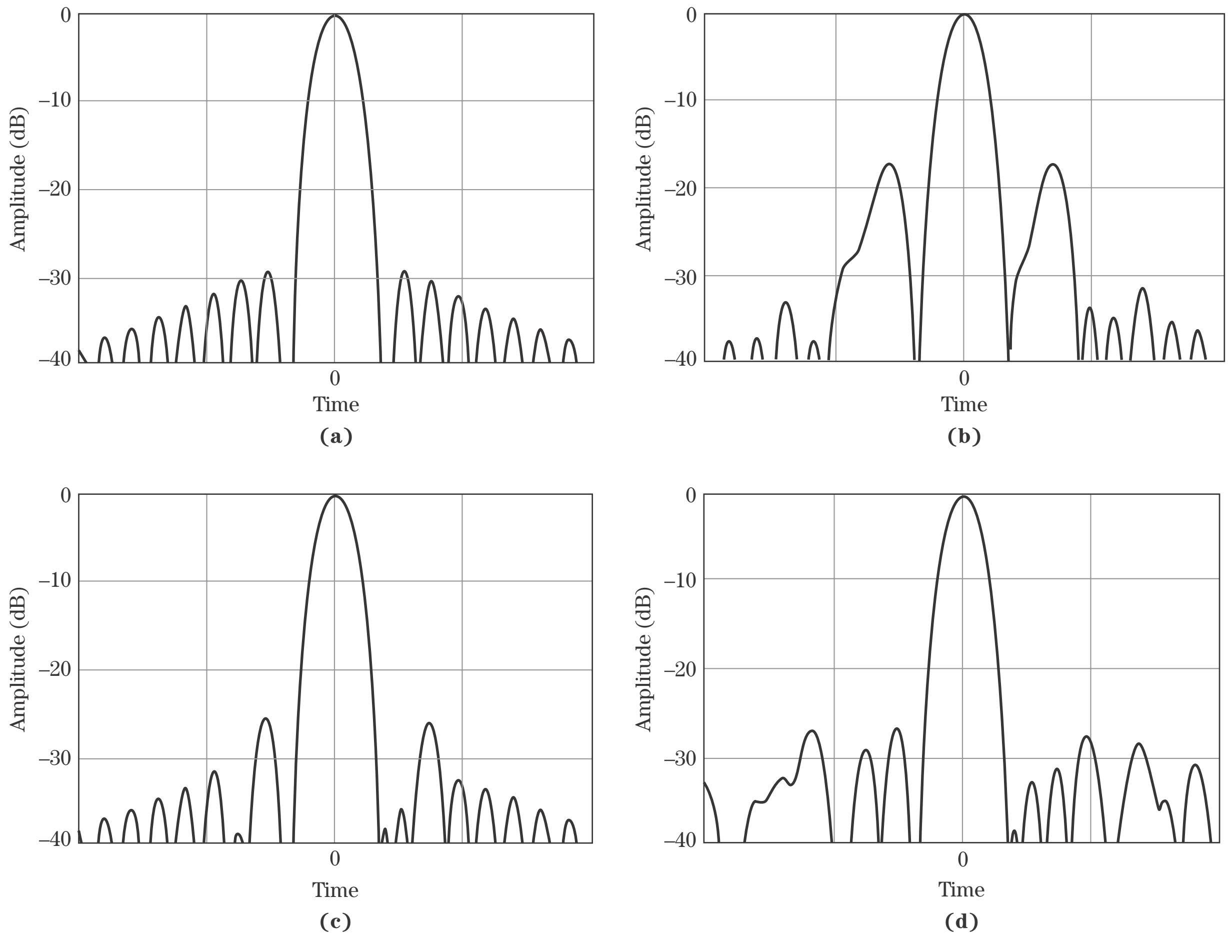


FIGURE 10-29 ■ Time sidelobe response with intrapulse modulation errors. (a) Idealized response with no intrapulse modulation error. (b) 3 cycles of 10 degrees rms sinusoidal modulation error. (c) 3 cycles of 2 degrees rms sinusoidal modulation error. (d) 10 degrees random modulation error.

power supply pushing and main signal excitation. Such independent error components will not experience the array factor gain since they will not add coherently.) They will appear as higher spurious modulation in the sidelobes of the array antenna pattern, but not in the main beam [35]. Spurious modulation that is correlated across the array achieves the same antenna directivity as the desired signal. Some examples include transmitter exciter/local oscillator phase noise, effects of power supply ripple, and noise that is common to all the elements. Generally effects with a given correlation interval (e.g., number of affected elements) will experience the spatial gain of that set of elements.

10.6.2.2 Nontime-Varying Errors

In pulse compression systems using LFM waveforms, variations in insertion phase and output power through an amplifier as a function of frequency produce range sidelobe degradation. The amount of degradation and range sidelobe spacing depends on the magnitude and spectral content of the phase and amplitude variations and follows *paired echo*

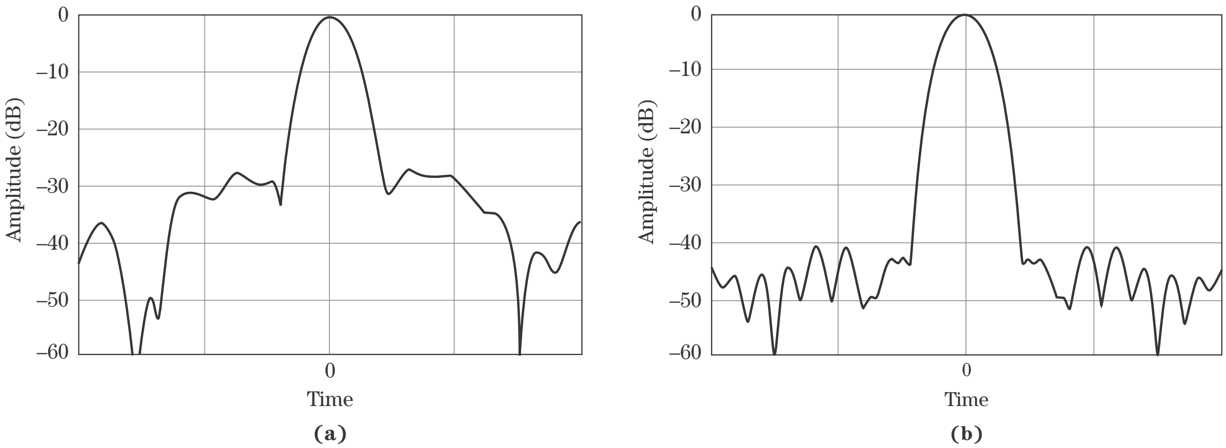


FIGURE 10-30 ■ (a) Range sidelobe response prior to TWT phase equalization. (b) Range sidelobe response after TWT phase equalization.

theory [36], which states that the stronger the modulation, the higher the sidelobes. Device nonlinearities can be viewed as mapping a complex error waveform on top of the ideal LFM waveform. Fourier analysis can be used to decompose the error waveform into individual sinusoidal terms. To some extent such errors can be corrected by means of phase equalization, which is commonly done externally for wideband TWTs or measured and corrected via predistortion in the transmitter exciter or through digital processing in the signal processor.

Figure 10-30a is processed data that show the wideband range sidelobe limitations of a high-power TWT amplifier. After correcting only for phase errors (not amplitude), these sidelobes can be brought down as in Figure 10-30b to the level inherent in the pulse compression technique that would exist even if the power supply subsystem were perfect and introduced no additive spurious signals or noise.

10.7 OPERATIONAL CONSIDERATIONS

Once a transmitter design has been optimized for a given application, the actual lifetime of the transmitter and the radar system itself will be dependent on the way the system is operated. The lifetime of the transmitter will be maximized by operating the transmitter within the tube or amplifier manufacturer's specified parameters. One of the major issues that affect transmitter reliability is overheating of the high-power components. Consequently, the radar designer must understand cooling requirements for transmitters. Safety issues must also be addressed during transmitter design.

10.7.1 Transmitter Reliability

A reliable radar is one that is available when it is needed other than scheduled down time due to, for instance, maintenance or system checks. Reliability implies that the transmitter and its critical components should have a long MTBF. The transmitter is typically the primary concern in determining radar reliability because the receiver processes radar signals at very low power levels, whereas the transmitter generates and processes signals at very high power levels or high voltage or current levels, causing high temperatures that

stress components and subassemblies. These high voltages and currents also often exist in the power supply and the modulator. Thus, making an accurate estimate of the reliability and life time of a radar transmitter will depend on the voltage, current, and power levels in the transmitter subsystems; the materials used in component construction; and the way the transmitter is operated. In addition, there are some distinctive traits of both tube-based and solid-state transmitters that affect reliability estimates.

Tubes are thermionic sources; the cathode operates at a high temperature. The expected lifetime of the electron gun design is determined by the cathode operating temperature, current density, and materials [2]. As a general rule, high-power ground-based tubes are designed with expected lifetimes on the order of 10,000 hours to 40,000 hours. However, it is possible to operate properly designed and constructed tubes for much longer periods of time. In one example, a klystron in operation in a ballistic missile early warning system (BMEWS) was still operating after 30 years, or 240,000 hours [37]. Tubes designed to operate on spaceborne platforms are highly derated to allow anticipated lifetimes of hundreds of thousands of hours. Such tubes (typically TWTs) are also designed with multiple collector stages to greatly improve efficiency and reduce prime power requirements. For more detailed information on tube reliability, see chapter 18 of Gilmour [11].

The limiting component in a tube-based, high-power transmitter may not be the tube itself, however. There will be many components with high voltage/high thermal stresses, and, if not carefully designed with adequate margin, faults can occur at multiple locations. Protective circuits must be included in the design to ensure that a fault in one location does not avalanche and cause faults at other locations in the circuit. For instance, in the event of an arc in the output waveguide system, RF must be inhibited quickly, and the tube should be turned off. Temperature sensors should be employed to remove power from the tube if temperatures become excessive. Key voltages and currents should be monitored and power shut down if they fall outside of normal ranges. Properly designed interlock circuits can help extend transmitter life expectancy by reducing tube failures that are caused by power supply or waveguide system faults.

T/R modules can be highly reliable (hundreds of thousands of hours) and solid-state systems can benefit from graceful degradation, whereby some percentage of modules can fail yet the radar can still operate. Sensitivity degrades with such failures, although sidelobe levels degrade at a faster rate (see Chapter 9). As with tube-based systems, however, in many cases the reliability-limiting components or subsystems may not be power amplifiers or oscillators themselves but instead may be the supporting subsystems, such as the power supplies. Power supplies for solid-state systems must usually provide very high current levels, which can result in severe thermal stresses on critical components. Even if the T/R modules themselves are highly reliable, if the power supply feeding the modules fails that subset of modules is effectively removed from the system. Power supplies can be interconnected or bussed together to provide redundancy, at the cost of complications to the design. The larger the number of modules fed by an individual power supply, the larger the effect on radar sensitivity and sidelobe levels from the failure of that power supply. The same argument holds for any subsystem on which a group of T/R modules depends, such as a driver amplifier at the subarray level in a phased array antenna.

10.7.2 Transmitter Cooling

One of the criteria for the radar designer is to make the system as efficient as possible. Losses occur at all stages of the process where prime power is turned into RF energy that

is to be radiated toward the target. These losses are usually manifested as heat, which further reduces efficiency, since additional effort must be expended to eliminate the heat and prevent it from damaging or destroying the radar. Thus, cooling the components in a radar system, especially those comprising the transmitter, is paramount to ensuring the reliability of the system.

Removing heat from the radar system is typically accomplished in one of three ways: (1) through normal air-convection currents; (2) through forced-air cooling; or (3) through liquid cooling. Cooling by normal air-convection currents is suitable for low-power radar systems, such as the "speed guns" used by law enforcement agencies. At the other extreme of a high-power microwave transmitter, the cooling system may need to dissipate as much as 70% of the input AC power in the form of waste heat. In these cases, a liquid cooled system is the only way to remove the large quantities of heat generated. In all cases, the manufacturer's specification will determine how much heat must be removed from the RF source, be it solid-state or vacuum tube.

Temperature control is important for microwave tube operation because the properties of the materials used to construct the tube will change as the temperature increases. For instance, electrical resistivity usually decreases as temperature increases, while the dielectric constant of several common tube materials increases as temperature increases. From a reliability standpoint, one of the most common failure points in tubes due to high temperatures is the metal-to-glass or metal-to-ceramic interface or seals in the tube. Above 250°C the seals can begin to deteriorate [38]. To prevent damage to the radar system, temperature monitors should be incorporated into key areas of the transmitter, including air or water inlets and outlets, near vacuum tubes, and also close to other power dissipating components such as transformers and loads.

10.7.3 Safety Issues

An important operational consideration is the safety of the personnel operating the radar system. In any system employing high voltages and currents there are the usual dangers associated with accidental electrocution. Because of this, high-power radar systems are designed with electrical interlocks to minimize danger to operations and maintenance personnel. These are often in addition to those used to provide overvoltage and overcurrent protection for the major subsystems of the radar, such as the power supply and the power amplifier.

Another potential hazard caused by high voltages and currents is the production of x-rays, which occurs when the electrons produced by a hot cathode are accelerated by a high voltage to impact on a metal anode within a vacuum tube. Because of cooling considerations, the usual anode material for high-power microwave tubes is copper. This leads to x-ray spectral lines at wavelengths of 0.139222 nm, 0.138109 nm, 0.154056 nm, and 0.154439 nm [39].

The maximum energy of the x-ray photons produced is determined by the energy of the incident electron, which is equal to the voltage on the tube. Thus, a 100 kV tube can create x-rays with energies up to 100 keV. For comparison, the voltages used in typical diagnostic x-ray tubes, and thus the highest energies of the x-rays, range from 20 to 150 kV. Higher-energy x-ray achieve greater penetration and therefore require more shielding to protect operators from the x-rays generated. For instance, a tube with a maximum voltage of 100 kV will require a minimum of 1.5 mm of lead to stop the x-rays that may be generated at that voltage [40].

Another safety issue arises from the fact that many high power vacuum tubes incorporate hazardous materials. Depending on the type of tube and the construction approach, the tubes may incorporate such materials as beryllium oxide (BeO) and antimony (Sb) as well as alkali materials such as potassium (K), cesium (Cs), and sodium (Na). As all of these are toxic, care must be exercised when working with the tubes so that personnel are not accidentally exposed to these materials, and they must be disposed of in a safe manner consistent with environmental regulations for hazardous materials.

Finally, there are the safety issues associated with the high RF power levels generated by the radar system. The specific concerns depend on the radar configuration and location. As an example, radar systems located on naval vessels must take into consideration the presence of personnel, ordinance, and other materials that absorb RF radiation. During on-loading or off-loading of ammunition, there is a danger that RF electromagnetic fields could accidentally activate electro-explosive devices (EEDs) or electrically initiated ordnance. This is a very real hazard to the ordnance, the ship, and the crew. Several occasions have been recorded when vessels of the U.S. Navy suffered severe damage due to RF radiation triggering explosions of ordnance aboard the vessels.

Several effects due to RF radiation have been observed in personnel. Some, such as the formation of cataracts at 10 GHz, are frequency dependent. The most common effect observed is tissue heating due to absorption of RF energy. Safe limits for RF exposures of personnel are based on the power density of the radiation beam and exposure time of the person being radiated. A common measure of this heating effect is known as the *specific absorption rate* (SAR) [41]. The SAR is related to the electric field at a point by the expression

$$SAR = \frac{\sigma |E|^2}{\rho} \tag{10.4}$$

where

σ = conductivity of the tissue (S/m).

ρ = mass density of the tissue (kg/m^3).

$|E|$ = rms electric field strength (V/m).

Acceptable limits on the SAR, which apply for many types of RF devices including cell phones and mobile radios, are given in ANSI/IEEE C95.1 [42] for the United States and in the International Commission on Non-Ionizing Radiation Protection [43] for Europe and most of the rest of the world.

Finally, voltages of enough potential to cause an RF burn can be induced on metallic items, such as railings or fences, that are near radar-transmitting antennas. However, there must be actual physical contact for the burn to occur. This contact can be prevented by ensuring that warning signs are properly placed to keep people away from locations where such voltages can be induced.

10.8 SUMMARY AND FUTURE TRENDS

This chapter has described radar transmitters as an integral subsystem of pulsed, pulsed compression, and active phased array radars. The transmitter consists of an RF power amplifier or high-power oscillator, a modulator, and a power supply. In addition to the technology descriptions, several transmitter system issues were discussed, including

transmitter configurations, impacts on the electromagnetic environment, and operational considerations.

The technology linked to radar has evolved over many years. For example, the magnetron microwave cross-field oscillator tube used today in many low-cost ship radars was invented in 1921 by A. W. Hull [44]. The klystron amplifier was described as early as 1939 [5]. The traveling-wave tube was invented in the 1942–1943 time frame. All of these tube types (now commonly referred to as VEDs) have been improved over time for higher efficiency, improved reliability, wider bandwidth, and higher output powers. By comparison, solid-state microwave power RF amplifiers are relatively recent developments. The first commercially available GaAs MESFET X-band (10 GHz) amplifiers with good performance emerged in the 1970s [45].

Future conventional radars will certainly take advantage of the continuing evolution of high-power VEDs such as klystron amplifiers, traveling-wave tubes, and magnetrons. However, future radar systems employing active electronically scanned array antennas [46] will make increasing use of sophisticated digital hardware and software coupled with state-of-the-art solid-state RF amplifier and switching hardware. High-power solid-state switches will permit the increasing use of active-switch modulators. The crowbar circuits that are necessary to protect transmitter components during arc overs but are a major source of radar failure will be a thing of the past. Next-generation high-efficiency GaN-based power amplifiers [47,48] will be available for AESA applications.

10.9 FURTHER READING

There are relatively few texts dedicated to radar transmitter technology. The text by Ewell [13] is very focused and contains a great deal of detailed design information. Ostroff et al. [49] focused on solid-state transmitters in their work. An excellent treatment of microwave power tubes, along with some good historical context, can be found in Gilmour's work [2,11].

There are considerably more individual papers on various subjects than complete texts. Examples of conferences that are good sources for radar transmitter literature are the Microwave Power Tube Conference and the IEEE Power Modulator Symposia. The primary journals for published research on radar transmitters are the *IEEE Transactions on Aerospace and Electronic Systems* (*AESS*) and the *IEEE Transactions on Microwave Theory and Techniques* (*MTT*).

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10.11 PROBLEMS

1. A 95 GHz oscillator tube (extended interaction klystron oscillator) is operated at a beam voltage of 21 kV. The modulation sensitivity of the tube is 0.2 MHz/volt, and the high-voltage power supply has 0.3% peak ripple during the pulse. How much FM is caused at the RF output by the power supply ripple? What must the ripple be to keep this FM down to 1 MHz?
2. A power amplifier tube has a small signal gain of 50 dB, noise figure of 40 dB, output power of 10 kW, and 500 MHz of bandwidth. With no input RF but with beam current flowing, how much noise will be produced by the tube in dBm/MHz? What will the total noise power output be in dBm? (Hint: Thermal noise power $= kT = -114$ dBm/MHz (at 290 K). Input tube noise per MHz $= (F - 1)kT$, where $k =$ Boltzmann's constant $= 1.3807 \times 10^{-23}$ Joules/K, $T =$ temperature in K, and $F =$ noise figure.)
3. A radar needs a power amplifier for a transmitter with the following characteristics: 50 kW peak power output, 5 kW average power output, 10% bandwidth, 5 W drive power available. What type of transmitter tube would be a suitable choice? Explain why.
4. A noncoherent search radar needs a transmitter tube with the following characteristics: 250 kW peak power, 1 μs pulse width, 2,000 Hz PRF. Cost is a major consideration. What type of transmitter tube would be a suitable choice, and explain why. What type of modulator configuration might be used?
5. A solid-state module has an output spectral purity requirement of −100 dBc of additive spurious noise. If the drain voltage and gate voltage sensitivities of the power amplifiers are 1 degree/volt and 100 degrees/volt, respectively, what are the voltage ripple requirements at the power amplifiers? Assume power amplifier additive noise is the dominant component, and budget for equal contribution from gate voltage and drain voltage ripple/noise.
6. A solid-state amplifier is operated at a drain voltage of 10 V. During transmit, the voltage ripple on that voltage is 100 mV peak (one-way, not peak to peak) concentrated at a sinusoidal ripple frequency of 1 MHz (since it is created by a 1 MHz resonant power converter). The amplifier drain voltage phase sensitivity is 1 degree/V. What is the approximate sideband amplitude relative to the carrier due to this voltage ripple?
7. This same solid-state amplifier also has a gate voltage sensitivity of 200 degrees per volt. The 10 V to the T/R module is regulated down to provide the gate voltage, reducing the ripple to 0.1 mV. What is the approximate sideband amplitude relative to the carrier due to this voltage ripple?
8. A TWT amplifier has the following electrode sensitivities: cathode voltage −0.1 deg/V, grid-cathode voltage of 0.2 deg/V, and collector voltage −0.01 deg/V. The nominal voltages applied are −30 kV (cathode), 10 kV (collector with respect to the cathode), and 1 kV (grid

with respect to cathode). What does the power supply ripple and noise need to be kept to maintain −75 dBc spurious additive noise? Allocate one-half of the total noise contribution to the cathode voltage and the remaining noise equally split between the remaining two voltages.

9. A radar uses a transmitter with a 5,000 W TWT amplifier operating at a transmit duty cycle of 10%. The cathode current is 1 A peak, the body current is 100 mA peak, the cathode voltage is –30 kV, and the collector voltage is 10 kV with respect to cathode. The collector can also be operated at ground if a separate power supply is not available. Calculate the prime power required for both the depressed collector and nondepressed collector configurations assuming an AC/DC conversion efficiency of 80% for the high voltage power supplies. What is the overall transmitter/power supply combined efficiency for both?

10. For the TWT described in problem 9, recalculate the prime power required if the AC/DC conversion efficiency is increased from 80% to 85% for both modes. Compare the results.

11. A MESFET microwave power transistor has a phase sensitivity of 10 deg/volt of bias change. The DC power supply peak ripple voltage is 100 mV. Calculate the spurious sideband amplitude expressed in dBc.

12. Which of the following statements are true regarding solid-state arrays versus tube-based arrays?

a. Solid-state arrays result in elimination of high-power waveguides.

b. Solid-state arrays generally result in lower antenna ohmic losses that have to be accounted for in radar sensitivity budgets.

c. Tube-based arrays don't degrade as gracefully as solid-state arrays (as a function of component failures).

d. Solid-state arrays eliminate some of the high-voltage and x-ray concerns associated with tube transmitters.

e. All of the above.

13. An X-band ($\lambda = 3$ cm) T/R module uses a power amplifier that exhibits a power added efficiency on transmit of nominally 33% over a peak output power range from 0.1 W to 10 W at 20% transmit duty cycle. In the transmit mode the module also requires 250 mW of DC power to power the background control electronics. In the receive mode the module requires 500 mW of DC power, including background control electronics. A radar is required to have a power-aperture-gain product of 80 dBWm^2. Assume nominally 4,000 elements per square meter as an element density to satisfy scan volume requirements. Tabulate and plot the DC prime power required by the array for peak module powers from 0.1 W to 10 W and examine the results.

14. For the module and radar of problem 13, what module power should be used to minimize the array aperture area? What would be the array area and number of elements?

15. Which of the following are typically measured to characterize the performance of a high-power transmitter? Choose all that apply.

a. Peak and average power.

b. Dynamic range.

c. Output harmonics.

d. AM/PM conversion.

e. All of the above.

16. Which of the following are true statements with respect to the use of solid-state modules for a phased array antenna versus a power tube-type transmitter?

a. Each module has a low-power phase shifter.

b. The solid-state active aperture array exhibits graceful degradation.

c. The solid-state active aperture array will have lower acquisition cost.

d. The solid-state active aperture array will have higher ohmic losses, reducing effective radiated power and increasing noise temperature.

e. All of the above.