LINEARIZERS FOR Q AND V-BAND TWTAS

By Allen Katz, *Fellow, IEEE*, Robert Gray and Roger Dorval, *Member, IEEE*

Abstract — The need for information transmission at ever increasing data rates is moving satellites to the millimeter-wave (MMW) bands. The efficient transmission of information requires linear systems. For satellites transmission linear high power amplifiers (HPAs) are essential both in orbit and on the ground. This paper describes linearizers that have been developed for use with TWTAs at Q (43.5-45.5 GHz) and the new V (47-52 GHz) satellite bands. The paper will also discuss linearizer work for even higher bands that will be needed in the near future. Today's TWTA linearizers can provide all the frontend functions needed by an HPA including up-conversion, gain, commandable attenuation, commandable predistortion, and the RF power for direct drive. The use of linearization at MMW is discussed and measured characteristics of the linearizers such as power transfer and carrier to intermodulation (IM) ratio (C/I) shared. Linearized MMW TWTAs are shown to achieve an AM/PM of <2° /dB, and at 3 dB output power backoff (OPBO) with a 16QAM signal, an adjacent channel power ratio (ACPR) of > 30 dB with an EVM of < 2%.

***Index Terms* — linearizer, predistortion, millimeter-wave, TWTA, high power amplifier, wideband.**

I. INTRODUCTION

Satellites with many times the capacity of the past are needed to satisfy the growing demand for higher rates of information transmission. For example, the ViaSat-2 satellite, launched in 2017, has a total throughput of 300 Gbps, almost three times the capacity of ViaSat-1 launched only 5 years ago [1]. The new satellites often employ multiple beams, but require that the satellite's total throughput be transmitted through a single gateway beam. Such throughputs necessitate much greater bandwidths since information rate (IR) is dependent on bandwidth (BW) and signal-to-noise ratio (SNR) as shown in Equation 1,

$$IR \leq BW[1 + \log_2(S/N)] \qquad (1)$$

where noise is the result of both conventional noise and intermodulation (IM) products resulting from distortion, (N = N + IM). Thus IR is dependent on the linearity of a satellite system, which is usually determined by the linearity of a satellite's HPAs.

The need for greater information thus promotes the move to higher satellite bands. Now extensive commercial use is being made of Ka-Band, and the move to Q and V-band has begun. Q-band has been used primarily for military applications that did not require linearity due to the low information rate-efficiency modulation used. New commercial applications are requiring bandwidths of up to 5 GHz and in some cases even more. The Q and V linearizers discussed in this paper are the first to be produced and made commercially available.

HPAs are normally reduced in power or "backedoff" to achieve satisfactory linearity. For an in-orbit satellite application, backing off an HPA is devastating. As output power is reduced, efficiency rapidly decreases, and the power needed to operate the satellite is increased [2, 3, 4]. Ground stations also extensively use linearizers to improve linearity and save cost. For satellite communications (SATCOM) applications linearizing a TWTA can provide more than 6 dB of additional output power and more than double the efficiency. The acceptable level of distortion for most SATCOM applications is not established by in-band IM products. It is the adjacent channel IMs that interfere with co-channel communications that determine the maximum output power. The need for in-band distortion correction has increased as more complex BW efficient digital modulations (BEM) have been utilized. Coding techniques are used to mitigate this form of distortion; however, even with advanced coding, linearization can still make a significant performance improvement [5]. At Q and V-band linearization is especially important because of the difficulty in generating power at these frequencies.

II. LINEARIZATION AT Q AND V-BAND

The techniques used for linearization at MMW are fundamentally the same as used at lower frequencies. Predistortion linearization (PDL) remains the only linearization technique capable of achieving the overall efficiency and bandwidth required for SATCOM applications at Q and V-band. No matter how high the frequency, the predistortor (PD) must produce transfer characteristics that correct for the nonlinear characteristics of the HPA in both gain and phase. A gain variation of the PD with input level must cancel any variation in gain of the HPA with input level. Similarly, a phase change of the PD must cancel any change in phase of the HPA. Ideally a linearized HPA should maintain a constant gain and phase with input level to the point of maximum HPA output power [6, 7]. This point is often referred to as saturation (SAT).

At MMW the required BWs are normally much larger than at lower frequencies. The very wide BWs required at V and Q-band make digitally generated PDL (DPDL) used for many microwave applications impractical. PDL requires a correction BW 3 to 7 times the transmission BW, which must be processed. Digital processing of a 10 GHz or greater BW may be feasible today, but is too costly both in economic terms and in dc power for practical applications [8, 9]. DPDL has other complications at MMW. When multiple MMW signals are to be amplified, they cannot be linearized individually and then combined. The signals must be moved down to baseband, combined and then digitized for processing. In many cases such processing is not practical [10].

The strength of the analog PD technology used for the linearizers described in the paper is its ability to produce specified nonlinear gain and phase transfer characteristics over frequency, and to electrically control these characteristics to match the variations of different HPAs of the same type.

What makes designing a PD especially difficult for Q and V-band 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 a surface with frequency as the parameter. Figure 1 shows the gain and phase surface for a typical Q-band TWTA linearizer. Since an HPA's nonlinearity

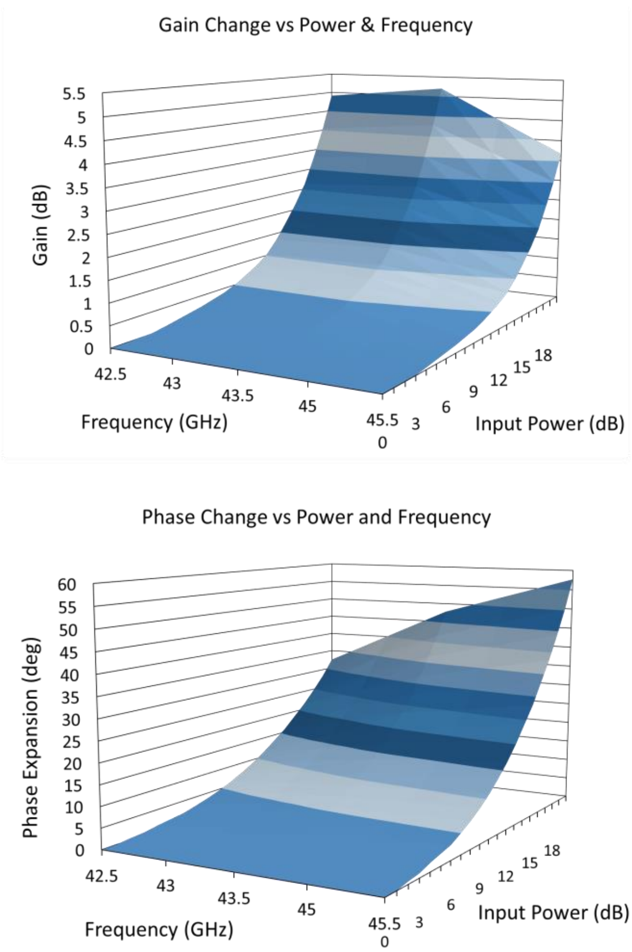

Fig. 1. Q-band linearizer relative change in Gain and Phase as a function of change in Pin and frequency.

varies with frequency, even a narrow band DPDL must change its nonlinear characteristics with frequency. To implement this change requires even more complex processing that further limits its capacity to handle wide BWs. Microwave DPDL systems adaptively change their correction characteristics to partially compensate for this degradation over frequency. At MMW the additional hardware (low distortion down conversion from MMW to baseband) add significantly to a DPDL's complexity and cost.

Analog PDs are designed to produce a gain/phase surface as a function of input level and frequency. The analog PD linearizers discussed in this paper shows how this technology has been extended to Q and V-band, and that appropriate PD action has been demonstrated to near 100 GHz. Instantaneous BWs of greater than 5 GHz have also been measured [11]. The PD design is an extension of the designs used successfully at microwave and Ka-band. It is based on an inline active FET PD, and employs GaAs HEMTs embedded in circuitry that is biased to provide the desired nonlinear transfer responses. The elimination of parasitic components not significant at lower frequencies was the major technical challenge. Extensive modelling was used to determine the critical components that required special attention. For example, the contribution of a via hole that could not be eliminated and was not significant at lower frequencies had to be worked around at these frequencies. In general it was learned that device size is a critical parameter for achieving the necessary PD characteristics.

III. LINEARIZERS FOR Q-BAND

A Q-band linearizer has been developed for use with SATCOM ground station TWTAs operating over a 43.5 to 45.5 GHz frequency range – see Figure 2. This linearizer module can be considered a min-system providing >40 dB of gain, a commandable 35 dB linear input gain attenuator, sufficient output power to directly drive available TWTAs (> 20 dBm), and requires approximately 6 watts of dc power. The unit also provides output attenuators, output power detector, a mute function, and utilizes 2.4 mm female connectors.

Fig. 2. Q-band linearizer module for a satellite uplink TWTA.

Figure 3 shows this linearizer's gain and phase transfer response as a function of frequency for small (< -30 dBm) and large signal input power levels (approximately TWTA SAT) across the satellite band.

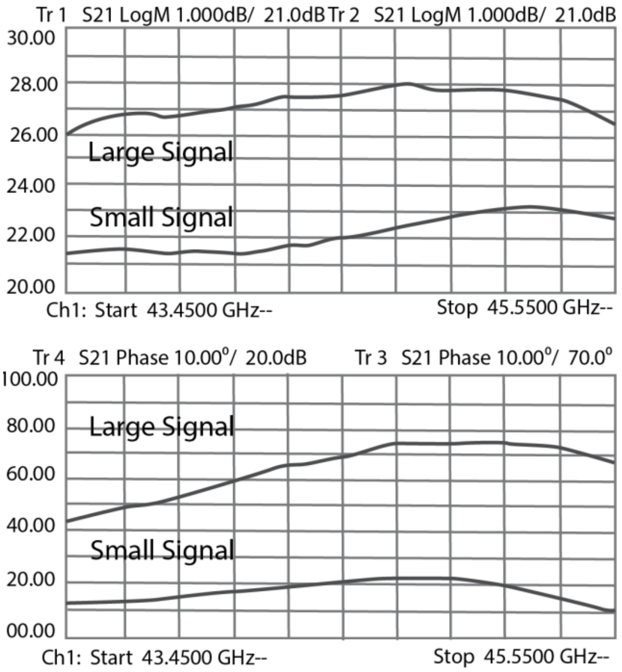

Fig. 3. Q-band linearizer's small and large signal gain and phase as a function of frequency.

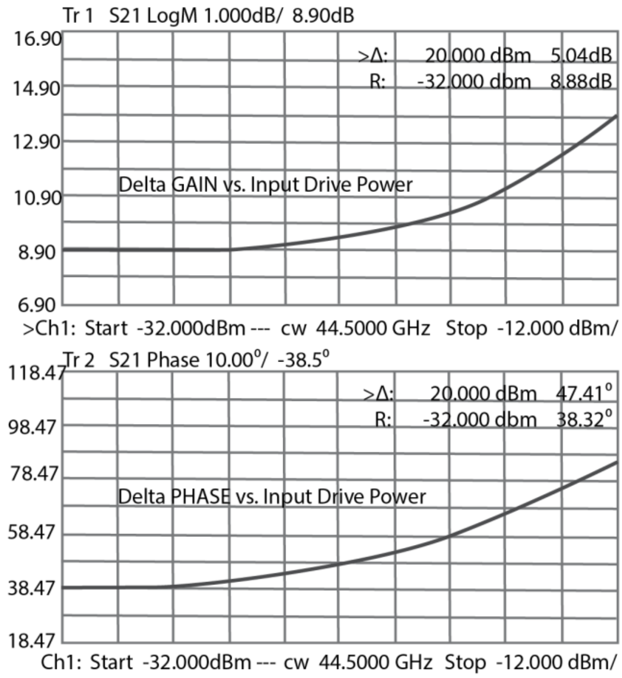

Fig. 4. Q-band linearizer's gain (AM/AM) and phase (AM/PM) transfer response at the center of the band (44.5 GHz).

Compensation of a TWTA's linear gain variations is essential for good linearizer performance. The linearizer's small signal gain has been adjusted to compensate the gain roll off of the TWTA's response. A 5.5 dB increase in gain with input drive power (gain expansion) is provided at the center of the band. In order to match the changing phase characteristics of the TWTA across Q-band, about a positive 30° change in phase with input drive power is provided at the low frequency end of the band. This phase change increases to near 60° at the high end. This difference is necessary in order achieve superior linearity across the band. Figure 4 shows the linearizer's gain (AM/AM) and phase (AM/PM) transfer response at the center of the band (44.5 GHz). Since TWTA's characteristics vary from tube to tube, the PD has been made electrically adjustable. It can, thus, compensate for a wide variety of TWTA nonlinear characteristics.

The linearizer was integrated with a TWTA and aligned for best linear performance. Figure 5 shows the measured transfer response of the TWTA without (a) and with the linearized (L-TWTA) (b).

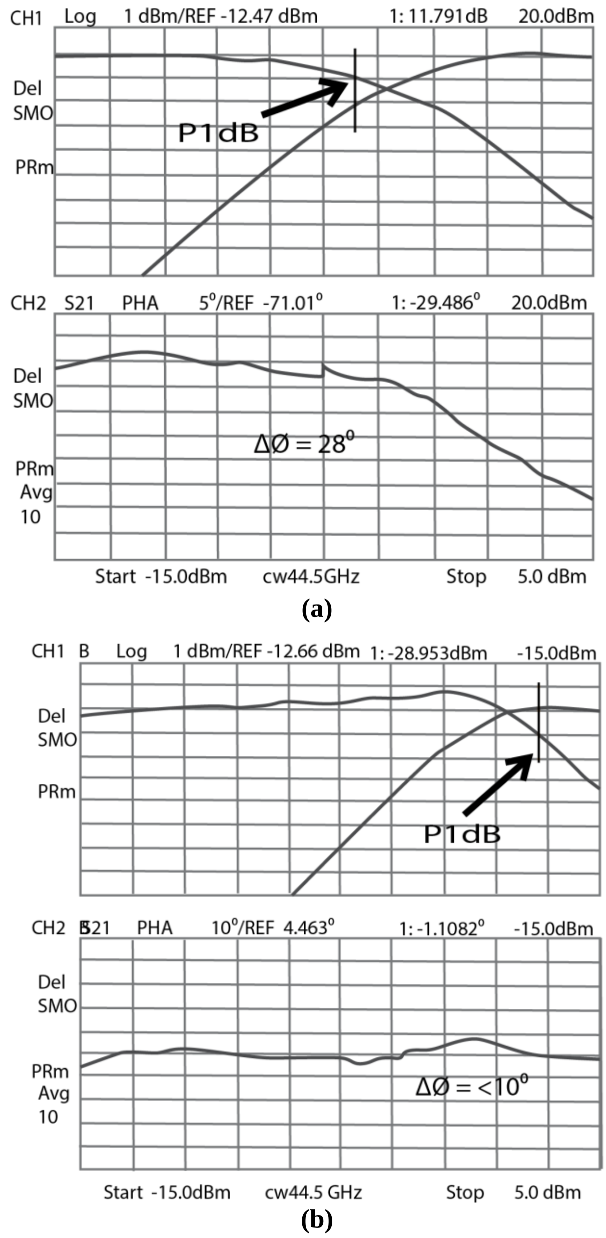

Fig. 5. Q-band gain and phase transfer response: (a) TWTA, and (b) L-TWTA; both at the center of the band (44.5 GHz)

The 1 dB compression point of the TWTA was moved from 7.0 dB to within 0.5 dB from SAT. Likewise, the change in phase was reduced from 28° to < 10°. These curves illustrate the ability of the linearizer to improve the linearity.

The measured 2-tone C/I versus OPBO with and without linearization is shown in Figure 6. Linearization allows the TWTA to operate at a 3 dB OPBO and provide more than a 26 dB C/I as compared to >8 dB OPBO for an unlinearized TWTA.

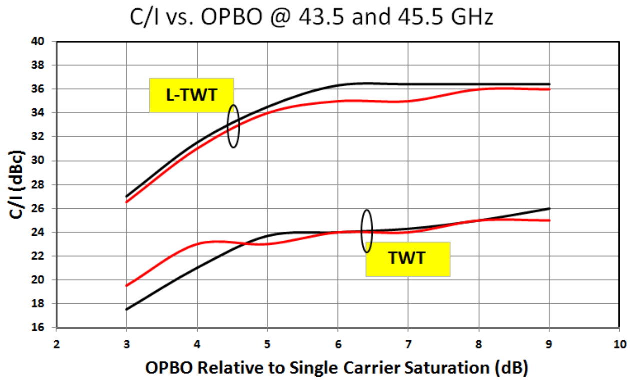

Fig. 6. 2-tone C/I of Q band TWTA and L-TWTA.

Table I shows the adjacent channel power ratios (ACPR) achieved with several different digital modulations at different OPBOs from SAT that were achieved with linearization.

TABLE I
ACPRS MEASURED WITH L-TWTA AT Q-BAND

MEASURE	7 dB OPBO	4 dB OPBO	3 dB OPBO
QPSK	44	40	36
OQPSK	45	38	35
64QAM	42	33	31

A TWTA linearizer has also been developed for the Q-band satellite downlink band located just below 40 GHz. The MMW circuitry is contained in the outboard module, which is made from Ni-Au plated Kovar with an Al inner cover and Kovar outer (sealed) cover and glassed-in hermetic DC and RF feedthrus. The substrates are 10 mil thick alumina ceramic; InGaAs pHEMT MMIC amplifiers are used with PIN Schottky diodes. The dc/control sections are basically the same as used in an earlier developed Ku-band flight linearizer [12]. Its functional block diagram is shown in Figure 7. The linearizer is shown in Figure 8.

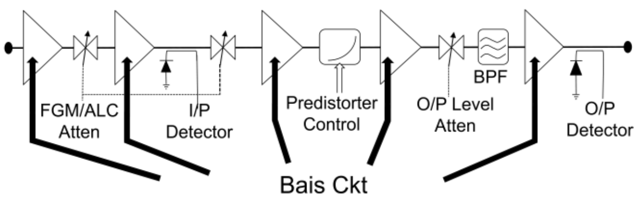

Fig. 7. Linearizer/Channel Amplifier (LCAMP) functional diagram.

Fig. 8. 40 GHz Satellite Linearizer/Channel Amplifier.

The linearizer's performance over the frequency range for 39 to 40 GHz is shown in Figure 9. The gain and phase transfer response at the low, mid and high ends of the band are shown. Note the increase in phase change between the low and high ends of the frequency range needed to correct the TWTA's expected nonlinear characteristics. Measured data for this linearizer with a 40 GHz flight TWTA is still not available.

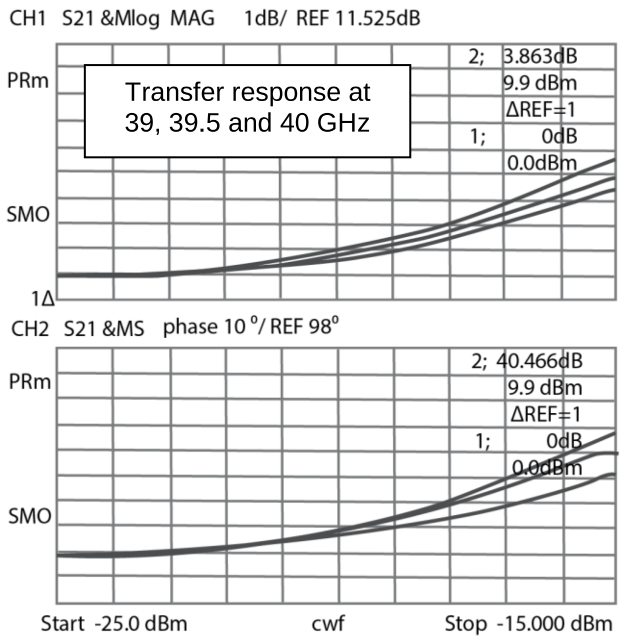

Fig. 9. 40 GHz linearizer gain and phase transfer response.

IV. LINEARIZERS FOR V-BAND AND ABOVE

A V band TWTA linearizer has been developed for the relatively new satellite uplink band from 47 to 52 GHz. At frequencies of Q-band and above, RF components have different characteristics, which must be considered during the linearizer design. The internal cavity size of the module becomes particularly critical to maintain stability. The V-band linearizer module is shown in Figure 10; it provides >40 dB of gain, produces an output power of +18 dBm and requiring approximately 4 watts of dc power. The unit includes a 30 dB input gain attenuator and utilizes 2.4 mm female connectors.

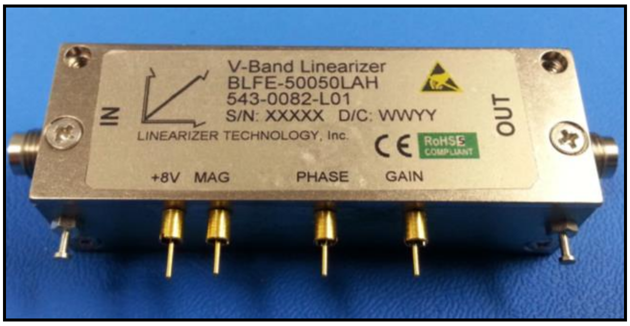

Fig. 10. V-band satellite uplink linearizer module.

The frequency response of the linearizer's gain and phase at both the small signal (< -30 dBm) and large signal (corresponding to TWTA saturation) input levels across the required 47 to 50 GHz band is shown in Figure 11. The linearizer has been designed to provide more gain at the low end of the band to compensate the TWTA's linear response. At mid band, the increase in gain with input drive power is about 6.5 dB, while the change in phase with is about 50°, which match the characteristics of the TWTA. Figure 12 shows the linearizer's AM/AM and AM/PM transfer response at mid-band, 48.5 GHz. The V-band PD is electrically adjustable as at lower frequencies to provide a wide variety of nonlinear characteristics versus frequency.

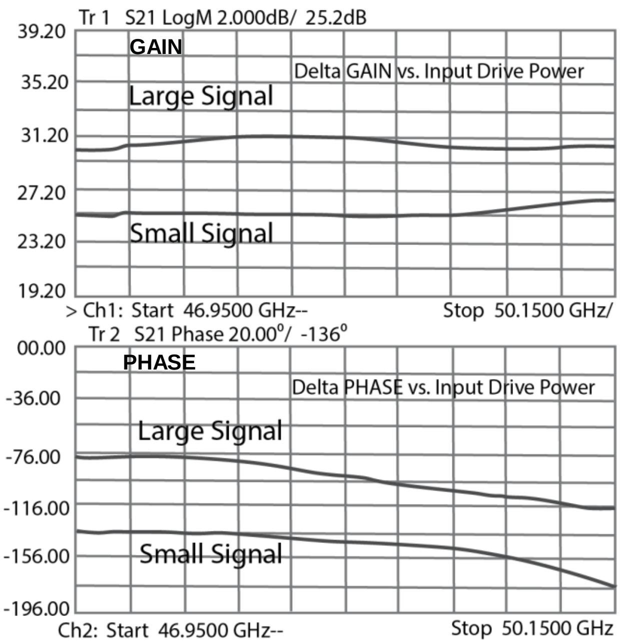

Fig. 11. V-band linearizer's frequency response showing both small signal and large signal levels.

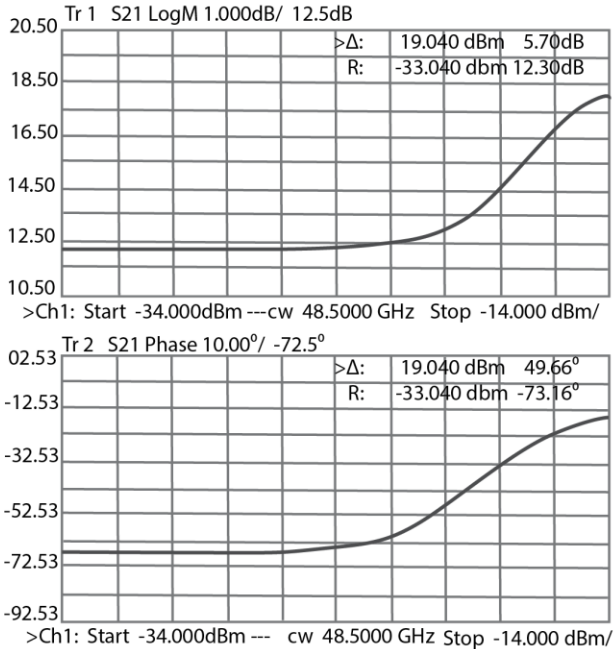

Fig. 12. Transfer response (AM/AM, AM/PM) of V-band linearizer at center band.

The results of testing with the TWTA was not available at the time of writing this paper; however, simulation software that shows the result of integrating the actual transfer data from the linearizer module and the TWTA show the resulting L-TWTA performance should be excellent. Figure 13 shows the TWTA power transfer response has about 7 dB of gain compression and 40 degrees phase change at SAT. The predicted transfer response of the L-TWTA is illustrated in Figure 14. Linearization moves the 1 dB compression point of the TWTA to within 0.5 dB in input power from SAT, and the phase change is reduced to < 3°.

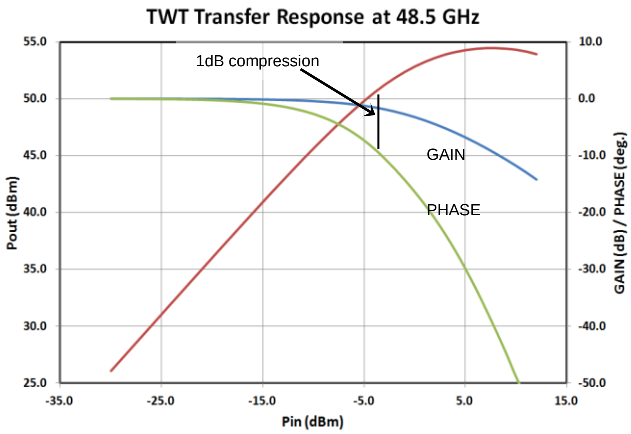

Fig. 13. Transfer response of V-band TWTA a center band.

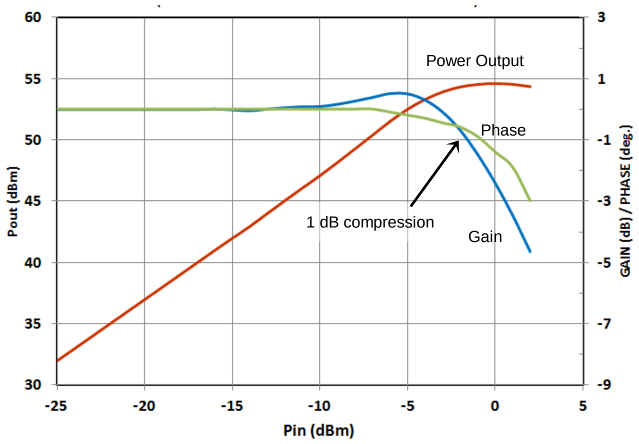

Fig. 14. L-TWTA predicted transfer response at 48.5 GHz.

These curves show the ability to significantly improve the linearity at V-band. Table II lists the simulated performance of 2-tone C/I, NPR, and ACPR at OPBOs of 3 and 4 dB.

TABLE II
SIMULATED ACPRS MEASURED WITH L-TWTA AT Q-BAND

MEASURE	OPBO=3dB	OPBO=4dB
2- Tone C/I	>25 dB	>30 dB
NPR	>16 dB	>19 dB
ACPR (1 symbol spacing)	>30 dB	>35 dB

There is also significant interest in linearizers for higher V-band frequencies (71 to 76 GHz), and E-band (81 to 86 GHz) and W-band (91 to 96 GHz). Figure 15 shows a demonstration linearizer produced for E and W band with SBIR funding. It provides > 35 dB of gain, produces an output power of +20 dBm, and requires approximately 6 watts of dc power. The unit utilizes WR-10 flanges for input and output connections. In tests with a variety of TWTAs, it has consistently demonstrated to increase linear output power by more than 5 dB as demonstrated in Figure 16 [13, 14].

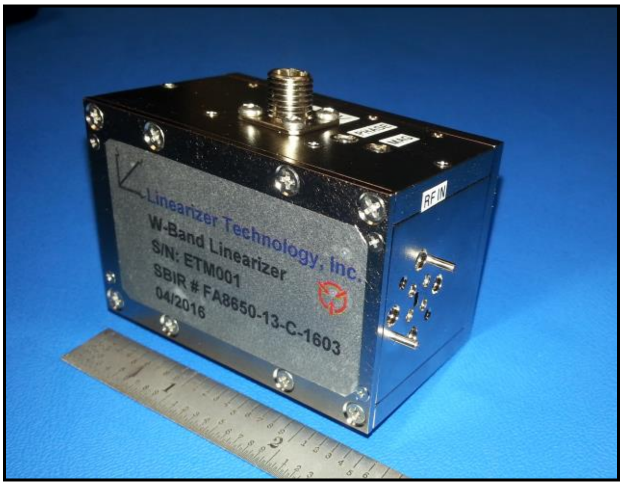

Fig. 15. Demonstration W and E band linearizer module.

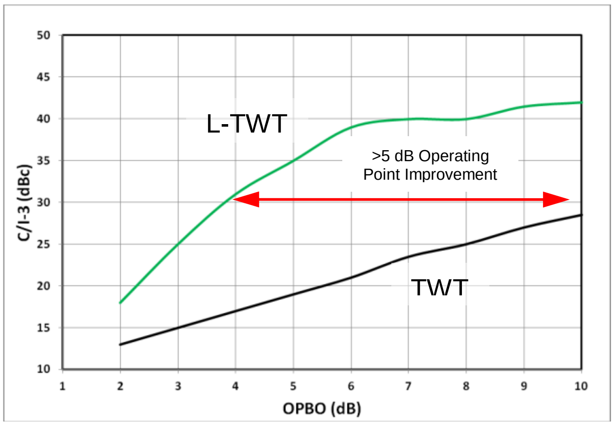

Fig. 16. Measured 2-tone C/I of L-TWTA at W-band.

V. CONCLUSION

The results in this paper clearly illustrate the ability to linearize TWTAs at Q and V-band. This combination makes linearized TWTAs highly attractive for commercial and military communications applications. The linearized TWTA provides higher power, higher efficiency and higher linearity. The linearizer allows a TWTA to provide 4 times the output power for C/Is > 30 dB, and more than a 10 dB improvement in C/I over much of its power range. Similar improvements in operation with single and multiple carrier digital BEM operation can be realized.

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

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