LINEARIZERS FOR V-BAND SATELLITE UPLINK AND DOWNLINK AMPLIFIERS

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Abstract – High throughput satellite (HTS) communication systems are needed for the demand of increased data rate capacity. Communications architectures are moving to higher frequencies to accommodate greater bandwidths necessary for these throughputs. To accommodate these greater bandwidths, new satellite systems have been designed to operate in the V-Band spectrum. Ground station uplink amplifiers (47-52 GHz) and satellite downlink amplifiers (38-42 GHz) are needed to provide linear high power to allow efficient transmission of these signals. This paper will discuss the progress in V-band analog predistortion linearizers for these new high power amplifiers (HPAs). Linearizers for both traveling wave tubes (TWTs) and solid-state power amplifiers (SSPAs) will be presented.

Overview

The fidelity of a satellite link is determined by both the linearity of the ground station HPA and the satellite HPA. To maintain distortion at acceptable levels, HPAs are normally reduced in power or "backed-off" (BO) to achieve satisfactory linearity [1]. Linearization reduces the power lost due to output power back-off (OPBO). However, on satellites, minimum OPBO is normally used to keep efficiency as high as possible at the expense of linearity. Efficiency is a critical satellite parameter that cannot be wasted. Efficiency decreases rapidly with OPBO and increases the power needed to operate a satellite. On the other hand, the ground side uplink HPA is operated at a greater OPBO, to provide greater linearity to compensate for the satellite's lower linearity. In both cases, the highest linearity is desired for the BO level.

Today, linearization is used in virtually all satellites to improve the HPA efficiency, as well as in ground systems to improve linearity and reduce cost. For most satellite communications (SATCOM) applications, the acceptable level of distortion is not determined by the in-band IM products; it is the adjacent channel IMs that interfere with co-channel communications that determine the operating OPBO. As more complex (and bandwidth efficient) digital modulations are exploited, the needed level of in-band distortion correction is increased. The effect of this distortion is measured by metrics such as Error Vector Magnitude (EVM) and Bit Error Rate (BER). In-band distortion can be mitigated using coding techniques. However, even with the most advanced coding, linearization can still make a significant performance improvement in BER, EVM and reduce the OPBO operating point [2].

On a satellite even a half dB of extra power more than justifies the use of linearization. On the ground, the case for linearization for this small level of improvement would be is harder to justify, but because of the higher linearity needed for the uplink, linearization can often give 3 to 6 dB of additional power and a 2X increase in efficiency with a corresponding reduction in HPA cost [3]. At V-band, where hardware is even more costly and power at a premium, the addition of a linearizer is easily justified.

Linearization

There are several reasons it is desirable to perform predistortion linearization (PDL) as close to the HPA as practical. In the simplest sense, the predistortor at any one frequency must produce the opposite of the HPA's transfer characteristics in both magnitude and phase as illustrated in Figure 1 [4]. The gain increase of the linearizer (GL) cancels the amplifier's gain decrease (GA), and the phase change of the linearizer (ØL) cancels the phase change of the amplifier (ØA). The desired result is the ideal limiter transfer characteristic illustrated as PD+HPA.

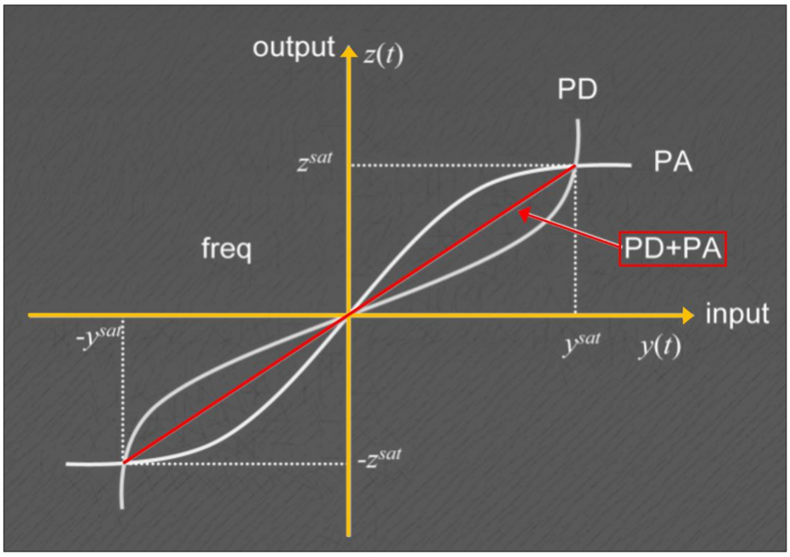

Figure 1. PD linearizer generates the opposite of a HPA's response in magnitude and phase.

The equations that relate the input and the output are rather complex:

$$GL(P_{inL}) \quad = \quad GL_{ss} + GA_{ss} - GA(P_{inL} + GL(P_{inL})) \qquad (1)$$

$$\Phi L(P_{inL}) \quad = \quad \Phi L_{ss} + \Phi A_{ss} - \Phi A(P_{inL} + GL(P_{inL})) \qquad (2)$$

In the equations ss stands for small signal and inL stands for input power into the linearizer. When the desired PDL's transfer characteristics are expanded in a power series, higher than third order terms are required to obtain the required correction transfer curve – even if the HPA produces only a purely third order nonlinearity as illustrated in Figure 2.

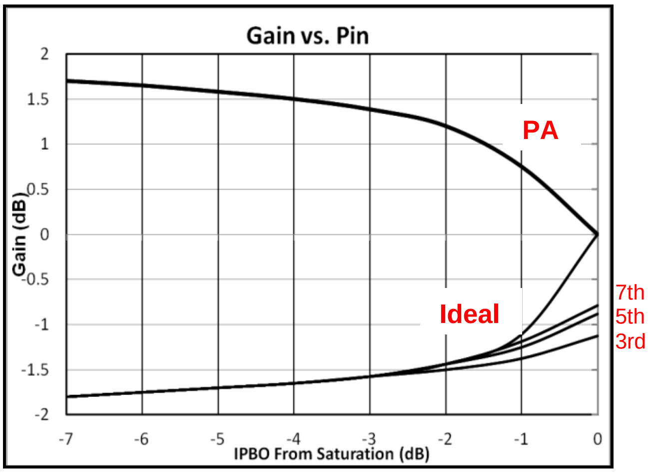

Figure 2. Gain vs. input power of cubic (3rd order) HPA with 3rd, 5th, 7th & infinite order PDL.

The ability of analog PDL (APDL) to modify its characteristics over a multi-GHz frequency band has been demonstrated numerous times and has made it the preferred method of linearization at millimeter-wave (MMW) [5]. APDL circuitry has been designed to operate beyond MMW frequencies and generates the required non-linear transfer curve needed to correct an HPA's non-linearity. APDL is the preferred method of correcting a wideband HPA's non-linearity due to carefully selected components and circuit configuration to provide instantaneous BWs of greater than 5 GHz. The design challenge is to develop APDL modules that can produce the required nonlinear characteristics at the uplink and downlink V-band frequencies. An APDL must generate transfer characteristics that are the complement of a HPA's nonlinearity in both magnitude and phase [6]. What makes designing an APDL especially difficult for V-band where components are extremely sensitive is that its nonlinear characteristics must be maintained not just at one frequency, but over the full frequency band where correction is needed. The linearizer must not only generate two transfer response curves (one for gain and a second for phase) versus input level but also a surface with frequency as the parameter. Figure 3 shows the gain and phase surface for a typical V-band TWTA linearizer. Since an HPA's nonlinearity varies with frequency, even a narrow band APDL must change its nonlinear characteristics with frequency.

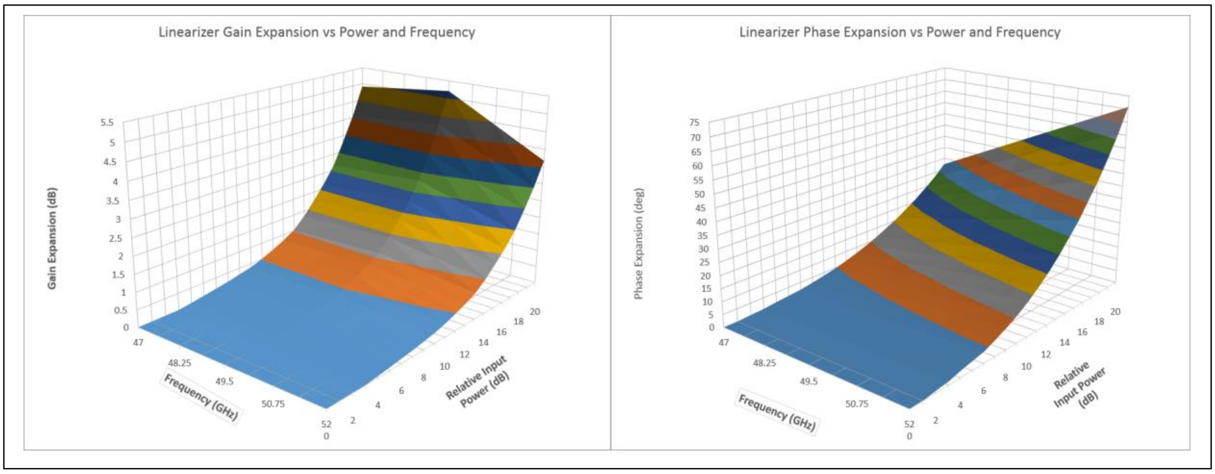

Figure 3. APDL surface for gain and phase compensation versus frequency.

The APDL can be configured to compensate the negative phase component of a TWT, or the positive phase component of an SSPA. The cascading of a linearizer with an HPA should approach constant gain and phase at all power levels up to saturation.

SATCOM Linearizers

APDLs for the common SATCOM uplink C through Q bands have been available for many years [7]. These linearizer modules are mini-systems providing optional up-conversion, high gain, commandable input and output attenuators, power detectors, predistortion and adequate RF output power (>1 watt) to directly drive a TWTA, Microwave Power Modules (MPM), or SSPA. Components are now available to produce these APDLs at much higher frequencies for the uplink and downlink for V and even E/W bands [8].

V-band Uplink TWT, MPM, SSPA Linearizers

V band linearizers have been developed for uplink ground station HPA's that operate from 47 to 52 GHz, see Figure 4.

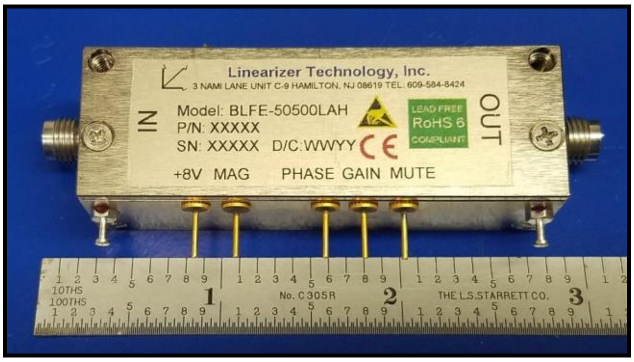

Figure 4. V-band linearizer module for a satellite uplink HPA.

A TWT linearizer module that provides >40 dB of gain, produces an output power of +18 dBm and requires approximately 4 watts of dc power will be discussed. This unit includes a 30 dB input gain attenuator and utilizes 1.85 mm female connectors. The same module can be used with an MPM, but due to the lower gain of an MPM, it must produce a higher RF drive power. Typical MPM drive power requirements are 25 dBm or greater. A functional block diagram is shown in Figure 5. At frequencies above Ka-band, many RF components can have characteristics that are different than expected. These differences must be considered during the linearizer design.

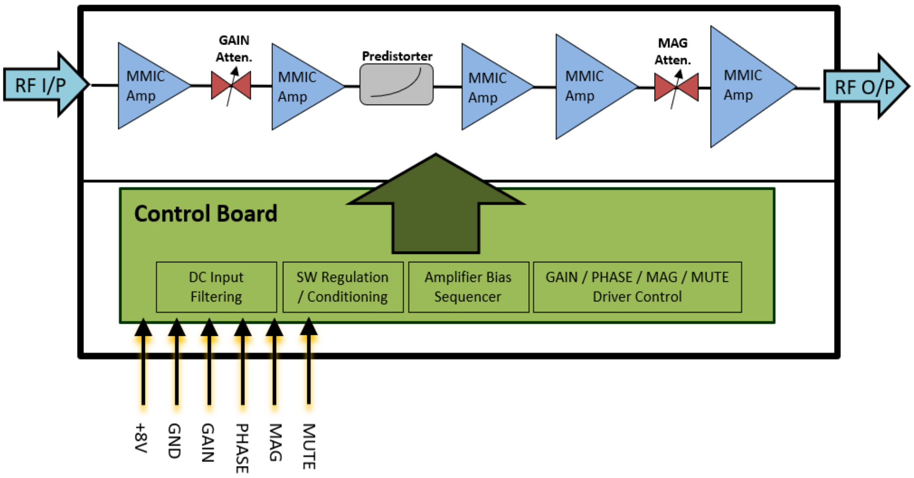

Figure 5. V-band linearizer functional block diagram.

The internal cavity of the module must be designed to minimize moding and to provide stability for the large amount of operational gain. Figure 6 shows the V-band linearizer's frequency response for both gain and phase at small signal (input power < -30 dBm) and large signal (input level corresponding to TWTA saturation) across the desired 47 to 52 GHz band. The gain increase with input drive power is about 5.5 dB. The change in phase with input drive power is about 52° at mid band, which matches the characteristics of the TWTA. Figure 7 shows the linearizer's AM/AM and AM/PM transfer response at mid-band, 49.3 GHz. As the power increases into the APDL, the gain and phase also increase to compensate for the TWTA gain compression and phase decrease. The APDL is electrically adjustable and can provide a wide variety of nonlinear characteristics versus frequency.

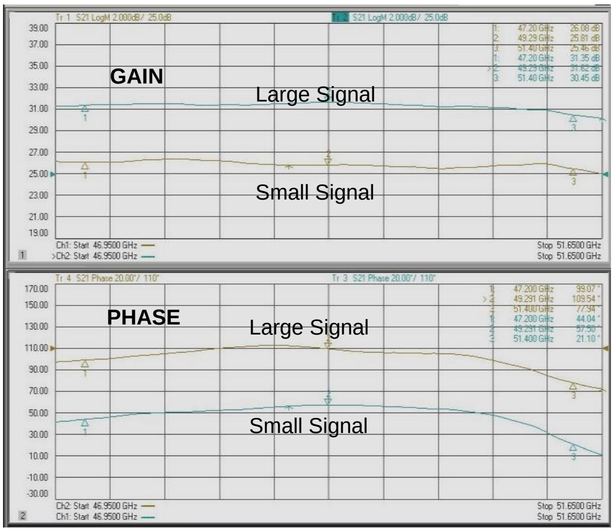

Figure 6.
V-band linearizer custom frequency response.

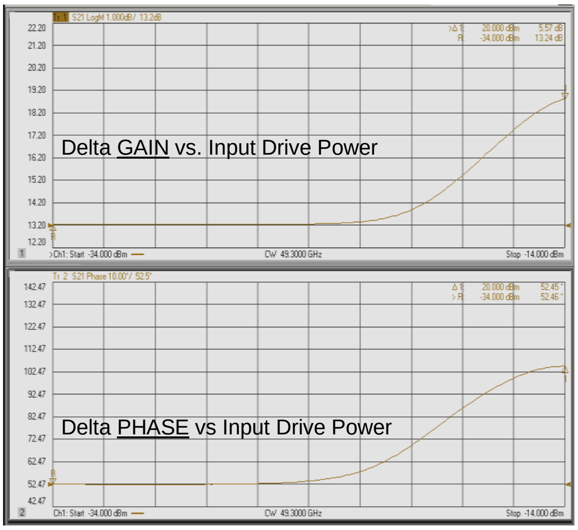

Figure 7.
Linearizer transfer response (AM/AM, AM/PM).

This linearizer was integrated with the Xicom Technology XTD-250QV HPA, as shown in Figure 8. This unit is a compact self-contained antenna mount power amplifier designed for low cost and long life. TWTs are available delivering 250 Watts peak power across the 47.2 to 51.4 GHz band.

Figure 8. Xicom Technology, XTD-250 Watt Peak Power HPA

Figure 9 shows the TWTA's power transfer response with 7 dB gain compression and 40 degrees of phase change at saturation. Figure 10 shows the measured transfer response of the linearized TWTA (L-TWTA). The 1 dB compression point of the TWTA was moved to within 3 dB input power from saturation. The change in phase was reduced to less than 8°.

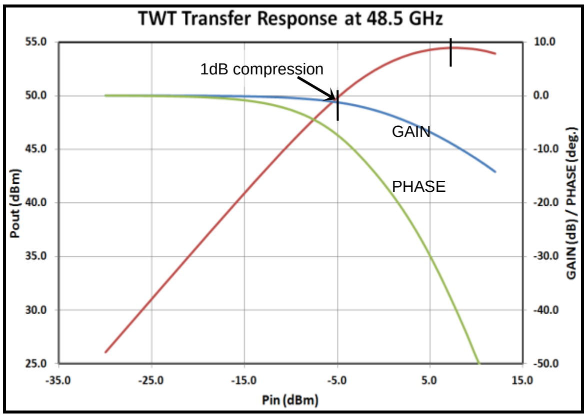

Figure 9. TWTA power transfer Response.

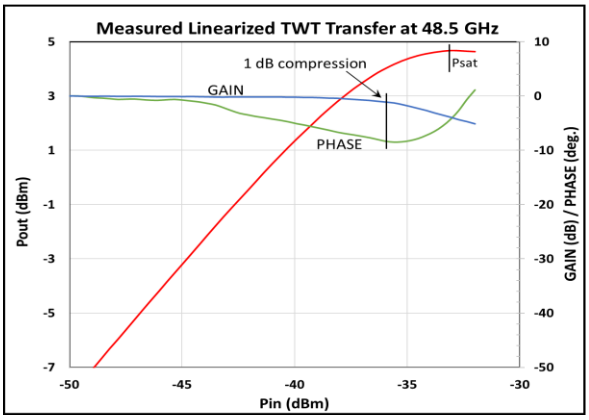

Figure 10. Linearized TWTA transfer.

These curves show the linearizers ability to improve the linearity. The linearized V-band TWTA is expected to exceed today's SATCOM spectral requirements [9]. Figure 11 lists the typical performance for 2-tone C/I, NPR, and ACPR that can be achieved at OPBO's of 3 and 4 dB. The APDL allows the HPA to be operated at 3-6 dB greater RF output power for the specified linearity, and at an increased efficiency, i.e., lower dc power.

	OPBO=3dB		OPBO=4dB	
LINEARITY STIMULUS	HPA	LINEARIZED HPA	HPA	LINEARIZED HPA
2- Tone C/I	16 dB	>25 dB	18 dB	>30dB
NPR	12 dB	>16 dB	14 dB	>19 dB
ACPR (1 symbol spacing)	25 dB	>30 dB	28 dB	>35 dB

Figure 11. Linearizered HPA results.

At MMW SSPAs are similar to TWTs and MPMs in regard to the non-linearities with the exception that the AM/PM (phase) transfer is usually positive versus input drive. The linearizer must be configured to generate a transfer function that provides positive AM/AM and negative AM/PM versus input drive to compensate the SSPA. Figure 12 shows the linearizer's AM/AM and AM/PM transfer response at 47 and 52 GHz for an SSPA. As the power increases into the APDL, the gain must increase and phase must decrease to compensate for the SSPA gain compression and phase increase. The APDL is electrically adjustable and can provide a wide variety of nonlinear characteristics versus frequency. The gain increase with input drive power is about 6.0 dB at 47 GHz and 4.5 dB at 52 GHz. The change in phase with input drive power is approximately 45° at 47 GHz and 35° at 52 GHz, which matches the characteristics of the SSPA.

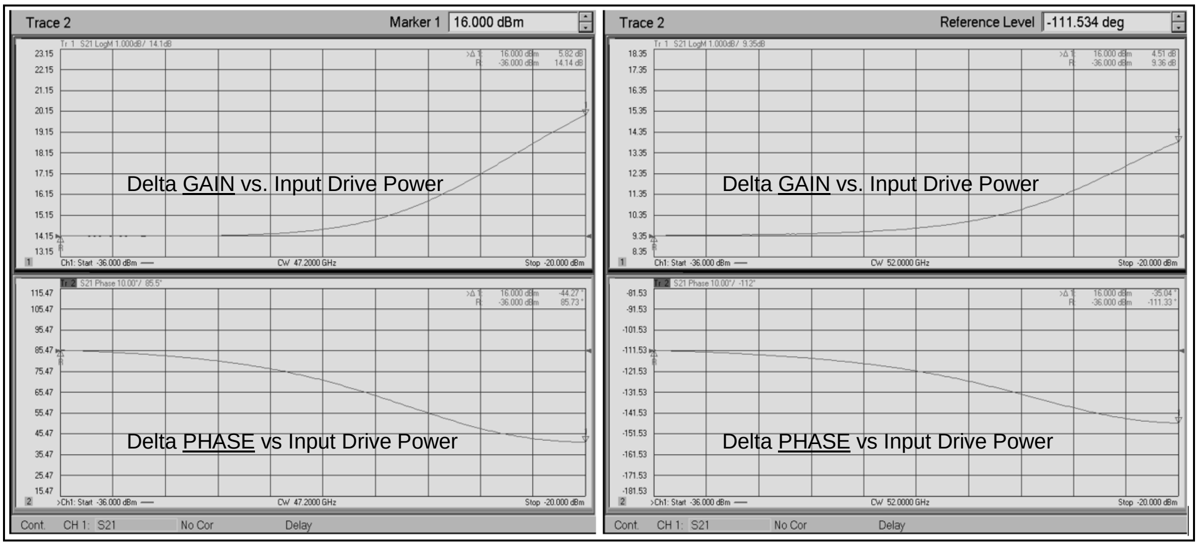

Figure 12. Linearizer transfer response (AM/AM, AM/PM) to compensate an SSPA.

Linearizered V-band SSPAs, just as linearized TWTAs, are expected to exceed today's SATCOM spectral requirements listed in Figure 11. SSPAs at any operating frequency can have issues that limit the linearity that can be achieved due to what is referred to as memory effects (ME). ME are changes in a power amplifier's (PA) non-linear characteristics resulting from the past history of the input signal.

$$Vo = f(Vin, time) \tag{3}$$

A major cause of ME is inadequate decoupling of the dc and RF circuitry of the PA devices. Changes in drain voltage amplitude and phase can modulate the PA output producing sidebands at the same frequencies as conventional intermodulation distortion (IMD). These issues must be addressed for the amplifier to achieve the best linearity performance.

V-band Downlink TWTA and SSPA Linearizers

The linearizer's designed for satellite downlink TWTAs and SSPAs are very similar to the uplink HPA linearizer designs [10]. The V-band downlink operating frequency band is from 38 to 42 GHz. The linearizer design must meet the environmental conditions and dc power challenges of todays on-orbit satellites. A dual Ku-band linearizer engineering test model (ETM) with one common controller that mounts to the top of the TWT electronic power conditioner (EPC) designed by Linear Space Technology (LST) is shown in Figure 13 [11]. This design is scalable to all the Satcom downlink frequency bands. The satellite downlink linearizer will require more operational gain to accommodate a large automatic level control (ALC) range due to atmospheric conditions at V-band. Just as the uplink HPA linearizer, the downlink will need to produce the opposite of the HPA's transfer characteristics in both magnitude and phase across the operating frequency. These units are mini systems providing fixed gain and ALC modes, commandable gain attenuator, output level control, input and output power detection, and a control for AM/AM and AM/PM transfer adjustment. The controller is based on a rad-hard FPGA, which handles the interfacing and digital temperature compensation.

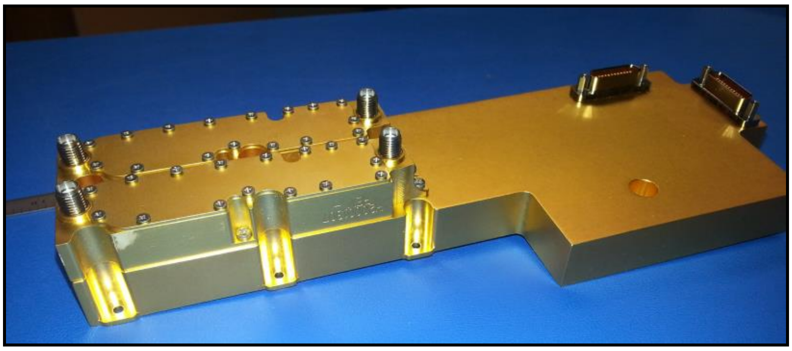

Figure 13. Dual linearizer with common controller designed by Linear Space Technology.

The linearizer power transfer and frequency response to compensate a TWT from 38 to 40 GHz is shown in Figure 14.

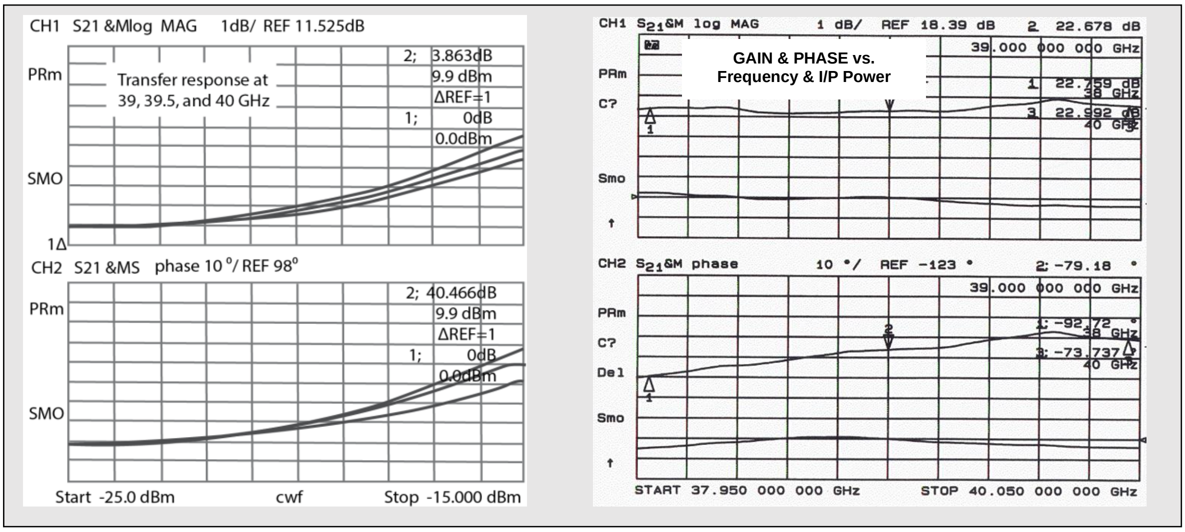

Figure 14. Linearizer transfer curve and frequency response to compensate a TWT, 38 to 40 GHz.

Linearization does not inherently improve an TWT's efficiency. It achieves a higher efficiency by allowing an TWT to operate at a higher output power for a given level of linearity. For a 2-tone C/I of 26 dB, linearization can provide more than 3 to 1 improvement in efficiency. For a C/I of 25 dB, linearization increased the available TWTA output power by > 3 dB, and for a C/I of 30dB linearization increased the available TWTA output power by > 5 dB as shown in Figure 15.

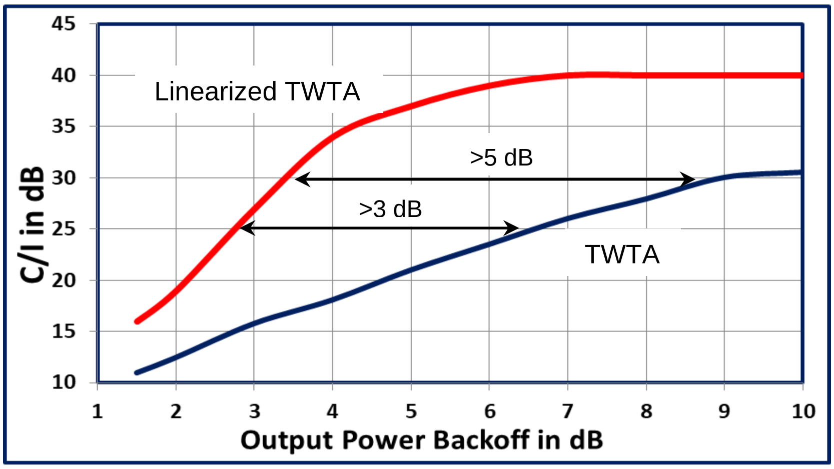

Figure 14. C/I improvement with linearization.

Summary

The results in this paper clearly illustrate the value of combining a linearizer with a HPA at MMW. This combination makes linearized HPAs highly attractive for commercial and military communications applications. A linearized HPA provides higher power, higher efficiency and higher linearity. A linearizer allows TWTAs, MPM, and SSPAs to provide 4 times the output power for C/I > 30 dB, and more than a 10 dB improvement in C/I over much of its power range. Similar improvements in APSK, QAM and WCDMA modulated signals' ACPR can also be realized.

Linearizers can turn HPAs into compact efficient high performance systems to better meet and exceed today's demanding MMW transmission requirements. This technology has value for both spaceborne as well as ground-based systems. MMW Portable, mobile and airborne communications systems are prime candidates for integration of this technology.

Acknowledgement

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