APPLICATION NOTE 11

DOMESTICATING THE TRAVELING WAVE TUBE*

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Introduction

In a report[1] on the status of traveling wave tubes at the Symposium on Modern Advances in Microwave Techniques last November, Dr. Watkins of Stanford characterized traveling wave tubes as "the most advertised, least delivered tubes in electronics history". A major reason for this state of affairs has been their failure to find wide application in the electronics industry. The unique characteristic of TWT's, wide bandwidth, poses a difficult question: How can it be used? This requires careful study of the types of systems in which it will be useful and intensive development of new techniques for handling such bandwidths. Some possible directions that broadband systems may follow will be indicated later.

In this discussion of TWT's, no tubes that are new or that have improved characteristics will be considered since the new advances have been well covered elsewhere[2]. Rather, it is proposed to consider only the most ordinary of TWT's that are advertised and in commercial production now. The gain, relative bandwidth, power output and noise figure of these tubes do not differ substantially from the first tube described by Pierce and Field[3] in 1946. These are tubes with about 30 db of gain, octave frequency coverage through X band, noise figures of 20 to 30 db, and output power of 10 milliwatts to 1 watt.

This power range is well suited to the vital functions of modulation and detection so that microwave circuits may be linked with information handling video circuits. It is suitable for stable oscillator circuits comprised of either microwave oscillators or low frequency oscillators followed by a frequency multiplier chain. The level is quite suitable for most microwave measurements and some new measurement techniques become possible due to the characteristics of the TWT. The upper power limit is adequate for a large portion of the fixed path propagation links in microwave systems. After all, this is about the same power range in which most electronic tubes operate!

As to the broad frequency range of the TWT, one can either take it or leave it. If the application requires a broad bandwidth, then the TWT is without peer. On the other hand, if the application requires only a narrow bandwidth, the TWT may still be used at any point in the wide amplification band provided by the TWT. In such cases, it is often advisable to filter the output of the tube to reduce noise. The narrow band filter is in a passive transmission line for the TWT, as contrasted with the tuned circuits of klystron or space charge control tubes that are in contact with the tube electrodes. In the latter case, the amplification is quite sensitive to the tuned circuit parameters so the design and adjustments become critical.

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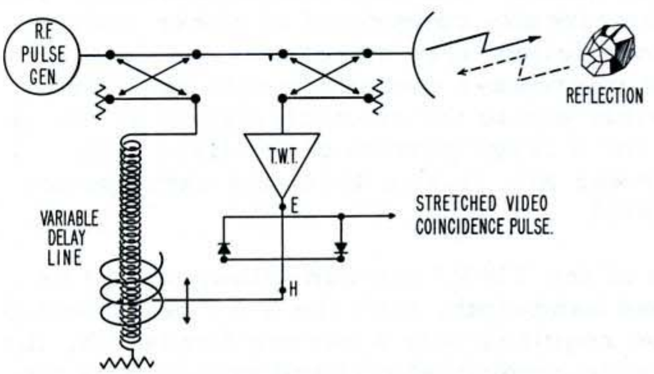
New Frontiers

One of the new frontiers that may be opened up by the bandwidth of the TWT is the transformation of video techniques and functions to the microwave domain. This would mean increasing the effective bandwidth from the tens to hundreds of megacycles now available to thousands of megacycles. This practice would increase by one to two orders of magnitude the resolution or speed of basic physical measurements, electronic measurement, communication, and computation.

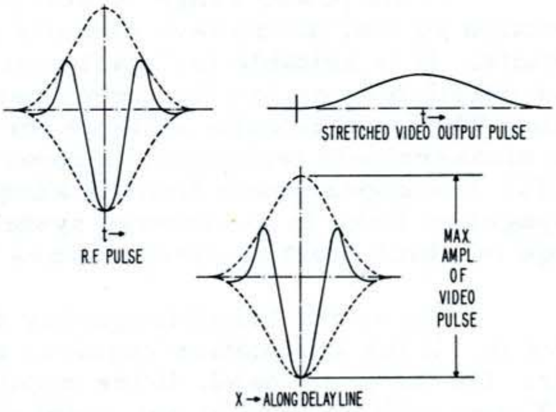
The first obstacle preventing such a transfer of video systems to microwaves is the lack of terminal devices, that is, how do we enter such a high speed elecsystem and then retrieve the new or processes information? Next, the internal functions of the microwave system, which determine the breadth of application, will demand intensive development. Such problems will require considerable effort befor very high speed microwave systems can be realized.

A.C. Beck[4] has recently demonstrated a millimicrosecond pulse system for locating waveguide faults. Another example of a very high resolution pulse echo system that could be achieved with present techniques where the resolution is determined mainly by the center rf frequency will be given. In this system a fast pulse and low phase distortion are also needed. Figure 1 is a block diagram of this type of system. The rf pulse generator, in which the rf carrier is phase locked to the repetition rate, may be of the regenerative type like Cutler's[5] if the phase precession can be eliminated or a beam deflection tube pulser[6] with a frequency multiplier and amplifier driven by the pulse repetition rate frequency and a modulator. The delayed rf pulse from the generator and the return pulse are fed into a microwave coincidence circuit which consists of a hybrid tee and a pair of crystal detectors with balanced reversed crystals. The microwave coincidence circuit shown in Figure 1 operates as follows:



PRECISION REFLECTION LOCATION

Figure 1



PRECISION RELECTION LOCATION WAVEFORMS

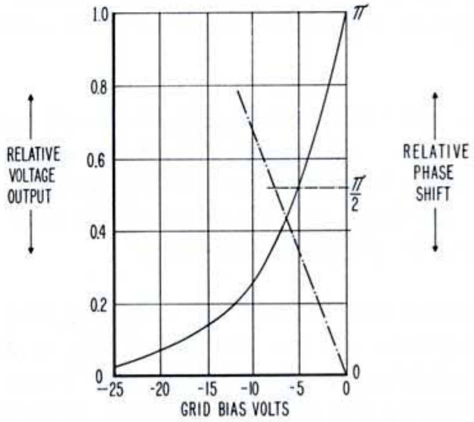
Figure 2

for an input in the E arm, the two crystals conduct during the same half cycle with equal outputs and opposite polarity. For an input in the H arm, one crystal conducts one half cycle and the other crystal in the second half cycle. Again over one complete cycle the average output is zero. For simultaneous inputs to the E and H arms and proper rf phases, the non-linearity of the crystal detectors cause a net output. When the crystals operate square law, the coincidence circuit shown is a cross-correlation detector. Figure 2 shows the resulting waveforms with the rf carrier phase stationary in the pulse. The accuracy of locating a minimum near the center of the pulse should be a fraction of an rf cycle, say 10 degrees, so for a carrier of 3, 000 mc a spatial resolution of about 1/10 inch could be expected. This is only an elementary example of a high performance system utilizing the bandwidths available from TWT's. This system could also be used in particle emission coincidence studies with an accuracy determined there by the pulse width.

It would be difficult to estimate the ultimate extent of TWT usage in the expanding electronics field. However, it does appear to be a fruitful field for exploration and invention. With the increasing dependence on electronics in industry and science today, certainly there shall develop a demand for greatly increased speed in electronic detection, processing, and control and the TWT is orders of magnitude ahead of any other electronic device.

Modulation Characteristics

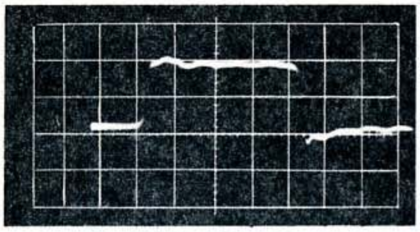
Now turning from the broad bandwidth feature, let us consider some more down to earth characteristics. A number of functions may be performed by modulating the TWT electrodes. The two variables are the beam current and beam velocity. The beam current may be varied by means of the potentials applied to one of the electrodes of the electron gun. A typical variation of the rf output voltage and its phase with electrode voltage is shown in Figure 3. The tube output can be amplitude modulated over the linear portion (about 10 db) but the attendant phase modulation is about 90 degrees. The amplitude modulation still can be useful where amplitude detection only is involved in demodulation.



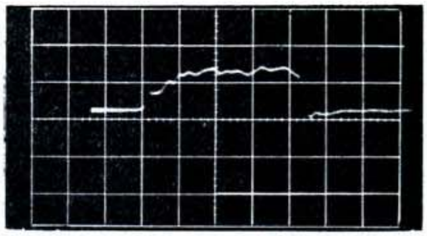
MODULATION CHARACTERISTICS

Figure 3

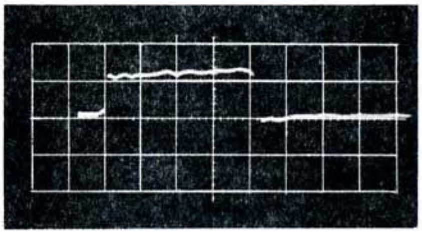
The effect of pulse modulation is shown in Figure 4 for various conditions of tube drive and pulse off-on ratio. In the top oscillogram, the tube is driven to saturation with an off-on ratio of 40 db. The modulating pulse had a rise time of about one millimicrosecond and an amplitude of 40 volts. The resulting rise time is 4 millimicroseconds which was close to the oscilloscope amplifier rise time. In the middle picture, the off-on ration is still 40 db but the tube is operating well below saturation. It seems that the entrance of the pulsed beam into the helix induces a voltage on the helix that in turn changes the beam velocity. When the electron beam wave velocity is shifted away



← (a)
PEAK T.W.T. OUTPUT.
40 DB OFF-ON RATIO.



(b) →
LOW T.W.T. OUTPUT.
40 DB OFF-ON RATIO.



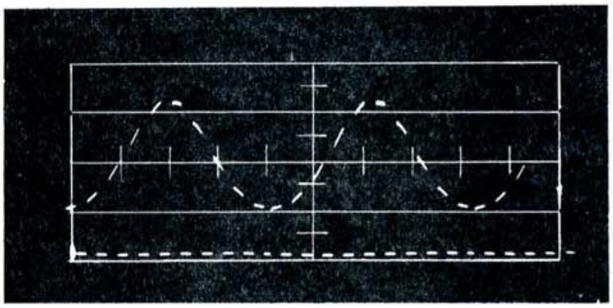
← (c)
LOW T.W.T. OUTPUT
18 DB OFF-ON RATIO.

10 MW, 2-4 KMC T.W.T. DETECTED PULSE OSCILLOGRAMS
(SWEEP 20 MμSEC DIV.)

Figure 4

from the helix wave velocity the TWT amplification decreases. Thus a transient period of reduced amplification occurs at the start of the pulse slowing the rise time to about 20 millimicroseconds. In the lower picture the off-on ratio has been reduced to 18 db by reducing the bias and pulse amplitude to about 15 volts so with this lower current ratio the rise time is good again. It can be seen from these pulse oscillograms that under proper conditions, the TWT may be used for generating low level pulses for testing the receiver portions of systems having fast rise time pulses in the transmitter.

In Figure 5, and amplitude modulated pulse train is shown. This was generated by applying a pulse and sine wave to the TWT grid. By this method, lobing or incidental flutter may be simulated in system testing.

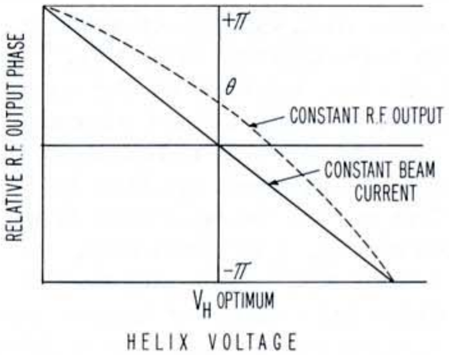


AMPLITUDE MODULATED
PULSE TRAIN

Figure 5

Figure 6 shows the effect of varying the helix or beam voltage on the phase of the output of a TWT amplifier. For constant beam current (solid curve) the phase change versus helix voltage is nearly linear. However, the output levels vary, being maximum at some optimum helix voltage and diminishing on either side. The amplitude may be held constant by an amplitude stabilization signal that is fed back to the grid of the electron gun. The resulting phase curve (dotted) is shown. It is not linear but the advantages of eliminating amplitude variations may outweight the effect of this phase characteristic distortion.

The amplitude and phase characteristics of TWT's have been presented and the interaction of the two effects due to grid or helix voltage variation. The amplitude modulation characteristics shown are similar to those found in any other amplifier tube, however, the large amount of phase modulation possible (over 360 degrees) can produce some interesting results.



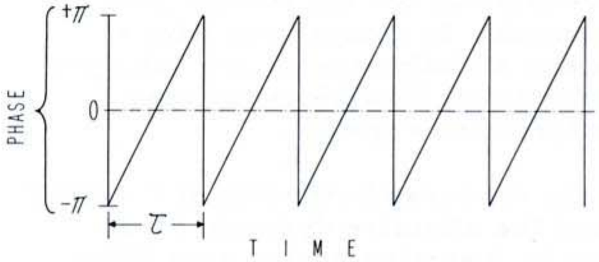
T.W.T. PHASE CHARACTERISTIC

Figure 6

Sawtooth Phase Modulation

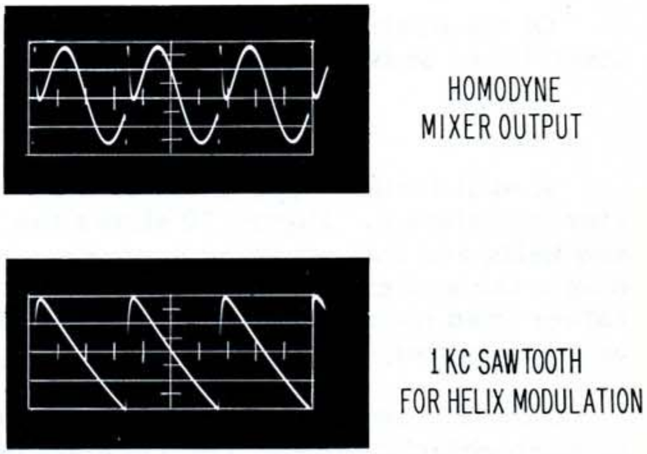
Mr. Ray Cummings[7] of Stanford University has devised a method of approximating phase modulation of unlimited deviation by its stepwise discontinuous equivalent. Consider a uniform phase change, constantly increasing, for instance, it may be approximated as shown in Figure 7 by increasing the phase constantly over a full rf cycle of 2π radians of phase and then quickly jumping back to the starting phase and then commencing to advance again at the previous constant rate. This is a stepwise discontinuous approximation to the continuous phase advance associated with the doppler shift of approaching source. Since one cycle of rf has been added during a period τ, the shift in frequency is just $1/\tau$.

Figure 8 shows oscillograms of the helix modulation voltage and the mixed product of the original signal and the frequency shifted output signal. Note the switching transient due to the finite flyback time of the sawtooth wave. This flyback time can be reduced considerably and thereby correspondingly reduce the error in doppler simulation. This system becomes a very accurate 2 terminal pair



SAW TOOTH PHASE MODULATION

Figure 7



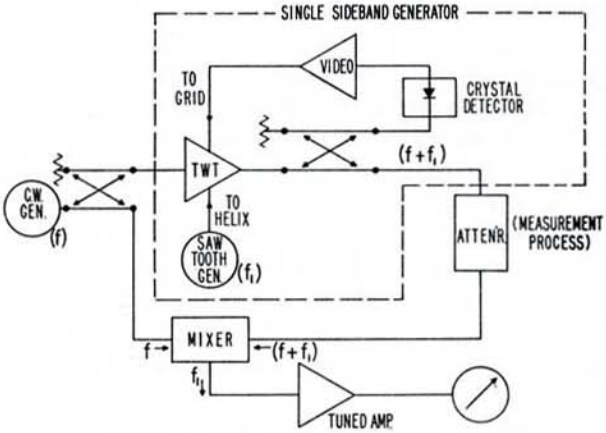
SINGLE SIDEBAND MODULATION

Figure 8

device for simulating doppler shifts from a few cycles per second to about a hundred kilocycles. This should provide a very satisfactory instrument for the design and test of cw doppler and coherent pulse radars.

Linear Detection In Microwave Measurements

Another powerful application of frequency offset or single side band modulation is the use of linear or homodyne detection which greatly extended the dynamic range of microwave measurements. Figure 9 shows a homodyne measurement system. The TWT provides a frequency offset f_1. This shifted frequency is then applied to the system under test that yields a weak output signal. The weak signal and the strong reference signal or local oscillator are then applied to a crystal mixer. The mixer is operated linearly and the beat frequency f_1, 1 kc possibly, is then applied to a tuned amplifier and meter such as a VSWR detector. Linear mixer output ranges approaching 100 db may be attained compared with an equivalent 50 db range for a square law detector. Thus the sensitivity and dynamic range for measurements is increased by a power ratio of about 10 billion.



LINEAR (HOMODYNE) DETECTION SYSTEM FOR MICROWAVE MEASUREMENT

Figure 9

The advantages of using the TWT for this frequency shifting function are:

1) low modulated signal out of the input terminals of the TWT. This limits the sensitivity attainable.

2) wide frequency coverage. The helix coupled TWT is useful even beyond the recommended 2:1 bandwidth.

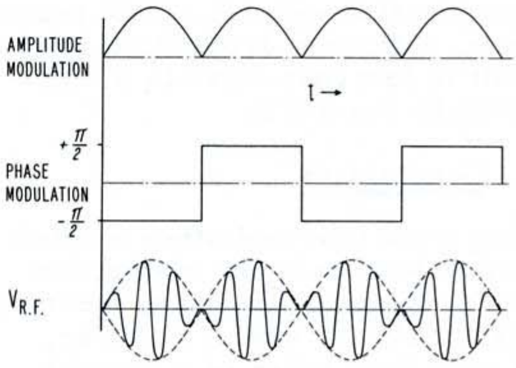
3) gain is provided in the weak signal channel.

Of the possible alternatives, rotating mechanical or ferrite phase shifters and other types of tubes, no one device has all three of the listed advantages.

General Applications

A still further type of modulation available with the TWT is suppressed carrier modulation. Figure 10 shows the required modulations for the control grid and helix and the resulting suppressed carrier rf output. In comparison with a magic tee and crystal balanced modulator, in this one all adjustments are voltages rather than mechanical positions and the TWT modulation characteristics may offer a greater degree of stability than balanced microwave crystals.

For narrowband work, the noise level due to the immense bandwidth of the TWT is often objectionable. The residual noise level and the effective dynamic range (noise to saturation level) may be greatly improved by inserting a band pass filter after the TWT. Under this condition the TWT should then be competitive with either a klystron or triode amplifier as far an dynamic range and gain are concerned, but since a few different TWT types can be adapted to this use anywhere in the microwave range up to 12 KMC, just three or four different tube types could do the job and require only the addition of a single bandpass filter in the output transmission line. The TWT does have greater time delay than its competitors and often the phase distortion has been excessive. The phase distortion is being constantly improved and with the coupled helix circuit on the outside of a tube with excellent internal phase characteristics, the phase distortion can be reduced even further with care in constructing the external microwave circuit.



SUPPRESSED CARRIER MODULATION

Figure 10

TWT's have been proven excellent as highly stable microwave oscillators. Hetland and Buss[8] of Stanford University have computed noise bandwidths of as low as 10^{-3} cps at 3 KMC. As compared with a stabilized reflex klystron, in which a tube with a relatively low Q oscillator cavity has its mean frequency corrected by a high Q reference cavity, the TWT uses the high Q cavity directly in the feedback circuit of the oscillator to control the instantaneous frequency.

Many other applications of TWT's are possible, since the fundamental component of any electronic system is the signal amplifier. In the role of amplifier, the TWT is rapidly opening up wide regions of the microwave spectrum to a much more flexible approach to system synthesis.

Coupled Helix Circuits

Another more speculative role for the TWT lies in the use of helically coupled circuits on the outside of the vacuum envelope. Figure 11 shows a tube with its amplifier circuit in place. The role of the vacuum tube is reduced to an active transmission line in one direction and a passive line in the other direction. Input and output couplers may be arranged along the tube at will, attenuating sections are applied to eliminate any return signal from output to input in the passive backward direction. These are the usual amplifier functions connected with making a stable amplifier tube. Variation of the tube length may be used to adjust the amplifier delay time which might open up the use of the tube for fast switching functions. External reactive and resistive circuit elements can change the frequency response as well as the non-linear characteristics of the active line. Some work has started along these lines; however, there is no estimate yet as to how far or how flexible these external circuitry methods are.

The immediate advantage of external circuitry has been that the internal vacuum tube has been reduced to its simplest form. An electron gun, a uniform helix, and a beam collector. The critical circuit functions of coupling in and out of the tube and stabilizing the amplifier are now made separate and may be adjusted. This can mean a substantial increase in production yield.

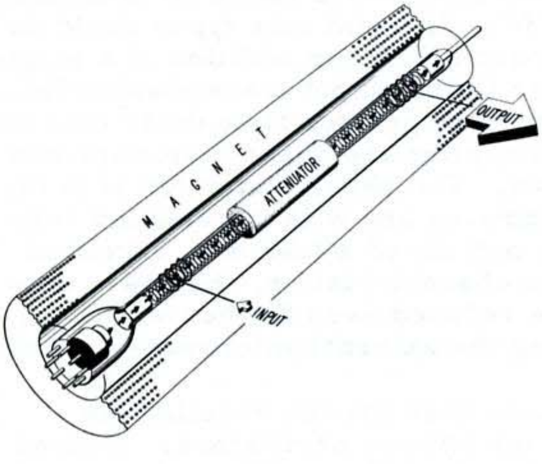


Figure 11

The precision machine work required on the capsule has been reduced to a minimum. The coupling helices and the mounting hole require precision while the rest of the manufacturing operations can be simple fabrication methods like sawcuts, stamping, and rolling. Thus with the versatility afforded by the wide bandwidth which also reduces the number of tube types, in conjunction with high yield manufacturing methods, sufficient demand may be expected to result in low cost-flexible microwave amplification by the TWT.

Conclusions

The traveling wave tube and other related distributed circuit-electron beam interaction tubes have been the object of intensive research and invention for nearly ten years; however, only in the past year have tubes of a general purpose nature become commercially available. Now it becomes necessary to critically examine the range of usefulness of the TWT. The use of the broadband property will require another research phase before it can be judged and given suitable employment. A broader less critical role can be filled by just a few types of tubes providing narrow band amplification and useful modulation characteristics through most of the microwave range.

It is hoped the modulation characteristics and possible applications presented here may suggest some useful tasks for the TWT.

Acknowledgements

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