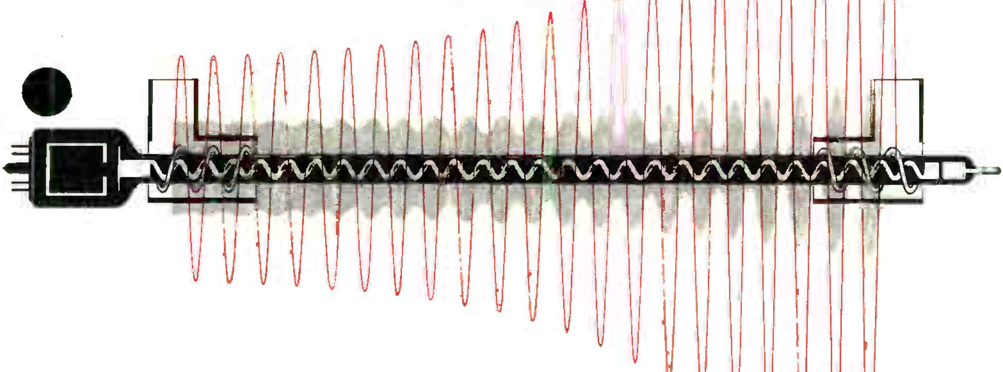
The Lenkurt Demodulator

VOL. 14, NO. 8 AUGUST, 1965

Introduction to the TRAVELING WAVE TUBE



Over the past years there has been an increasing demand for wideband communications services, such as video and high-speed data, using microwave radio facilities. Early microwave amplifiers, however, were not capable of providing bandwidths greater than about 1 percent of the operating or center frequency. A broadband high-gain microwave amplifier, therefore, was seriously needed. To fulfill this need, a microwave tube was developed that provided high gain over bandwidths greater than 10 percent of the operating frequency. This remarkable device became known as the traveling wave tube.

This article briefly describes how a traveling wave tube works and discusses some of its important operating characteristics.

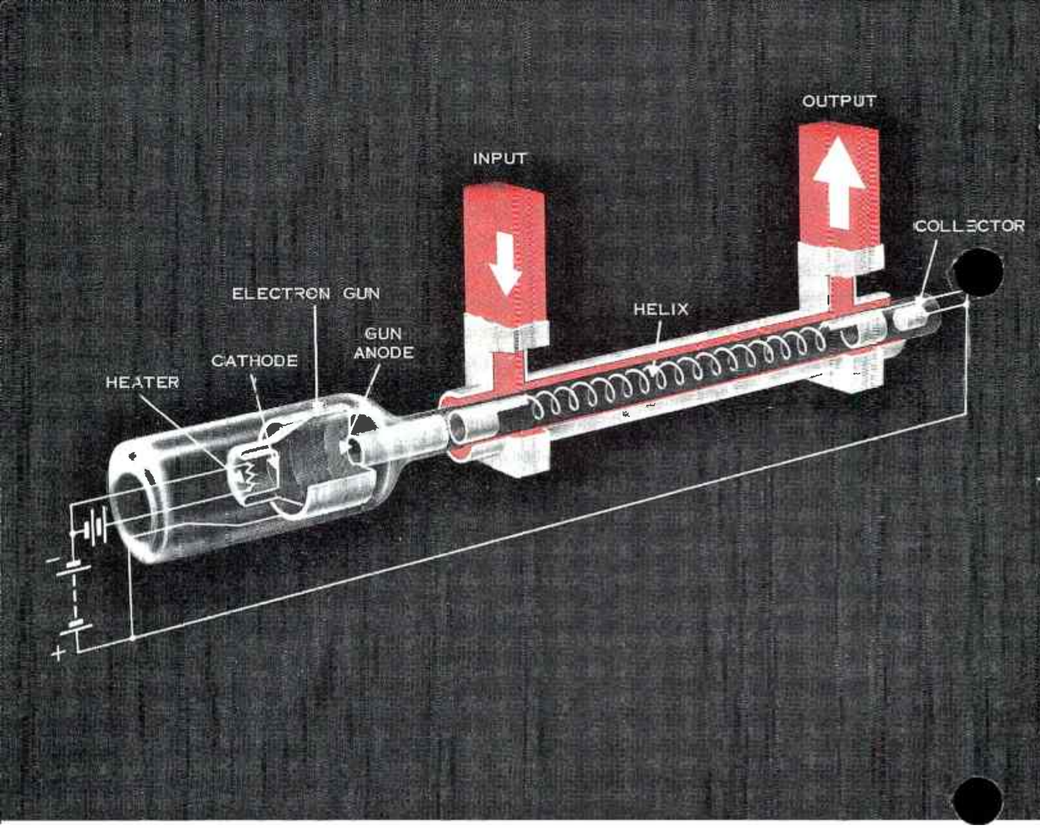


Figure 1. Construction of a typical traveling wave tube, showing the electron gun, the helix, and the collector.

The ever-increasing demand for more and more communications services soon crowds the available radio frequency bands. To acquire more radio channels, it has been necessary over the years to develop communications equipment capable of operating at higher and higher frequencies. Such progress upwards within the radio frequency spectrum was carried out successfully using so-called conventional electron devices — until the microwave region was reached. Here, things changed.

Conventional electron tubes, for example, cannot operate satisfactorily at frequencies above a few hundred megacycles. The most serious limitation of these tubes at higher frequencies is caused by a phenomenon known as the *transit time effect*. This phenomenon occurs when the period of one cycle of a signal applied to the control grid of such a tube is *less* than the time it takes an electron to travel from the cathode to the plate. When this happens, the voltage of the alternating signal applied to the control grid may completely reverse itself before the electrons in transit have had time to reach the plate. As a result, these electrons are not able to follow the signal variations exactly. This, of course, distorts the signal at the output of the tube, and also decreases gain.

Some method of controlling the flow of electrons had to be devised that could overcome the transit time limitation of ordinary electron tubes. Oddly enough, the first electron tubes that were developed to generate and handle microwave frequencies actually made use of the transit time effect. These tubes, known as klystrons, became quite successful primarily as oscillators, but are also capable of providing considerable gain at microwave frequencies. Unfortunately klystrons are inherently narrow-band resonant devices having a useful bandwidth of only tens of megacycles. However, they were the beginning of a family of microwave electron tubes which also includes the magnetron. Later, a very useful device known as the *traveling wave tube* (TWT) was added to this family. Traveling wave tubes are non-resonant devices and proved to be capable of amplifying microwave signals with enormous bandwidths.

The traveling wave tube was invented in England in 1943 and first used in a television relay link which began operating in March, 1952. Since then, it has found wide application in communications systems, primarily because of its broad bandwidth capability.

Description

The construction of a traveling wave tube is relatively simple. It consists essentially of an *electron gun,* a wire *helix,* usually encased in a glass envelope, and a *collector*, as shown in Figure 1. The electron gun, attached to one end of the helix, produces a focused beam of electrons which are directed through the center of the helix. The helix is simply a wire conductor that has been formed into a uniform spiral in order to slow down the forward progress of an RF signal fed into the tube for amplification. The collector, attached to the opposite end of the helix, is an electrode which receives the spent electrons that have traveled through the tube.

The focused electrons emanating from the gun are held in a tight beam usually by some type of magnetic field

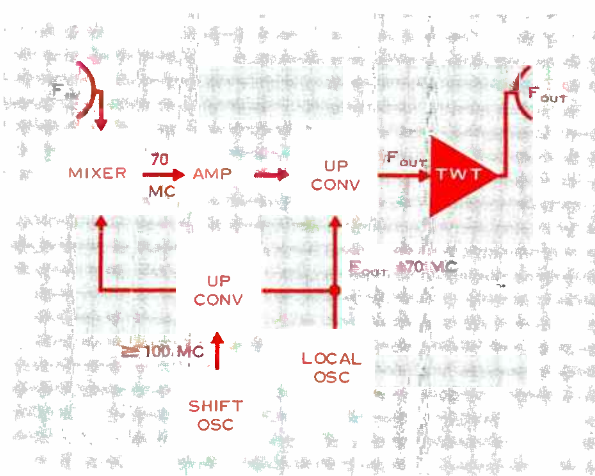


Figure 2. Circuit diagram of a typical I-F heterodyne repeater using a traveling wave tube.

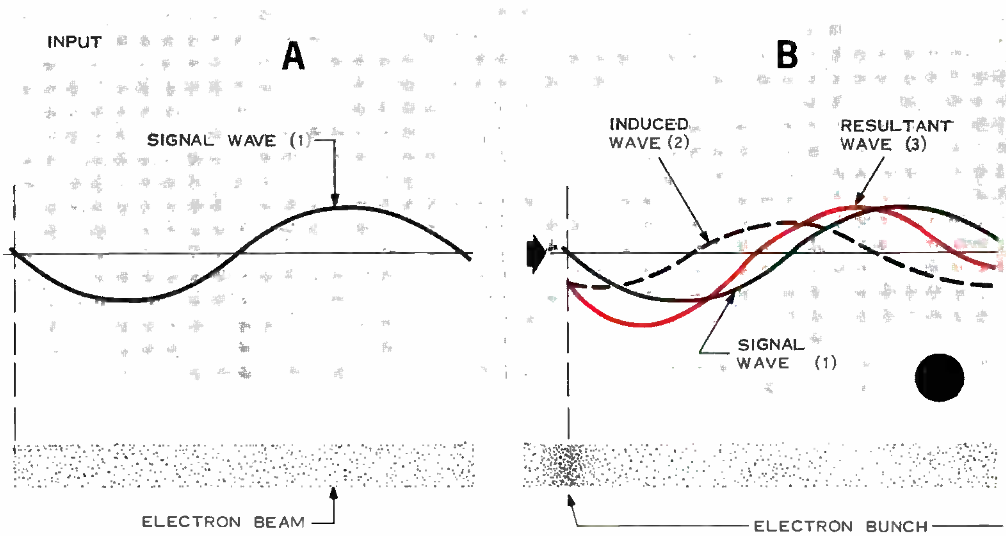
surrounding the helix. There are several methods used to prevent the beam from spreading, such as the electrostatic method, the electromagnetic method, and the periodic permanent magnet method. The periodic permanent magnet method is used most commonly in traveling wave tubes. In this method, permanent magnets are arranged in some periodic manner along the length of the tube.

How It Works

When an electron is in motion, it has a certain amount of kinetic energy. Increasing the velocity of the electron increases its energy, while decreasing its velocity decreases its energy. The energy given up by an electron whose velocity has been decreased *must go somewhere*. This basic principle underlies the operation of the traveling wave tube amplifier.

Operation of the traveling wave tube is similar to other types of microwave tubes in that the transfer of power from a direct current source to an RF signal is accomplished by *velocity modulating* a beam of electrons. This type of modulation causes the electrons in the beam to form into periodic groups or *bunches*. To accomplish this bunching, some electrons in the beam are accelerated while others are slowed down or retarded. If more electrons are retarded than are accelerated, the excess kinetic energy given up by the retarding electrons is transferred to the modulating RF signal. The bunching of the beam electrons by the modulating signal and the transfer of energy from the retarding electrons to the signal is called *interaction*. Interaction in a traveling wave tube is continuous and cumulative and is the basis for amplification.

The electron beam in a traveling wave tube is generated in the same manner as the electron beam in a typical cathode ray tube. Electrons are emitted from an indirectly heated cathode, controlled and initially focused by a grid, and accelerated by the electron gun



anode. As they leave the anode, the density of the electrons is uniform. The beam electrons are accelerated, by a positive voltage potential on the helix, to a velocity U_0, which is proportional to the square root of the helix voltage, V, as shown in the following equation.

$$U_0 = 5.93 \times 10^5 \sqrt{V} \text{ meters/second} \qquad (1)$$

This equation assumes that the initial electron velocity is zero and the relationship is, therefore, approximate.

The signal to be amplified by the tube is coupled into the gun end of the helix. This RF signal travels as a surface wave around the turns of the helix, toward the collector, at about the velocity of light. The forward or axial velocity of the signal is slower, of course, because of the pitch and diameter of the helix. This forward movement of the wave is analogous to the travel of a finely threaded screw where many turns are required to drive it into position. The signal wave generates an axial electric field which travels with it along the longitudinal axis of the helix. This alternating electric field interacts or *velocity modulates* the electrons in the beam.

The relationship between the initial velocity of the beam electrons given in equation (1) and the velocity of the axial electric field is very important. In order to achieve continuous and cumulative interaction, the initial beam velocity must be slightly greater than the axial velocity of the alternating electric field.

When the electrons in the beam enter the helix they are accelerated or decelerated by the alternating electric field associated with the RF signal wave. Electrons acted upon by a positive electric field take energy from the field, and therefore, are accelerated. Electrons acted upon by a negative electric field give up energy to the field and, therefore, are decelerated or retarded. Since the initial velocity of the beam electrons is slightly greater than the axial velocity

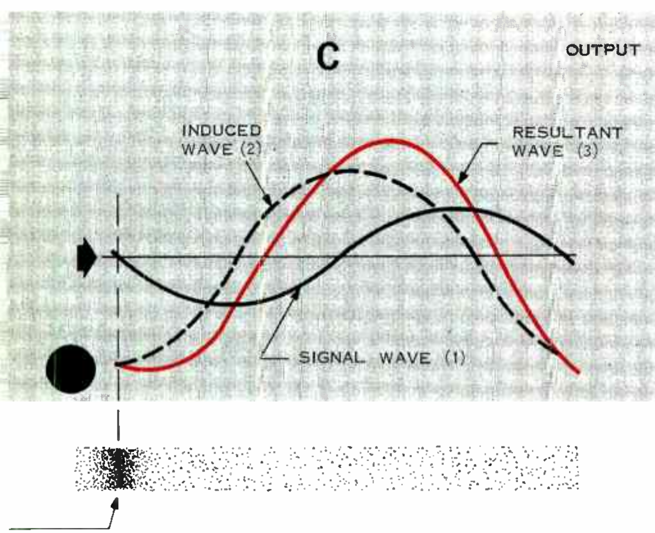


Figure 3. As the signal wave travels down the tube, electron bunches induce a second wave on the helix. The resultant of the signal wave and the growing induced wave increases exponentially.

of the electric field, more electrons are retarded than are accelerated. This means that more energy is transferred to the field than it gives up. Because this interaction is continuous and cumulative, the amplitude of the RF signal wave *grows* as it travels down the helix.

Consider a group of beam electrons that have just entered the helix in the presence of a signal wave (1) as shown in Figure 3A. Electrons at the point of zero field intensity are neither accelerated nor retarded. However, electrons just to the left of the zero point are accelerated by the positive electric field and therefore catch up with the electrons at the zero point. Electrons just beyond the zero point are retarded by the negative electric field and are overtaken by the electrons nearer the zero point. As shown in Figure 3B, this action causes the electrons to become more and more dense at the point of zero field strength, as they travel down the tube.

The electrons in this dense bunch induce a second wave (2) on the helix. This second wave produces an associated axial electric field that lags behind the first electric field by a quarter wavelength. As the electron bunch travels down the tube it accumulates more and more retarding electrons which are giving off energy. As more retarding electrons are accumulated, the amount of energy transferred to the induced wave increases, thereby causing it to *grow* in amplitude. The resultant wave (3) caused by the addition of the signal wave (1) and the growing wave (2) increases in amplitude exponentially as it travels down the helix until it reaches the output of the tube, as shown in Figure 3C.

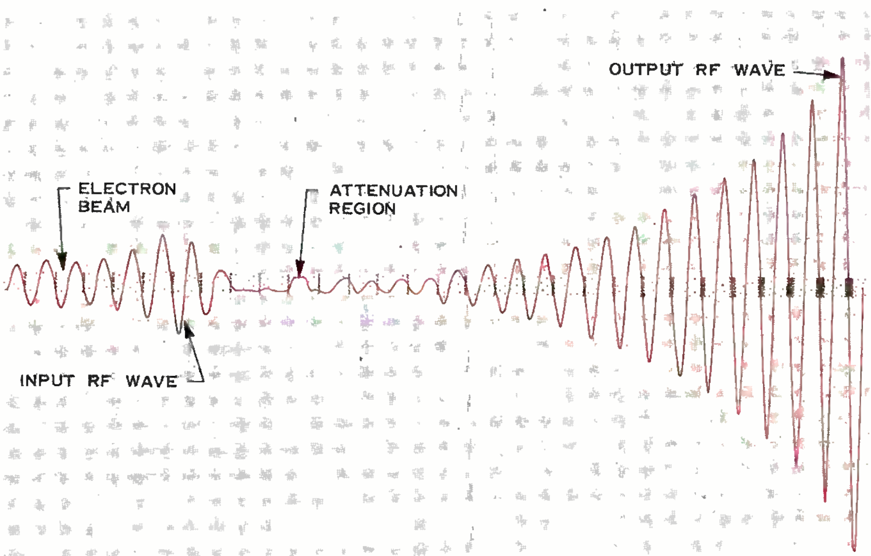


Figure 4. The growing signal wave is reduced by the attenuator but reappears at the output of the attenuator and begins to grow again.

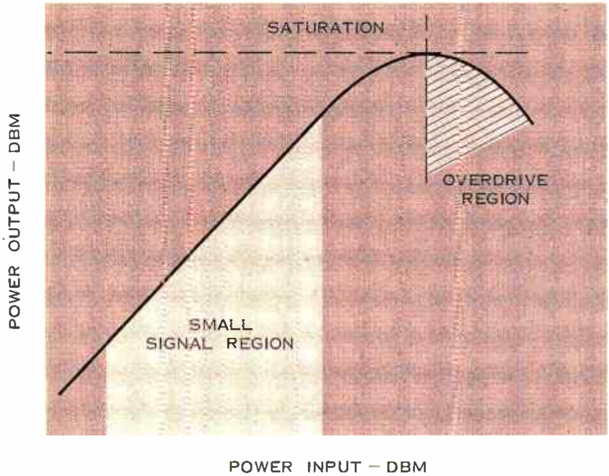


Figure 5. Power output vs. power input.

The net effect of this cumulative interaction is to reduce the *average* velocity of the electrons in the beam. The kinetic energy, given up by this reduction in electron velocity is transferred to the signal wave. Thus, amplification has occurred through the interchange of energy from an electron beam to an RF wave.

It is necessary to attenuate reflected waves on the helix to prevent spurious oscillations. This is accomplished by placing an attenuator between the gun-end and the collector of the helix. In ordinary low-power tubes, the attenuator consists of a resistive material that is sprayed around the helix.

The attenuator reduces the waves on the helix to practically zero while the electron bunches are essentially unaffected. When the electron bunches emerge from the attenuator, the waves begin their growing process all over again.

Wave Analysis

A mathematical analysis of the wave propagation along the helix of a traveling wave tube results in the following equation for the instantaneous axial component, E_z, of the electric field strength.

$$E_z = E_{max} (\cos\beta_p) (U_p t - z) \qquad (2)$$

where

E_{max} = *the crest value of the wave*
β_p = *the axial phase shift*
U_p = *the axial wave velocity*
t = *time in seconds*
z = *the distance along the helix at any instant*

When an electron passes through an electric field, a force, F, is exerted on the electron that is equal to the electric field strength, E, times the electron charge, e.

$$F = Ee \text{ newtons} \qquad (3)$$

The electric field strength exerts a sinusoidal force on the electrons within the beam. Since the electrons are free to respond to this force, their velocity will fluctuate sinusoidally. The magnitude of this sinusoidal velocity fluctuation, $|U_e|$, is

$$|U_e| = \frac{1.76 \times 10^{11} E_{max}}{\beta_p} \times \frac{1}{(U_p - U_o)}$$
meters/second (4)

The axial wave velocity, U_p, is fixed by the helix while the initial beam velocity, U_0, is proportional to the helix voltage as shown in equation (1). The quantity $|Ue|$ is a measure of the *perturbation* of the electron velocity by the wave and, therefore, gives an indication of the kinetic energy that is available for transfer to the signal wave. For maximum perturbation, hence maximum energy available, the *average* velocity of the electrons should be approximately the same as the axial wave velocity, U_p. As stated previously, the initial velocity, U_0, of the beam electrons must be slightly greater than the axial velocity of the wave. This is necessary so that the beam electrons can give up more energy than they receive and still have an average velocity approximately the same as the axial wave velocity.

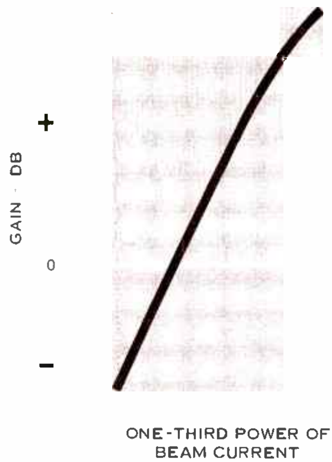


Figure 7. Gain vs. beam current.

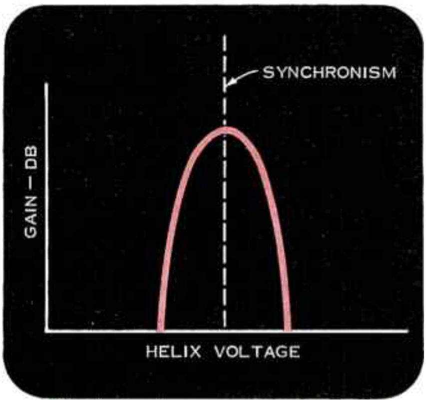


Figure 6. Gain vs. helix voltage.

The signal wave will grow exponentially when the traveling wave tube is operating in what is known as its *small signal region*. However, a point of maximum net energy transfer, called *saturation*, is eventually reached. This point is determined essentially by the dc operating parameters of the tube. Beyond the saturation point, the gain of the tube begins to decrease. Here the tube is operating in a condition or region known as *overdrive*. The small signal region, the saturation point, and the overdrive region, representing the dynamic characteristics of a traveling wave tube, are shown in Figure 5. Traveling wave tube amplifiers are operated, of course, somewhere in the small signal region.

Gain and Output Power

Gain and output power of a traveling wave tube are a function of the helix voltage and beam current. A particular helix voltage will synchronize the electron velocity with the phase velocity of the signal wave. During synchronization, interaction efficiency is at its highest and maximum gain is obtained. If the helix voltage varies from this point of synchronization, the gain decreases as shown by the curve in Figure 6. Operation above synchronous voltage extends the small signal region and increases the available output power at the expense of gain.

The gain at any frequency is essentially a function of the one-third power of the beam current and decreases as beam current is decreased, as shown in Figure 7. By operating the grid of a traveling wave tube more and more negatively with respect to the cathode, a point is reached where the gain of the tube becomes negative and it acts like an attenuator. At higher current levels, gain, saturation power, and power in overdrive all increase. The electrical and thermal characteristics of a particular traveling wave tube tend to limit the allowable beam current. Like any electronic device, traveling wave tubes are designed to operate below certain limits of input power. Operating a tube above these limits almost always degrades its performance.

Traveling wave tubes achieve gains ranging from 10 to 60 db, with continuous wave (cw) output powers above 1 kilowatt using an ordinary helix.

AM/PM Conversion

When the RF signal applied to a traveling wave tube approaches a high value of amplification near the saturation region, the average beam velocity decreases making the circuit appear *longer* to the beam electrons. The result is that the electrical length of the helix becomes proportional to the RF energy level and is indicated as a relative phase change. The mathematical slope of the RF signal level versus relative phase shift curve is a parameter called amplitude modulation/phase modulation conversion, or more commonly, AM/PM conversion. AM/PM conversion, expressed in degrees/db, is an indication of the amount of phase modulation of the RF signal contributed by the traveling wave tube. The effects of AM/PM conversion usually result in a compromise between gain, power levels, and allowable noise contributions. Traveling wave tubes used in communication systems generally are required to exhibit AM/PM conversion figures less than 2 degrees/db.

Bandwidth and Noise

The useful bandwidth of a traveling wave tube is determined by the range of frequencies over which the phase velocity of the wave is essentially constant. Bandwidth is limited at the low frequency end of the band by *dispersion* (change in phase velocity with fre-

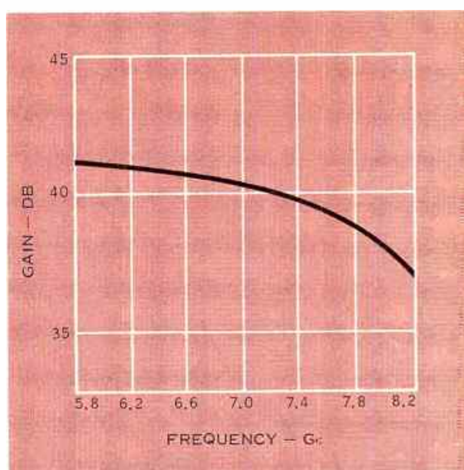


Figure 8. Typical gain vs. frequency.

quency) and at the upper end by reduction of field intensity with an increase in radial distance from axis to helix.

The flattest gain-bandwidth characteristic is obtained when the helix voltage optimizes gain at or near the high frequency end of the band. Under this condition, synchronization with the wave at the high end compensates for the radial decay of the RF field with frequency. At the same time, operation away from synchronization at midband lowers the maximum gain which occurs at the band center. These two effects work to minimize gain variation.

The bandwidth of a traveling wave tube is limited more by the input and output couplers than by the propagating characteristics of the helix itself. However, bandwidths greater than one octave have been achieved.

The types of noise associated with traveling wave tubes are *thermal noise* which is caused by random currents in the conductors, *shot noise* resulting from the random nature of emission characteristics and electron flow in the beam, and *partition noise* which develops as electrons are intercepted at grids and on the helix. Thermal noise is a function of temperature and bandwidth. Shot noise can be reduced by designing the cathode to operate at the lowest possible temperature. Partition noise is reduced by maintaining the electron beam in a tightly focused envelope.

Uneven emission from cathode surfaces can increase noise by producing a nonsymmetrical beam. Thus, as a traveling wave tube ages, it may become noisy unless the emission decreases evenly over the entire surface of the cathode. Partition noise increases when cathode emission becomes non-uniform as the tube ages and manifests itself as an increase in helix current at rated collector current. Normally, the useful

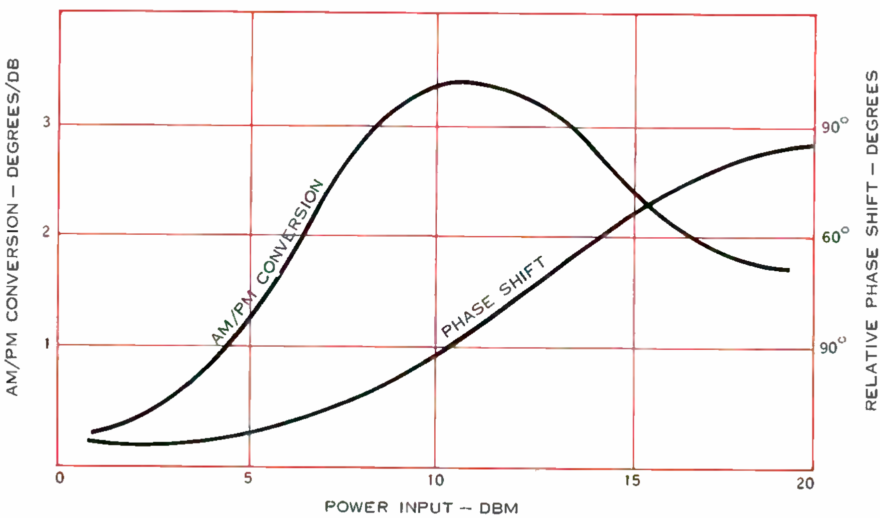


Figure 9. RF signal level vs. phase shift.

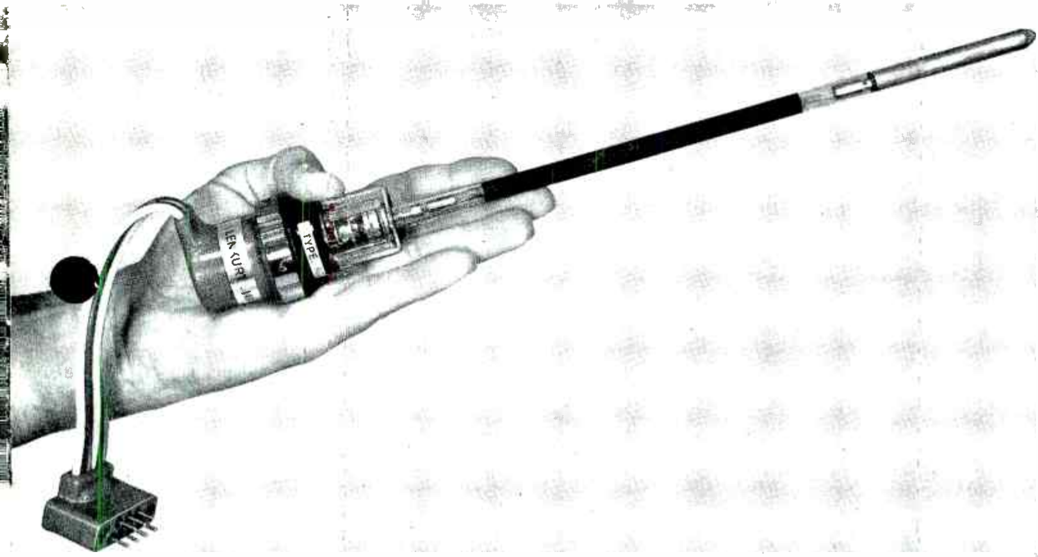


Figure 10. Photograph of typical traveling wave tube used in a microwave heterodyne repeater system. Tube operates in the 6000 megacycle band.

life of a typical communications traveling wave tube is in excess of 7500 hours.

Conclusion

The traveling wave tube is indeed a remarkable device. It overcame the bandwidth limitation of other microwave tubes and has proved to be an extremely valuable tube in modern communications systems. In fact, traveling wave tubes have been launched into space aboard certain communications satellites that are in orbit today.

Before the traveling wave tube was developed, microwave amplifiers were limited to bandwidths of about one percent of the center frequency. Traveling wave tubes have achieved bandwidths greater than 10 percent of the center frequency because of the cumulative nonresonant interaction between the electron beam and the RF signal.

This tremendous broadband feature has made the traveling wave tube especially useful in the development of *heterodyne* or non-demodulating repeaters for use in wideband transmission systems. With the expanding need for more and more wideband communications services such as high speed data and video or television, the traveling wave tube will certainly provide a significant contribution.

Lenkurt Electric Co., Inc.
San Carlos, California

Bulk Rate
U.S. Postage
Paid
San Carlos, Calif.
Permit No. 37

MR. E. A. GA[illegible]IA
CHIEF OPERATOR
% MILWAUKEE ROAD DEPOT
SAVANNA, ILL.

R-24913 6B

RETURN REQUESTED

MICROWAVE SYSTEM WITH HETERODYNE REPEATERS

Lenkurt's 75A Microwave Radio is a high performance wideband system designed for heavy-density, long-haul routes. Operating in the 6000 Mc band, the 75A handles up to 960 voice channels or a color television signal. Superior system noise performance is achieved using I-F heterodyne repeaters with traveling wave tube output amplifiers. The technical characteristics and design features of this flexible microwave radio system are described in Form 75A-P4, available on request from the Sales Promotion Manager.

The Lenkurt Demodulator is a monthly publication circulated free to individuals interested in multi-channel carrier, microwave radio systems, and allied electronic products. Permission to reproduce material from the *Demodulator* will be granted upon request. Please address all correspondence to the Editor.