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TWTA Linearization

by Dr.Allen Katz
Linearizer Technology, Inc.
www.lintech.com

ABSTRACT

New communications services have created a demand for highly linear high power amplifiers (HPA's). TWTA's continue to offer the best microwave HPA performance in terms of power, efficiency, size and cost, but lag behing solid state power amplifiers (SSAPs) in linearity. This paper discusses techniques for improving TWTA linearity. The significance and methods for evaluation of linearity are reviewed, and the merits of various linearization methods compared. The use of predistortion linearization is shown to provide TWTA performance comparable or superior to conventional SSPA's.

INTRODUCTION

Technological developments are rapidly changing the communication business. These changes have created a demand for highly linear HPA's. In the past, the bulk of satellite transmissions have been single carrier video signals. Digital compression now allows several television signals to be transmitted in the frequency space previously occupied by a single signal. Non-video, multiple signal VSAT (very small satellite terminals) and mobile telephone services are altering traditional satellite loading. New terrestrial microwave services for the transmission of video, data and personal communications are appearing daily. Virtually all these services involve the transmission of multiple signals and / or large quantities of information at high data rates. For such signals, whether transmitted by frequency division multiple access (FDMA) or time division multiple access (TDMA), amplifier linearity is a major consideration.

NEED FOR LINEARITY

Distortion can be thought of as the creation of undesired signal energy at frequencies not contained in the original signal. Distortion is produced by a loss of linearity. Amplitude linearity can be considered a measure of how closely the input-output transfer response of an amplifier resembles a straight line. When an amplifier's input level increases by a certain percent, its output level should increase by the same percent. A deviation from a straight line can be represented by a power series.

$$Vout=K1\ Vin + K2\ Vin^2 + K3\ Vin^3 ... Kn\ Vin^n \qquad (1)$$

When a single carrier input signal, represented by a sine wave, is substituted into this expression the output waveform will contain the original sine wave and harmonic distortion products. For all but the most wide band communications applications (bandwidths of an octave or greater), these harmonics can be eliminated by filtering and do not pose a problem. However, when more than one carrier is present, *beat* products are produced in the vicinity of the input signals. These new signals are known as intermodulation distortion (IMD) products. They are located at frequencies above and below the input carriers, and at frequency intervals equal to the separations of the input carriers. This is illustrated in Figure 1. IMD products can not be easily eliminated by filtering as they are located on the same frequency or near to the desired input signals.

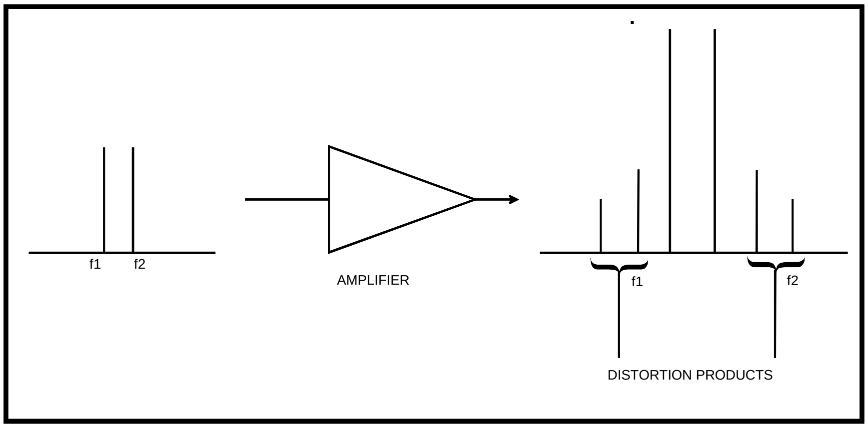


Figure 1. When two or more signals are amplified, distortion products appear in the vicinity of the desired signals.

Modulation of a carrier can also result in the production of IMD products. When a single carrier is amplitude modulated (AM) with a modulation index (M), multiple signals are produced.

$$[1+M\cos(\omega_m t)]\,A_c\cos(\omega_c t) = A_c\cos(\omega_c t) + M A_c\cos([\omega_c+\omega_m]t) + M A_c\cos([\omega_c-\omega_m\}t) \quad (2)$$

Even pure frequency modulation (FM) results in an effective multi-carrier signal when the signal is filtered. Band-limiting an FM signal introduces AM modulation which in turn produces multiple signals and consequent IMD.

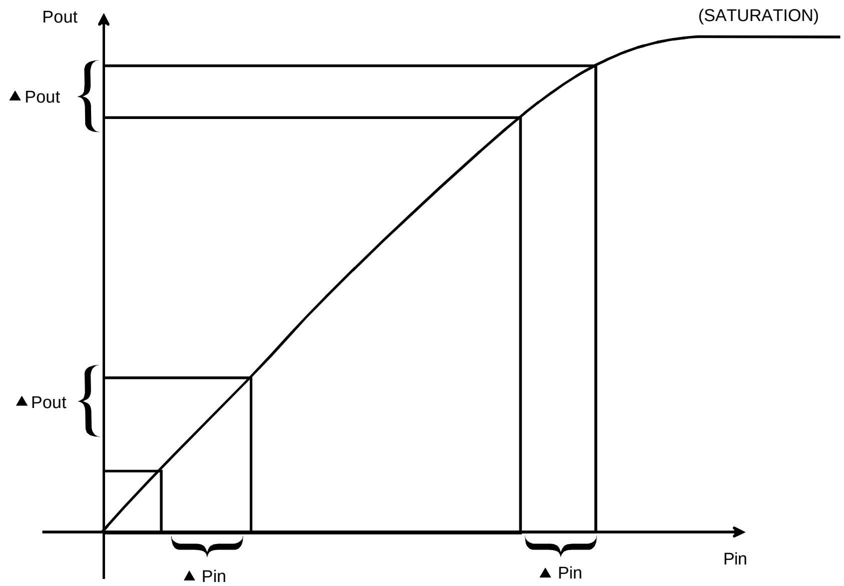


Figure 2. As an amplifier is driven closer to saturation, its output level will increase by a smaller amount, for a fixed increase in input signal.

All real amplifiers have some maximum output power capacity. This is referred to as an amplifier's saturated power. Driving the amplifier with a greater input signal will not produce an output above this level. Generally an amplifier's greatest efficiency will occur at or near saturation. As an amplifier is driven closer to saturation, its deviation from a straight line response will increase. Its output level will increase by a smaller amount, for a fixed increase in input signal as shown in Figure 2. Thus, the closer an amplifier is driven to saturation, the greater the amount of distortion it produces.

Distortion is also produced by phase non-linearity. The shift in phase angle that a signal encounters in passing through an amplifier is a measure of the time delay. Ideally this phase shift, or time delay, should be constant for all power levels.

$$\theta(P) = \text{constant} \quad (3)$$

In practical amplifiers there can be a substantial change in phase with power level. This change in phase with amplitude converts variations in signal level to phase/frequency modulation.

For a sinusoidal signal envelope,

$$P(t) = M \cos[\omega m t]$$

the resulting spectrum resembles that of a sinusoidal modulated FM signal

$$Ac \cos(\omega c t + M\cos[\omega m t]) = Ac\sum_{n=-\infty}^{n=\infty} J_n(M) \cos([\omega c + n\omega m]t) \qquad (4)$$

Thus, phase non-linearity produces IMD products in a similar fashion to amplitude non-linearity. In some systems, phase non-linearity is the principal cause of distortion.

When multiple signals are sent through a communications system, an amplifier must be operated at a reduced power level (backed off) in order to keep distortion at an acceptable level. The acceptable IMD level usually depends on the carrier-to-noise ratio (CNR) required at the receiver. IMD products are consider to add to the receiver noise level. For a carrier to IMD ratio

C/I = CNR the resultant CNR = CNR -3 dB

C/I = CNR + 6 dB $\rightarrow$ CNR = CNR-1 dB

C/I=CNR+10 dB $\rightarrow$ CNR = CNR-0.5dB (5)

If a CNR of 16 dB (10 dB FM threshold + 6 dB for rain fading) is required, and the IMD products are to have a small effect, a C/I $\geq$ 26 dB is required.

Multiple signals may be present due to the use of FDMA transmission, or the result of digital modulation of single carrier. For FDMA applications TWTA's are typically backed-off 5 to 7 dB, and sometimes more to keep distortion at an acceptable level. This is about a 4 to 1 reduction in usable power. For TDMA applications the back-off is less, usually 2 to 4 dB, to keep distortion in the form of spectral regrowth from interfering with adjacent channel communications.

Linearization

A linearizer is a device which reduces an amplifier's distortion. Use of a linearizer allows an amplifier to produce more output power and operate at a higher level of efficiency for a given level of distortion.

Linearizers have been used in video broadcasting for years. Microwave applications generally require a different approach than broadcasting because of their wider bandwidths. There are many different ways of linearizing an amplifier. Feedforward, feedback and predistortion are some common methods. Figure 3 shows block diagrams and lists the characteristics of these approaches. Instead of operating a backoff of 7 dB for FDMA, a linearized TWTA may be operated at 3 dB. Likewise with digital modulation only a 4 dB backoff may be required.

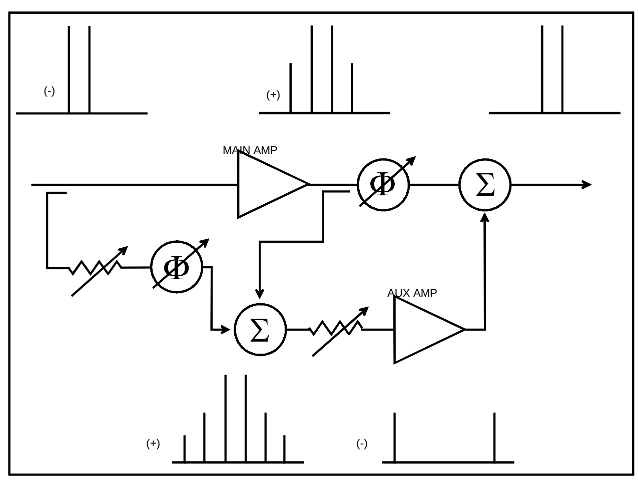


Figure 3a. Feedforward is relatively complex, but can provide wide-band and excellent distortion reduction.

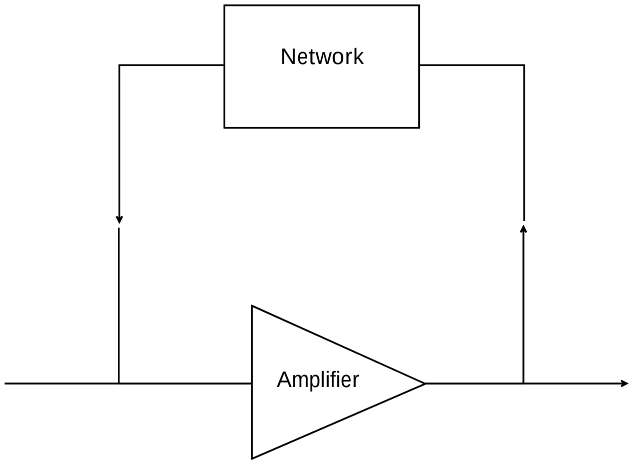


Figure 3b. Feedback is relatively narrow band and has potential stability problems.

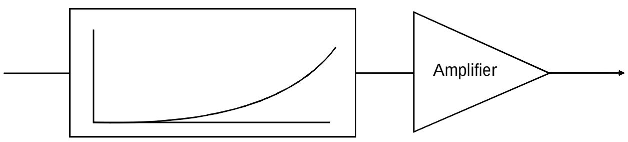


Figure 3c. Predistortion is relatively simple to implement, can provide wide bandwidth and is widely used with TWTA's.

In feedforward, the input signal is subtracted from a sample of the main amplifier's output signal. This leaves only the amplifier's distortion products. This distortion signal is amplified and then subtracted from the main amplifier's output signal to produce an *ideally* distortion free signal. Feedforward has been extensively used with solid state amplifiers, and functions well with TWTA's, but is considerably more complex than the other two methods. It requires an auxiliary amplifier, approximately 20 percent of the size of the amplifier to be linearized. A phase shifter and combiner must be added after the HPA. These components introduce loss and must be capable of handling the peak output signal level. Consequently feedforward is not easily added to an existing amplifier. When comparing feedforward with other linearization techniques, the power of the auxiliary amplifier should be added to the power capacity of the main amplifier to establish a common point for reference.

Feedback linearization can take a variety of forms. All these approaches tend to have a limited bandwidth and potential stability problems. There has been little application of feedback linearization to TWTA's.

Of various types, predistortion linearizers have been favored for microwave and satellite services because of their relatively wide band characteristics and ability to function as a stand alone unit. Predistortion linearizers generate a transfer characteristic that is the opposite of the power amplifier's saturation characteristic in both magnitude and phase. The gain of the linearizer increases by the same amount the amplifier's gain decreases. Likewise, the phase shift introduced by the linearizer increases by the same amount the amplifier's phase decreases. The desired result is the composite linear transfer characteristic shown in Figure 4. This is the response of a so called *ideal limiter*.

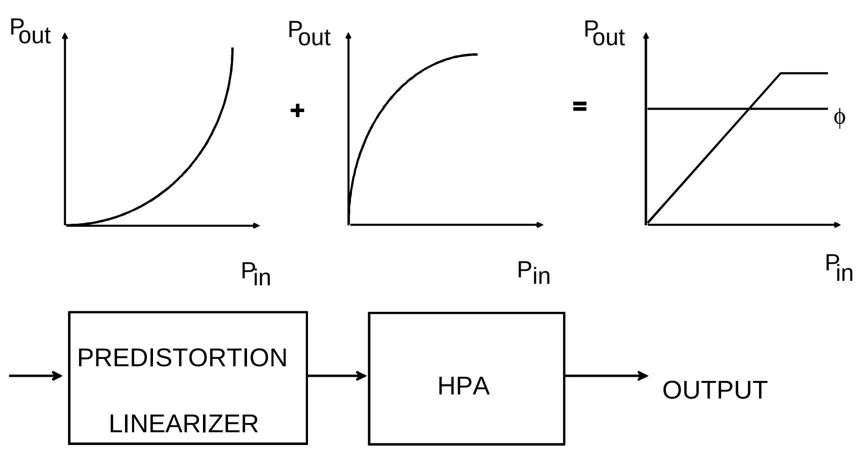


Figure 4. Predistortion linearizers generate a response opposite to a TWTA's characteristics in both magnitude and phase.

Once a TWTA has saturated, it is impossible to obtain more output power by driving the amplifier harder. Thus, the best a predistortion linearizer can do is to produce an *ideal limiter* characteristic. Despite this limitation, it is possible for a linearizer to provide large benefits in signal quality, especially as output power is reduced from saturation. Some improvement is possible even at saturation and beyond as the linearizer can correct for post-saturation phase distortion and power slump.

An alternate way of thinking about a predistortion linearizer, is to view the linearizer as a generator of IMD products. If the IMD's produced by the linearizer are made equal in amplitude and 180 degrees out of phase with the IMD's generated by the amplifier, the IMD's will cancel.

Predistortion linearizers can be produced by subtracting the output signals from parallel linear and nonlinear paths. This results in gain expansion as illustrated by the vector diagram of Figure 5.

The gain of the linear path (Vlin) remains constant with increasing drive level, while the gain of the nonlinear path (Vnl) decreases as saturation is approached. Thus, the overall gain (Vout) increases. Adjustment of the angle (Φ) between the two paths allows the change of phase with level to be controlled.

Recently design advances have greatly simplified predistortion linearizers. Past linearizers were complex and difficult to adjust. New designs use in line networks. They are much smaller in size and offer wider bandwidths - full C, X and Ku-band coverage, enhanced performance, easy alignment and excellent stability.

$$Vout = Vlin - Vnl \quad (6)$$

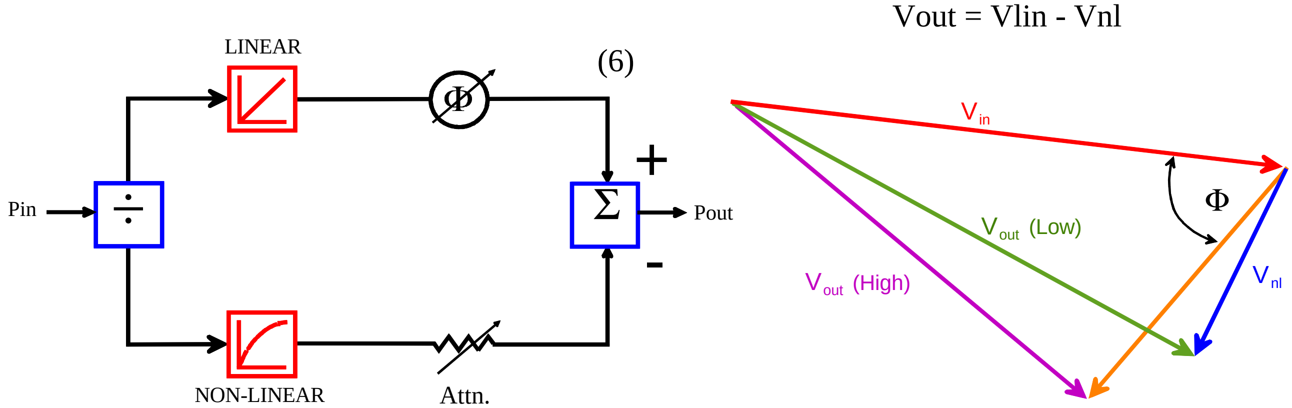


Figure 5. Gain expansion can be produced by subtracting a linear path from a nonlinear path.

LINEARIZER ADVANTAGE

Figure 6 shows the transfer characteristics of a typical TWTA and the corrected response provided by a contemporary predistortion linearizer. Note how the shape of the linearized Pout/Pin curve approaches the desired ideal limiter characteristic of Figure 4. The separation of the 1dB compression point (CP_{1dB} point where the gain has dropped by 1dB) from saturation is a good indicator of linearizer performance. Ideally the CP_{1dB} is located 1dB in input power beyond saturation. It is not unusual for TWTA's to have the CP_{1dB} occur 10 to 12 dB before saturation. In Figure 6 the CP_{1dB} is moved from 6.25 dB before saturation for the TWTA, to just about saturation for the linearized TWTA. The linearizer also reduces the change in phase with power level from more than 40 degrees for the TWTA alone to a near flat line.

Some authors have tried to define the point of saturation in terms of gain compression. They have suggested using 6 dB compression as an indicator of saturation. This approach clearly will not work in the case of a linearized amplifier. Figure 6 shows that saturation occurs at about 6 dB compression for the unlinearized TWTA, but only at 2 dB for the linearized case.

IMD data are also sometimes presented in terms of input-power-backoff (IPBO). IPBO is more difficult to interpret, and in some cases can be misleading as it depends on the gain transfer characteristics of the amplifier. Definition of the exact point of saturation is also more critical when IPBO is used. The use of OPBO is recommended since the distortion at a required level of output power is the real parameter of concern.

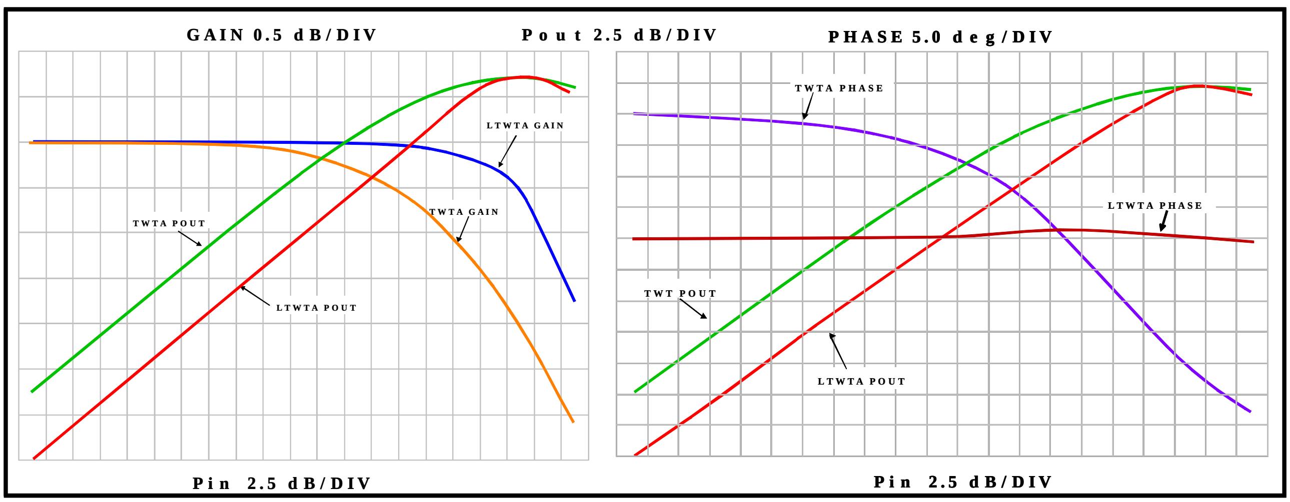


Figure 6. Transfer characteristics of TWTA and linearized TWTA.

EVALUATION OF MULTI-CARRIER DISTORTION

Many different standards have been used for the evaluation of distortion. This makes comparison difficult. IMD data are usually presented as a function of output-power-backoff (OPBO) relative to saturation. The reference saturated power should be for single carrier saturation. Two-carrier saturation is typically about 1 dB lower. Noise saturation can be even lower.

Distortion is most often evaluated in terms of the ratio of carriers to third order IMD products (C/I3)- IMD terms closest to the carriers. With linearizers it is not uncommon to find the fifth order IMD terms equal to or even greater than the thirds. This is illustrated in Figure 7.

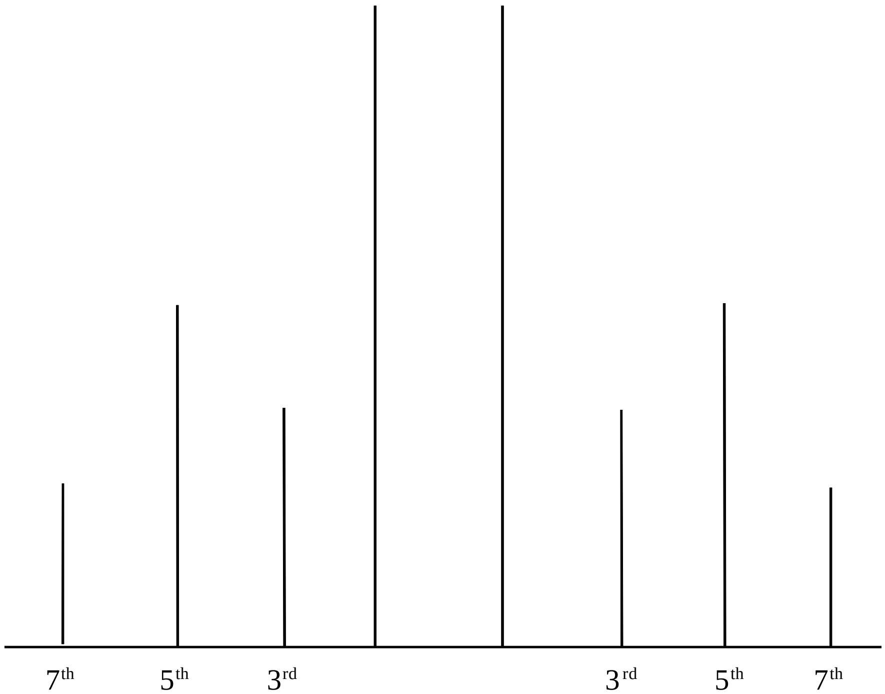
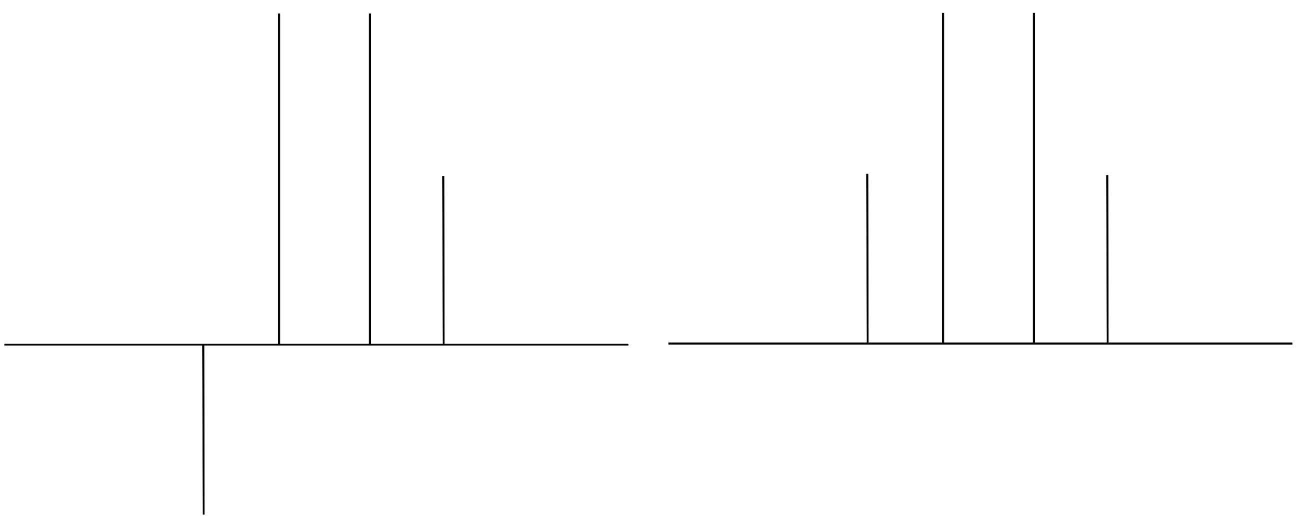


Figure 7. Linearizers can produce 5th order IMD terms equal or greater than 3rd order terms.

IMD terms can also be non-symmetrical. This imbalance is due to the presence of both amplitude and phase induced IMD products. Upper and lower frequency IMD terms generated by gain compression (AM/AM) are in phase. However, upper and lower frequency IMD terms generated as a result of phase change with power (AM/PM) are 180 degrees out of phase as illustrated in Figure 8. This phase difference is a result of the properties of the Bessel function in equation (4). When the AM/AM and AM/PM induced terms combine, the result is a non-symmetrical IMD spectrum.



a. Upper & lower odd order AM/PM terms out of phase.

b. Upper & lower odd order AM/AM terms in phase.

Figure 8. IMD terms can be non-symmetrical.

A preferred C/I measure is to use the ratio of the carrier power to the total IMD power (C/It),

$$C/It = \left(\sum_{n=1}^{N} Cn^2 \Big/ \sum_{m=1}^{\infty} Im^2 \right)^{1/2} \quad (7)$$

where N is the total number of carriers. Because of the calculation involved in the measurement of C/It, C/I is often evaluated as the ratio of carrier power to the power of the largest IMD product, regardless of its order. This method is used for the C/I data presented in this paper.

The two-tone output spectrum of a typical TWTA at 4 dB OPBO with and without linearization is shown in Figure 9. A reduction in IMD of greater than 15 dB is common at this OPBO level.

although a higher level of back-off will be required for the same C/I level as the number of carriers is increased.

The data shown in Figure 10 is typical for two carriers spaced 10 MHz apart at the top, center and bottom of a satellite band. It represents *Static* bandwidth, the ability of a linearizer to equalize an amplifier over frequency with the carriers relatively closely spaced. There is another type of bandwidth which needs to also be considered. This is the *Dynamic* bandwidth and measures the ability of the linearizer/amplifier to function with a rapidly changing signal envelope. It can be measured by increasing the frequency spacing of a two-tone test signal. TWTA's generally have superior dynamic bandwidths than SSPA's and can be linearized to carrier spacings of 300 to 500 MHz.

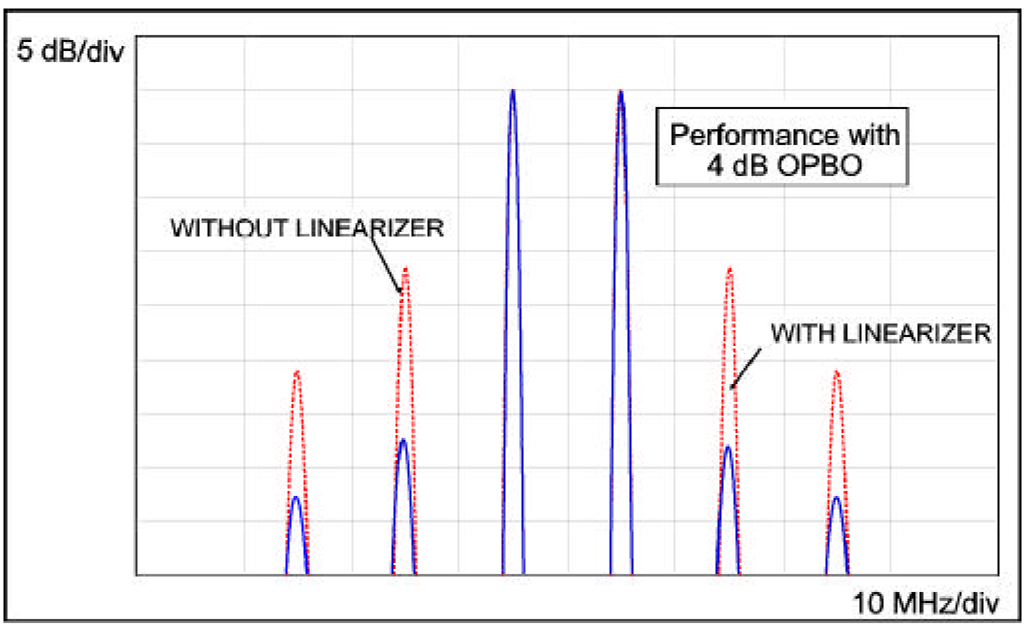


Figure 9.
A two-tone C/I improvement of greater than 15 is common at 4 dB OPBO.

The improvement in two-tone C/I as a function of OPBO achieved by using a linearizer with a TWTA is depicted in Figure 10. For the C/I of 26 dB of equation (5), a greater than 3 dB increase in output power is provided. If a C/I ratio of 30 dB is required, the TWTA would have to be backed-off at least 10 dB, but with the linearizer it need only be backed-off 4 dB. This is a 6 dB increase in output power. A comparable or superior output power increase can be achieved for signals of more than 2 carriers,

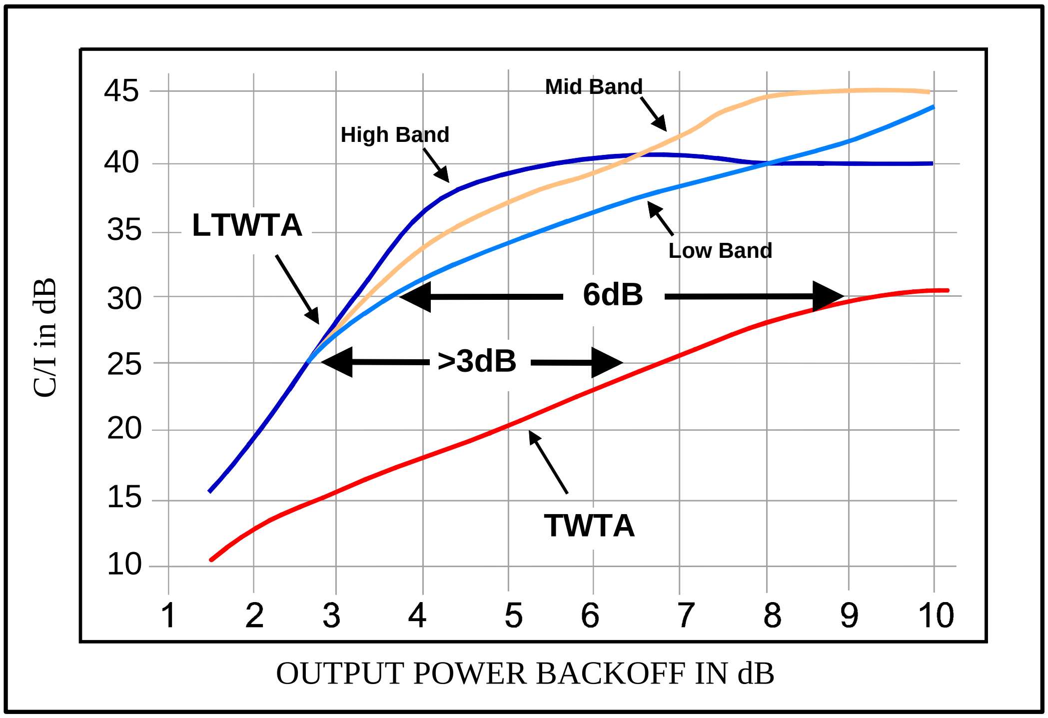


Figure 10. Two-tone C/I of TWTA and improved C/I of linearized TWTA.

Figure 11 shows how efficiency is related to OPBO for a modern high efficiency TWTA. For a C/I of 26 dB, the use of a linearizer can provide greater than a 70 percent efficiency increase.

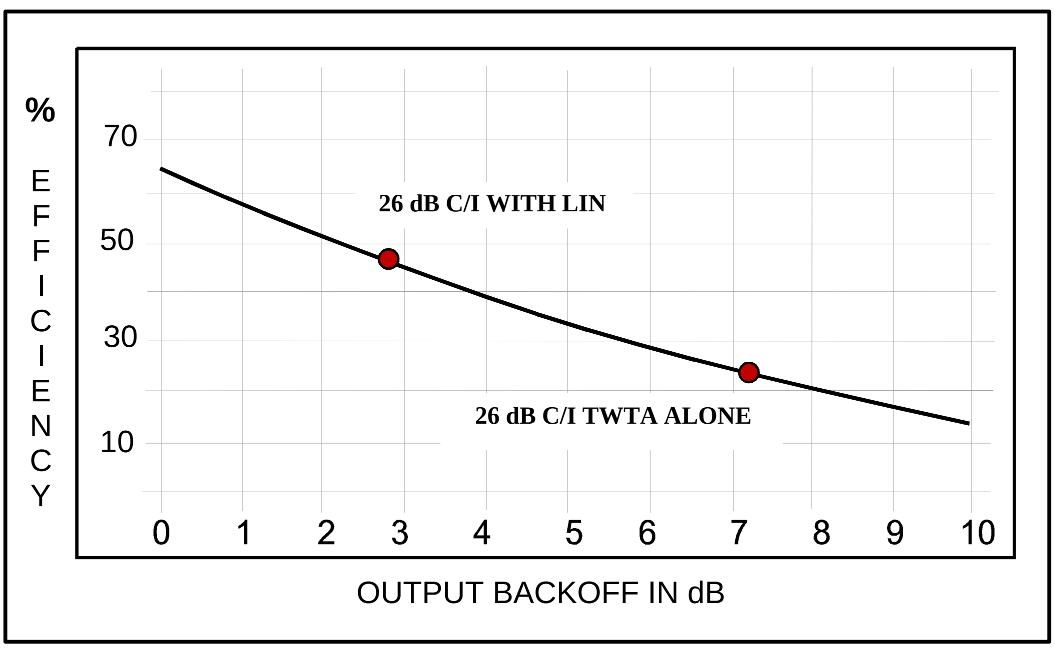


Figure 11. A 70 percent increase in efficiency can be achieved for a C/I of 26 dB.

NOISE POWER RATIO

The performance of a linearized TWTA with many carriers (>10) is normally tested using a noise power ratio (NPR) measurement. In this test white noise is used to simulate the presence of many carriers of random amplitude and phase. The white noise is first passed through a bandpass filter to produce an approximately square spectral pedestal of noise of about the same bandwidth as the signals being simulated. This signal is then passed through a narrow band-reject filter to produce a deep notch at the center of the noise pedestal as shown in Figure 12.

The width of the notch should be about 1 percent or less of the width of the noise pedestal. This noise signal is used to excite the test amplifier. Amplification will produce IMD products which tend to fill in the notch. The depth of the notch at the output of the amplifier can be observed with a spectrum analyzer, and is the measure of the NPR. NPR test signals are usually generated at IF and upconverted to the microwave band of interest. Care must be taken to insure the notch depth is not degraded by this process. The notch depth of the test signal should be at least 10 dB greater than the maximum NPR to be measured. The NPR's of a typical TWTA and a linearized TWTA are shown in Figure 13.

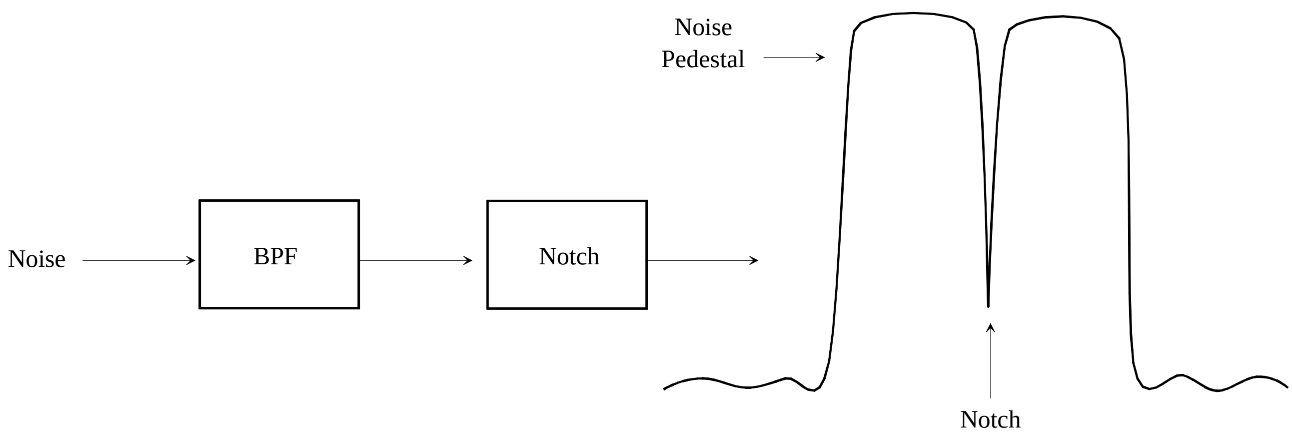


Figure 12. An NPR test generator consists of a white noise source connected in cascade with a bandpass filter and a notch filter. Notch depth can be measured with a spectrum analyzer.

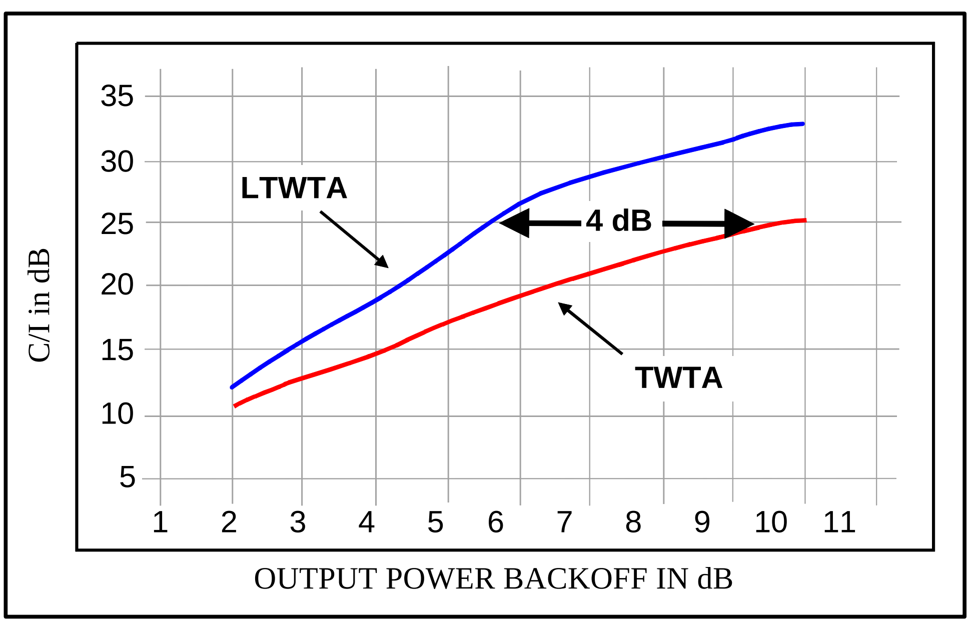
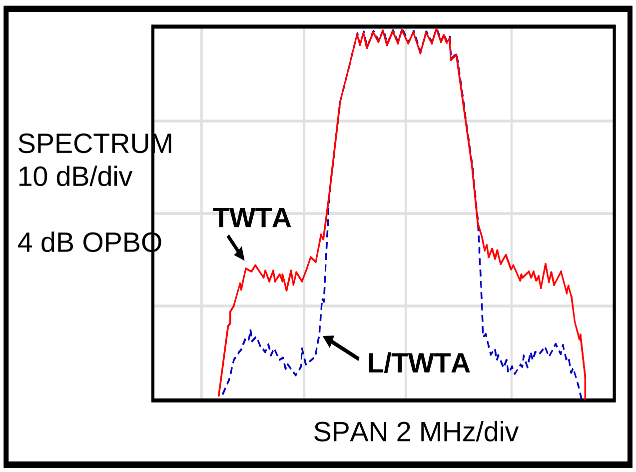


Figure 13. NPR predicts the improvement provided by linearization of a TWTA with many carriers.

SINGLE CARRIER SIGNALS

Even with single carrier signals, a linearizer can often be of benefit. For example, HPA's transmitting single carrier QPSK (quadrature phase-shift-keyed) and OQPSK (offset QPSK) signals are usually operated at a reduced output level. They are backed off to prevent spectral regrowth, caused by amplifier non-linearity, which can interfere with adjacent channel signals. Linearization can reduce this spreading to an acceptable level (> 25 dB for OPBOs of ~ 0.5 dB from saturation, > 30 dB for OPBOs of ~ 2 dB from saturation). Figure 14 shows an illustration of the improvement provided by a linearizer for a QPSK satellite signal. At 4 dB OPBO, about a 10 dB decrease in interference level is achieved. Figure 15 shows the reduction in sprectral regrowth achieved by linearization as a function of OPBO. If a 2-tone C/I > 25 dB can be achieved, the spectral regrowth will be > 30 dB down. Linearization also improves the bit-error-rate (BER) of digital modulated signals. In general the greater the required BER, the greater the improvement provided by linearization.



SUMMARY

Linearizers are needed to increase TWTA's power capacity and efficiency when handling multi-carrier and high data rate digitally modulated traffic. New linearizer designs have greatly enhanced performance and bandwidth, made alignment easier, and provided excellent stability and reliability. These linearizers can deliver up to a four fold increase in TWTA power capacity, and more than double TWTA efficiency. With the increasing demand for greater data transmission rates, it seems likely that in the near future virtually all TWTAs will be operated with a linearizer.

Figure 14.
The bandwidth/noise reduction of QPSK signal achieved by linearization of a TWTA.

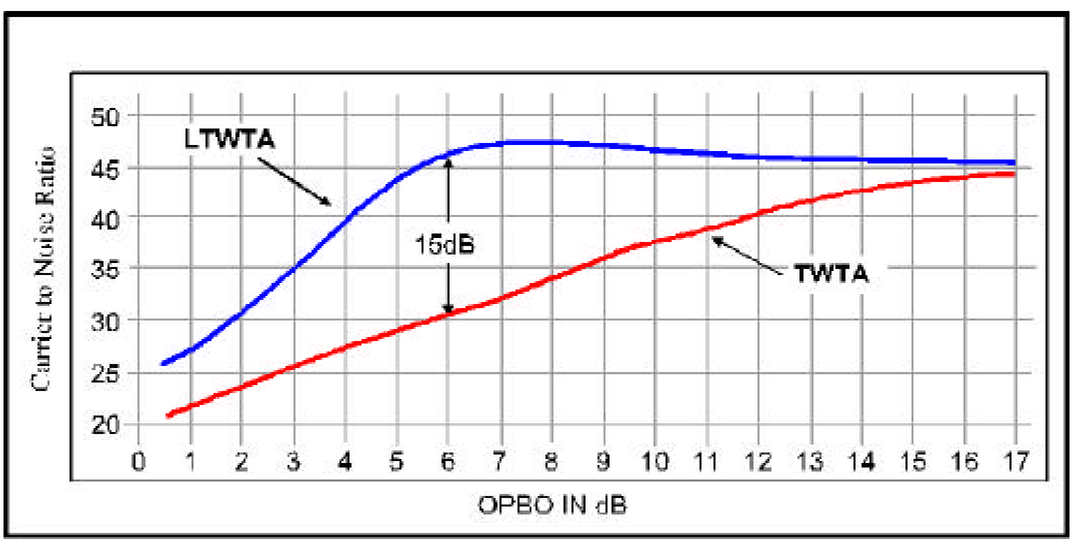


Figure 15. Reduction in spectral regrowth provided by linearization of a TWTA.

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