A Novel Technology for Linearizing Traveling Wave Tube Amplifiers

Tong Chen, Yehuda Goren, Charles Jensen, Phil Lally, and Don Gagne

Teledyne Electronic Technologies, Mountain View, CA 94043, USA

Abstract — **The Traveling Wave Tube (TWT) has great potential to provide high power for wireless communication. However, its poor linearity has limited its application. This paper describes a new method to linearize TWTs based on the physics of the device[1,2]. The technique requires low-cost circuitry. The test results show a dramatic improvement.**

I. Introduction

The modulation and multiplexing schemes used in most communication systems result in signals having highly time-varying envelopes. Power amplifiers employed in those systems are required to operate with a very high degree of linearity. This is accomplished by backing off the amplifiers output power, away from saturation. Conventional solid state amplifiers lack the power and efficiency capabilities required by many of those systems. As a result, vacuum tube power amplifiers are essential components of many modern microwave systems, including space telecommunications, radar, electronic warfare, and navigation systems, because microwave tube amplifiers can provide microwave energy at levels of power higher by orders of magnitude and with much higher efficiency than semiconductor microwave amplifiers. The higher power levels offered by tube devices are facilitated by the fact that electrons can travel at a much higher velocity in a vacuum than in a semiconductor. The higher velocity permits use of larger structures with the same transit time. Larger structures, in turn, permit greater power levels. High efficiency is possible with TWT's, since electron collection is separated from interaction with the RF. The electrons can be collected at potentials lower than that of the RF circuit, recovering much of their residual kinetic energy.

II. Theory

Traveling wave tubes, as well as other vacuum electronic microwave devices, amplify microwave signals through exchange energy between electrons and microwave fields. Because the mechanism is very different from solid state amplifiers, the nonlinearity characteristics are very different too. The typical way of linearizing solid state devices may not be suitable for TWTA's [3]. For example, the phase nonlinearity, usually called AM-PM conversion, is typically 10 times worse in a TWT than in solid state devices. This phenomenon dominates TWT nonlinearity while the amplitude nonlinearity, known as AM-AM conversion, dominates solid state devices. Our approach starts with understanding the physics of how the nonlinearity was generated.

The heart of the TWT is a slow wave structure, such as a helix, which propagates a wave with a phase velocity slower than the speed of light. A TWT employs this structure to match the microwave phase velocity with the electron velocity. When the velocities are nearly equal, there is interaction between the wave and the electrons resulting in amplification of the microwave signal and a decrease in the average electron energy.

To a first approximation, the phase velocity of the wave follows the electron velocity. However, this relation can only be maintained up to certain microwave power level. When the microwave power is higher than the ideal design, the electrons will slow down more so that they cannot keep up with the phase velocity of the slow wave structure. This results in a phase shift through the TWT. The more power extracted from the electrons, the greater is the phase shift. This is the main reason that causes AM-PM nonlinearity in TWTs. Before getting into deep saturation (maximum output power), the change of phase increases. The phase change from small signal to near saturation is typically about 60°. The maximum slope is about 6°/dB.

When a TWT is designed and built, the slow wave structure, as well as the phase velocity as a function of distance along the axis, is fixed. One cannot adjust it to follow the power variation. However, we can compensate for the phase slippage by changing the electron energy according to the input microwave power. To the first order, this is quite effective.

The second factor that affects output power is the current of the electron beam. The power in an electron beam is the product of voltage (electron energy or velocity) and current. Usually, a TWT works with a constant energy and current electron beam. Therefore, a

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growing microwave is absorbing energy from a fixed power source. Besides phase slippage, the output power will approach saturation as the input increases. This results in the so-called AM-AM nonlinearity. It is not difficult to see that one can use the other parameter, the electron current, to compensate for this effect.

Of course, the reality is much more complicated. Any effects depend on multiple parameters, as least at higher orders. There are multi-body group effects, space charge effects, and other complicated beam dynamic issues. They all, to a certain extent, have effects on nonlinearities. However, we believe the phenomena we mentioned above are the lowest order, dominant ones, and the correction method we propose can effectively reduce the nonlinearity down to a level to meet wireless communication requirements.

III. Apparatus Configurations

Based on the analysis in previous section, we conclude that we can compensate primarily the AM-PM nonlinearity of the TWTs by changing electron energy as a function of input microwave power level. Because the AM-PM is the dominant part of the nonlinear effect in TWT, this correction alone can bring the TWT nonlinearity down to the level of a bare solid state device. The character is similar to solid state devices too. From there, one can use popular linearization methods, such as predistortion and feed forward, to make the system meet the wireless communication requirements.

If a better linearity is desired, we can apply correction on both electron energy and current. This will correct both AM-AM and AM-PM nonlinearities to a certain extent. The fine-tuning of the combination of the corrections can enhance the TWT linearity significantly.

There are several ways to vary the energy of the electrons in the tube. It is obvious that one can apply the variable voltage to the cathode of the tube. This method can be easily applied to any TWT since the correction circuit can be built into the power supply. One of the down sides of this method is that the correction circuit has to float on top of the high voltage end. To avoid that, one can apply the voltage to the slow wave structure, typically a helix. This requires the TWT built in such a way that the helix is DC insulated from the rest of the tube.

The electron current can be adjusted by applying a small voltage to the grid in front of the cathode. Some TWTs do not have a grid. Then the voltage may be applied to the focussing electrode.

The required correction voltage usually is not a linear function of input power. To get a correct voltage, one can do one of the following:

A. Direct Feed

When a traveling wave tube is manufactured, its non-linear characteristics are pretty much fixed and can easily be measured. Therefore, the correction voltage as a function of input power is well predictable. A function generator, either analog or digital, can make the correction.

In this scheme, an envelope detector, typically consisting of a directional coupler and a crystal detector or diode, is attached at the input. The signal of the detector is transformed through the function generator, and amplified. Finally, a voltage driver provides the correction voltage to the helix or cathode. If the voltage is applied to the cathode, the signal has to be coupled through an insulated device in order to add the correction voltage on top of the normal cathode power supply. This can be accomplished by transformer or electro-optical coupling.

Between the envelope detector and the actual input of the TWT, a delay line is needed to compensate for the delay in the circuits mentioned above, so that the power variation and the correction are synchronized.

Figure 1 shows the schematic configuration of the direct feed scheme with correction voltage applied to the helix and focussing electrode, as an example.

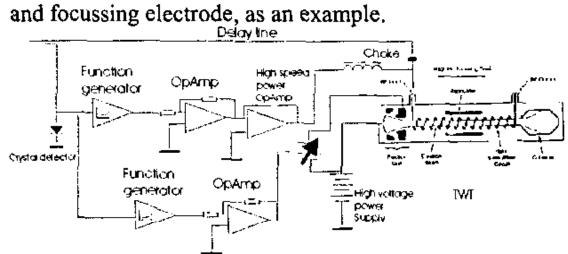

Fig. 1. A schematic configuration of a direct feed scheme example.

B. Feed Back Loop

A different approach can avoid using a nonlinear function generator. Because the correction voltage is very small compared with the total voltage applied to the electron beam, it can be considered as a perturbation, and the phase offset and the correction voltage can be well related as a linear function. Therefore, one does not have to measure and set up the phase-power function for each kind of tubes.

In this approach, the phases of the input and output of the TWT are compared, as well as the amplitudes. The signal from the output side is attenuated and phase adjusted so it is at the same level as the input signal. The difference is amplified and sent to the desired components as a correction voltage. When the electron velocity is corrected, the phase off-set approaches zero. The process is similar to a phase locked loop or other feedback loops. It automatically corrects the nonlinearity by keeping the phase off-set minimum. Similarly, the amplitude difference can be fed back to change the electron beam current so that the AM-AM nonlinearity can be cured. Figure 2 shows the schematic of this approach.

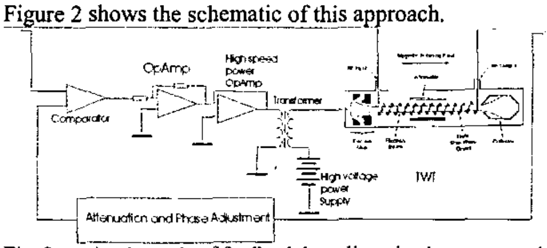

Fig. 2. A schematic of feedback loop linearization system with correction voltage applied only to the cathode through a transformer.

This approach is relatively simple and can be easily applied to various types of tube. However, the draw back is a limit of the bandwidth, due to the delay in the tube as well as the feed back circuits.

Comparing with other TWT linearization technology, the method described in this paper employs circuits of base band frequency, instead of carrier frequency. This translates into significantly lower costs.

The other advantage of this method is that it is independent of carrier frequency. As long as the circuit can cover the instantaneous bandwidth, the same traveling wave tube amplifier can work on different bands because TWT inherently has an extremely wide band, typically an octave.

IV. Experiment Result

To test our concepts we choose to work with a 1 kW TWT operating over 1GHz of instantaneous bandwidth from 1.9 to 2.9 GHz with 35dB gain. Figure 3 describes the helix compensation effect on the carrier to intermodulation ratio (C/I) as a function of the output power for two tones at 2.3GHz. Over 10 dB improvement in linearity at 300W can be observed, with about 4 dB improvement at 100W. The diminished effect of the helix phase compensation is due to the shift in dominance role from phase non-linearity at high power levels to amplitude non-linearity at lower power levels. To farther improve the TWT linearity we add a grid compensation circuitry as in Figure 1. Figure 4 is the spectral output of the uncompensated TWT at 200W (53dBm) at 2.3GHz. Figure 5 is the compensated output. 23 dB of improvement can be observed. At this point the non-linearity of the low power solid state driver amplifier becomes the dominant effect. This amplifier was operated at 60 mW (+18dBm), at a back-off of 9dB.

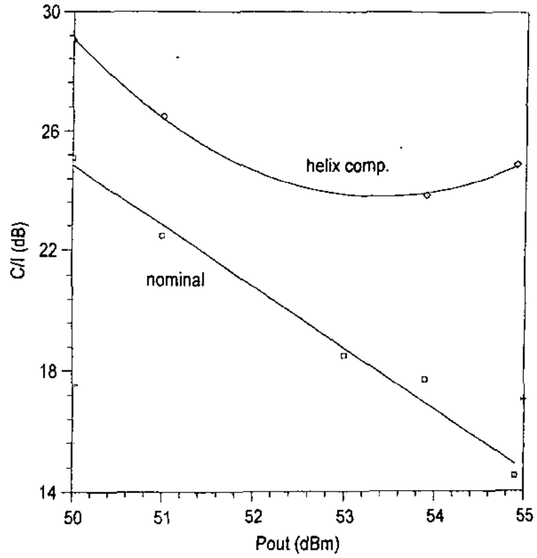

Fig. 3. Helix compensation effect on C/I

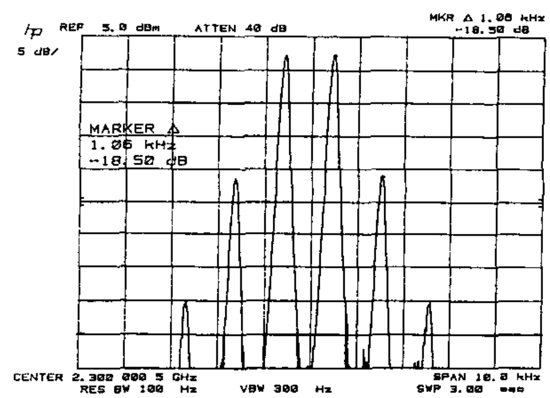

Fig. 4. The measured two-tone intermodulation on a TWTA before linearization compensation.

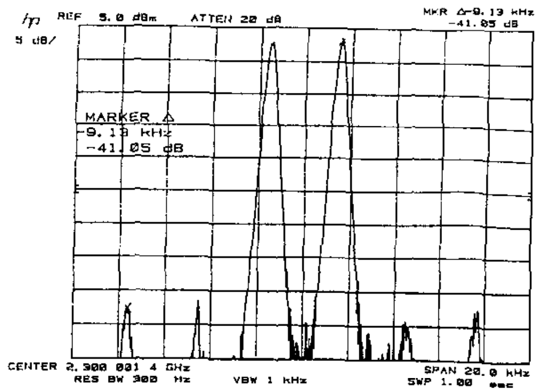

Fig. 5. The measured two-tone intermodulation on a TWTA after linearization compensation.

V. CONCLUSION

A Traveling Wave Tube Amplifier has great advantages over a solid state amplifier in power, bandwidth and efficiency. It should be re-examined for today's increasingly demanding wireless communication needs. Our new linearization technology for TWTs enables the application by improving the TWT linearity to meet the wireless communication requirements. Our technology requires only a circuit operating at base band frequency, that leads to low cost. It is also independent of carrier frequency so that one may benefit in upgrading or re-configuration.

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