Advances in Ka/Q Band Linearization

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ABSTRACT

It is now more than ten years since Linearizer Technology, Inc. (LTI) introduced the first millimeter wave (MMW) linearizers. During this time the capabilities of MMW linearizers have advanced tremendously. Today's MMW linearizers operate at higher frequency (> 45 GHz), provide wider bandwidth (> 10 GHz), and give greater performance (> 20 dB NPR at 4 dB OPBO). They also operate with a wider variety of MMW power devices (TWTAs – helix and coupled cavity, Klystrons and EIKs, MMPMs and SSPAs). More than 1 kW of MMW linear power can be produced today with high efficiency in a relatively small package. This paper discusses the state-of-the-art in MMW linearization and provides a road map of what to expect in the future.

INTRODUCTION

At MMW both highly efficient and linear high power amplifiers (HPAs) are indispensable in radio systems. Applications include satellite terminals, broadband wireless communications and high-speed data links [1,2]. For Ka-band and above, RF power is both difficult to generate and expensive. In order to send information at a high data rate over a limited bandwidth, linearity is essential. For satisfactory performance, MMW HPAs often need to be backed off from their rated power level by 6 to 10 dB and sometimes even more. The only solution to the MMW power problem is linearization. Linearization reduces amplifier distortion, allowing an amplifier to provide greater output power, and operate at higher efficiency [3].

In 1997 LTI started production of the first commercially available MMW linearizers [4]. These linearizers operated up to 30 GHz, over not much more than a GHz of bandwidth and did not equal the performance of linearizers on the microwave bands. They were also designed to operate only with helix type TWTAs. Since 1997 great strides have been made in MMW linearizer design. This paper reviews some of the milestones in Ka-band linearizer development, provides data on the performance that can be achieved today with different forms of MMW HPAs and makes some projections on what to expect in the future.

MAXIMUM FREQUENCY OF OPERATION

Prior to the introduction of MW linearizers, the highest frequency in production was for DBS band (17.3 to 18.4 GHz). These linearizers were produced using packaged devices. It was recognized that to achieve satisfactory performance a chip and wire approach was needed to avoid the parasitic affects of packages. The first units operated in the frequency range from 26.5 to 30 GHz. It was not until 2002 that requests were received to extend the frequency of operation to 32 GHz, which did not require a significant modification of the existing design.

In 2004, the maximum frequency of operation was moved to the edge of Q-band. Linearizers were produced for the 38 to 40 GHz frequency band [5]. A new design in a smaller RF cavity was developed for this application. The excellent frequency response achieved is shown in Figure 1A. This figure shows the linearizer's gain and phase at both small signal power and at a power level corresponding to saturation. Note the increased change in phase (with power) at the high end of the frequency range. This characteristic is normally required for best performance across a wide band by TWTAs. Figure 1B shows the corresponding gain and phase transfer responses at 38, 39 and 40 GHz.

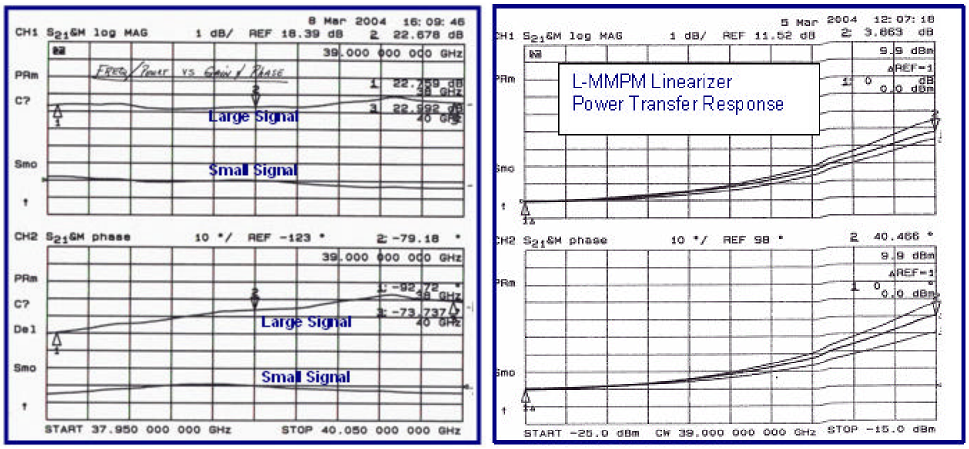

Figure 1. 40 GHz linearizer: a) Gain and phase correction at small and large signal, b) Power transfer at 38, 39, and 40 GHz.

In 2007 a Q-band linearizer was developed to bring the maximum frequency of linearization to above 45 GHz. A picture of this new Q-band linearizer is shown in Figure 2. Its frequency response and transfer characteristics are shown in Figure 3. Although the need does not presently appear to exist, it should be possible to push the MW linearizer operating frequency into V-band and even as high as 100 GHz using the same techniques used to produce the Q-band linearizer.

Figure 2. Q-band linearizer operating from 43.5 to 45.5 GHz.

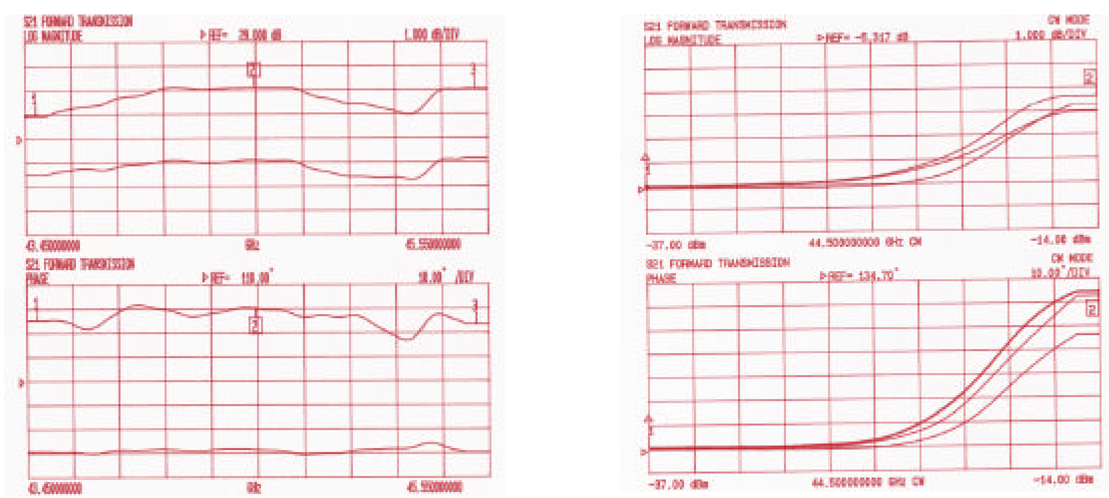

Figure 3. Q-band linearizer: a) Gain and phase correction at small and large signal, b) Power transfer at 43.5, 44.5 and 45.5 GHz.

BANDWIDTH

The first MW linearizers required bandwidths of 1 GHz or less, but as interest in linearizers for satellite applications grew after 2000, the operational bandwidth was extended first to 2 GHz, then to 3 GHz and finally to 3.5 GHz. More recently there has been interest in very wideband linearizers [6]. Figure 4 shows the frequency performance of an experimental MW linearizer having more than 10 GHz of useful bandwidth. These results are believed to be the widest MMW (and TWTA linearizer) results reported. In the future it is expected that the demand for such wide band linearizers will increase for applications other than communications, such as radar, where the value of linear amplification is only beginning to be appreciated.

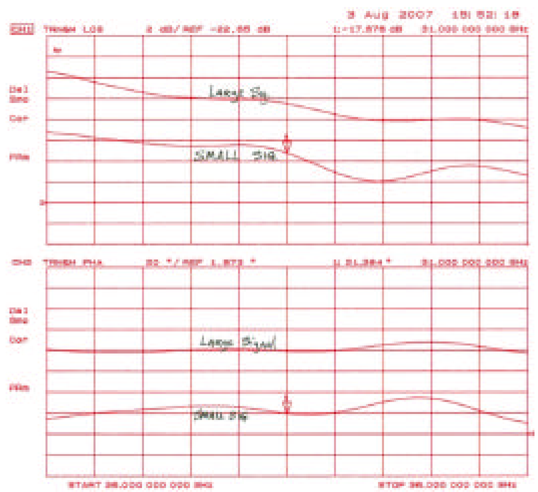

Figure 4. Frequency response of MMW experimental linearizer having > 10 GHz of useful bandwidth.

Besides operational bandwidth, dynamic bandwidth is a concern at MMW. Even though a linearized HPA may have a wide operational bandwidth (corrects the distortion of a narrow, fractional, bandwidth signal across the full band), it may not work well with a very wide band signal or multiple widely spaced signals. The dynamic bandwidth depends on both the linearizer and the HPA. At Ka-band there was concern that linearized TWTAs would function with very widely spaced multi-carrier and/or complex modulated signals. Tests were conducted to verify linearizer performance with very wideband signals. Figure 5 illustrates the performance of a linearized TWTA with two groups of simultaneous multi-carrier signals spaced almost 2 GHz apart. Two 40 MHz wide noise pedestals were actually used to simulate the multi-carrier signals. The measured noise power ratio (NPR) is shown in the figure. This data demonstrates that widely spaced groups of signals can be successfully linearized. Since these tests were conducted, several satellite systems employing linearized TWTAs with widely spaced signals, such as IPSTAR, have been put into service.

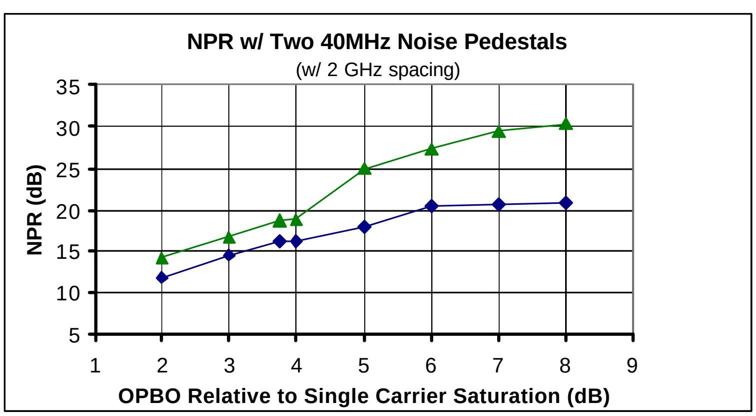

Figure 5. NPR of two noise pedestals linearized simultaneously.

VERSITILITY

Performance with helix TWTAs: A linearizer's transfer characteristics must be the opposite of the HPA's in both magnitude and phase. The gain increase of the linearizer must cancel the amplifier's gain decrease. Likewise, the phase change of the linearizer must cancel the phase change of the amplifier. The closer the linearizer comes to achieving this task, the better its performance. The ability to tailor and adjust a linearizer's gain and phase transfer response is the key to a successful linearizer. Since producing the first MMW linearizers, LTI's ability to produce different linearizer non-linear characteristics has been greatly enhanced. Today, the resulting intermodulation (IMD) suppression at Ka-band should in every way be as good as can be achieved on the microwave bands and come close to that of an ideal limiter. Typical MMW linearized TWT IMD specifications are given in Table 1. Superior performance can often be obtained. The figures shown are for production linearizers and include the affect of temperature.

Table 1 Linearized TWTA Performance

MEASURE	OPBO = 3 dB	OPBO ≥ 4 dB
2-TONE C/I	> 25 dB	> 30 dB
NPR	> 16 dB	> 19 dB
ACLR AT 1 SYMB SPACING	> 30 dB	> 35 dB

High IP TWTAs: In addition to linearizing conventional helix TWTAs, linearizers have been developed for operation with high intercept point (IP) TWTAs [7]. These TWTAs are designed for linear performance and efficiency and can normally not be operated at an output power backoff (OPBO) of less than 3 dB. The use of linearizers with these tubes still gives a large dividend. Even with the OPBO restriction, for a single QPSK modulated carrier requiring an adjacent channel level ratio (ACLR), spectral regrowth, of 30 dB at 1 symbol spacing, the linearizer still provides almost 3 dB of additional RF power.

Microwave power modules (MPMs): MMW linearizers have been tailored for use with MPMs. An MPM is a microwave power amplifier that integrates a miniature traveling wave tube (TWT), a solid- state driver amplifier and a power supply into a single housing [8,9]. This combination takes advantage of the small size, low noise and high gain of solid-state devices at low power levels and the high efficiency and small size of TWT technology at higher powers to produce what has been described as a "super component". At MMW, MPMs are referred to as MMPMs.

One of the first MMPMs employed a miniature high IP TWT with a linearizer to provide very high linearity and high efficiency for high-speed data links. This MMPM is pictured in Figure 5. It is housed in a package 9.5" x 5.9" x 1.6" and has a mass of 4.2 lb. Figure 6 shows respectively the ACPR calculated for 16QAM, 64QAM and 256QAM signals as a function OPBO for the MMPM with and without linearization. At 7 dB OPBO (20 watts), the linearized case shows > 45 dB ACPR for all three modulation rates, while at 10 dB OPBO the unlinearized case shows < 40 dB ACPR. The corresponding measured spectral responses of the linearized MMPM at 7 and 10 dB OPBO are shown in Figure 7 a and b respectively. The use of linearization in this application provides almost a 3 to 1 reduction in dc power and related HPA efficiency.

Figure 5. First Ka-band linearized MMPM used a miniature high IP TWT.

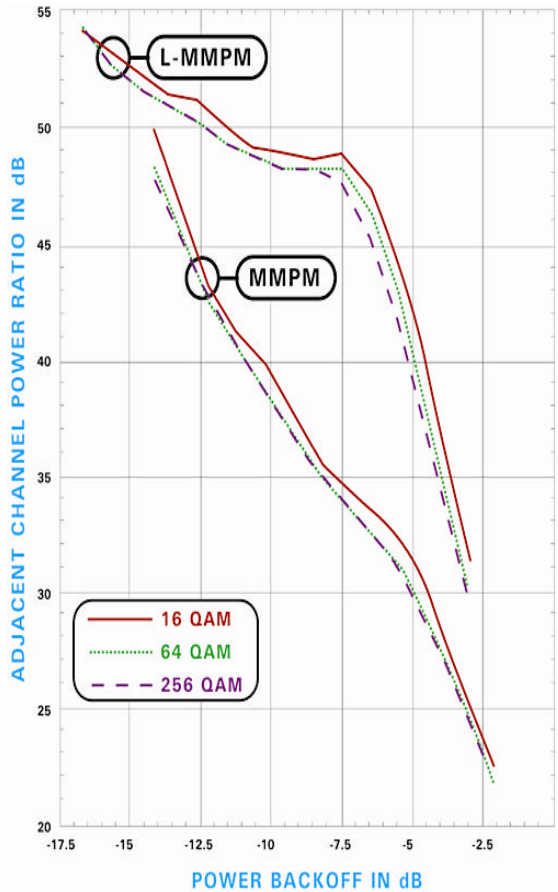

Figure 6. MMPM calculated ACPR with 16, 64, and 256QAM with and without linearization.

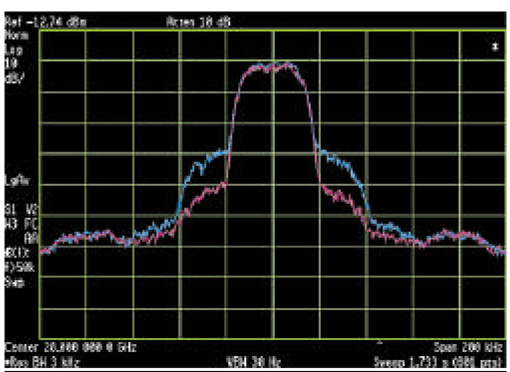

Figure 7a. Spectral response of MMPM with a 16QAM signal at 7 dB OPBO with and without linearization.

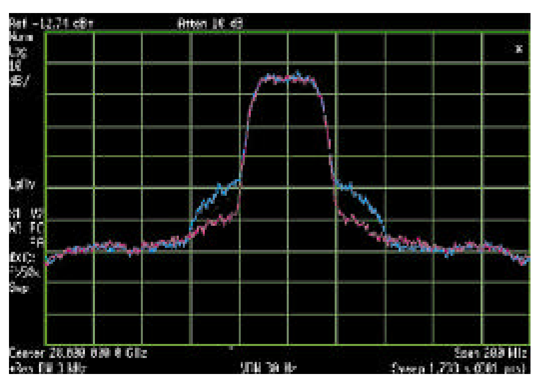

Figure 7b. Spectral response of MMPM with a 16QAM signal at 10 dB OPBO with and without linearization.

Coupled-cavity TWTAs: A MMW linearizer was developed to correct coupled-cavity TWTAs (CC-TWTAs) distortion. CC-TWTAs tend to have non-linear characteristics similar to helix type TWTAs, but with much greater variation over frequency and usually a lower change of phase with power level. The challenge with coupled-cavity TWTAs is to tailor the linearizer's non-linear characteristics over frequency to match those of the CC-TWTA. This process involves changes in both the linear and non-linear characteristics of the linearizer over frequency. LTI has had good success linearizing CC-TWTAs [10]. Figure 8 shows the performance achieved by a linearized 500 watt Millitron CC-TWTA.

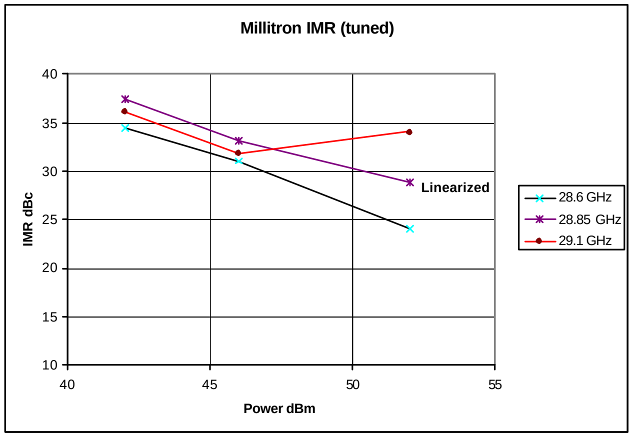

Figure 8. Two-tone C/I achieved with 500 watt Millitron HPA.

Klystrons and EIKs: Klystrons power amplifiers (KPAs) have non-linear characteristics similar to CC-TWTAs, but with a narrower bandwidth. The principal advantage of KPAs is their ability to produce high power levels. LTI has had limited experience linearizing KPAs at MMW, but has demonstrated the ability to linearize both standard and EIK KPAs at MMW.

SSPAs: SSPA non-linear characteristics are much more varied than TWTAs and KPAs. At microwave and MMW frequencies GaAs (and in the future GaN) FETs are the primary solid state devices of interest for HPA applications. At lower microwave frequencies these devices usually produce more linear amplifiers than TWTAs and KPAs, but at higher frequencies their linearity degrades. At MMW, SSPAs show little or no linearity advantage over vacuum technology and benefit greatly from linearization. The transfer characteristics of a linearizer developed for a GaAs Ka-band HPA is shown in Figure 9.

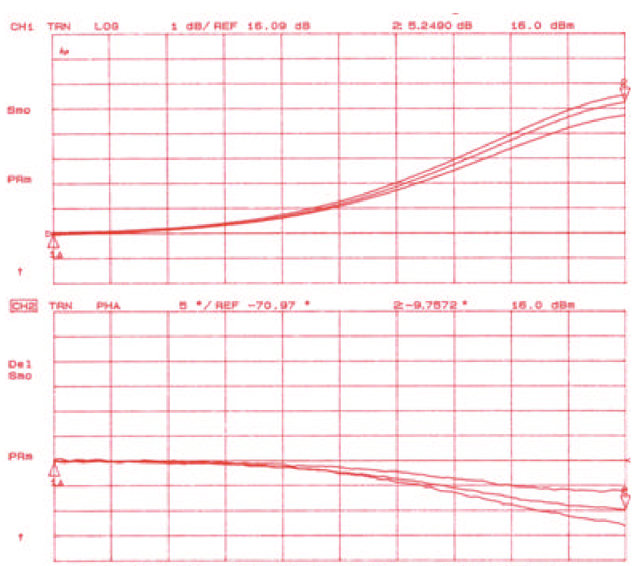

Figure 9. Typical MMW SSPA linearizer gain and phase transfer characteristics at 30, 30.5 and 31 GHz.

Note that the phase decreases with increasing power – see Figure 1. This change is the opposite of TWTA/KPA linearizer characteristics, and is typical of what is required by GaAs and GaN SSPAs. Figure 10 shows the C/I achievable with linearization. The data shown is for a 20 watt 30 to 31 GHz SSPA using GaAs MMIC power devices, and at the frequency of the worst C/I performance across a 1 GHz band. At a C/I of 25 dB, linearization provides nearly at 6 dB power advantage. GaN devices tend to be even more non-linear than GaAs, thus there should be an even greater advantage to linearizing GaN SSPAs when they become available at MMW. Because of the huge benefits, it is very likely that there will be more use of linearization with MMW SSPAs in the future.

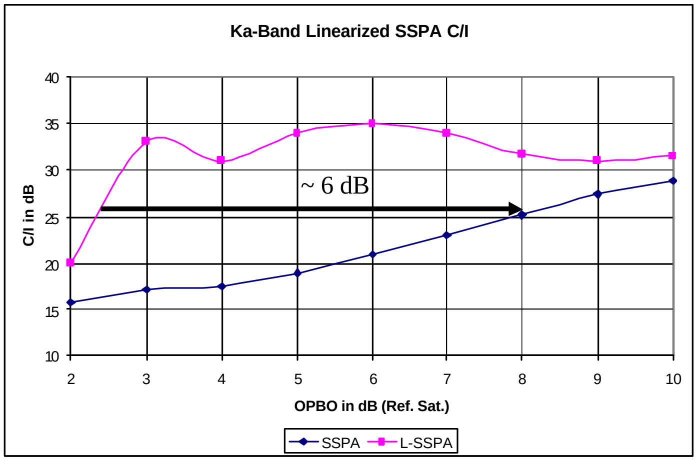

Figure 10. C/I improvement achieved by linearizing a MMW SSPA.

Dynamic bandwidth can be an even greater concern for SSPAs than TWTAs. Proper decoupling of an SSPA's bias circuits is important for a wide dynamic bandwidth. Fortunately, achieving proper decoupling is easier at MMW than at lower frequencies.

PACKAGING AND FUNCTIONALITY

The size and related mass of MMW linearizers have decreased since their introduction. Figure 11 shows the housing for a BAFL-28000G linearizer.

Figure 11 The BAFL28000G was the first MMW linearizer.

This unit was the first MMW linearizer to be put into production and initially provided only basic linearization. It is 0.79" x 2.75 x 3.95", has a mass of about 235 g (depending on options) and uses K connectors. This form factor linearizer is still very popular, but besides linearization it can include all the functions (high gain, wide range attenuator, limiting …) of a complete linearized frontend (BLFE). In 2004 a smaller package was developed for Ka applications. This housing is the BAFL-28000L (or BLFE-28000L with linearized frontend). It is 0.85" x 0.69" x 2.5" in size and 45 g in mass. It was used for the Qband linearizer illustrated in Figure 2. For applications above Ka-band 2.4 connectors are used. An even smaller package was developed for MPM/MMPM applications and is shown in Figure 12. This module is 0.6" x 0.6" x 2.75" and has a mass of only 37 g.

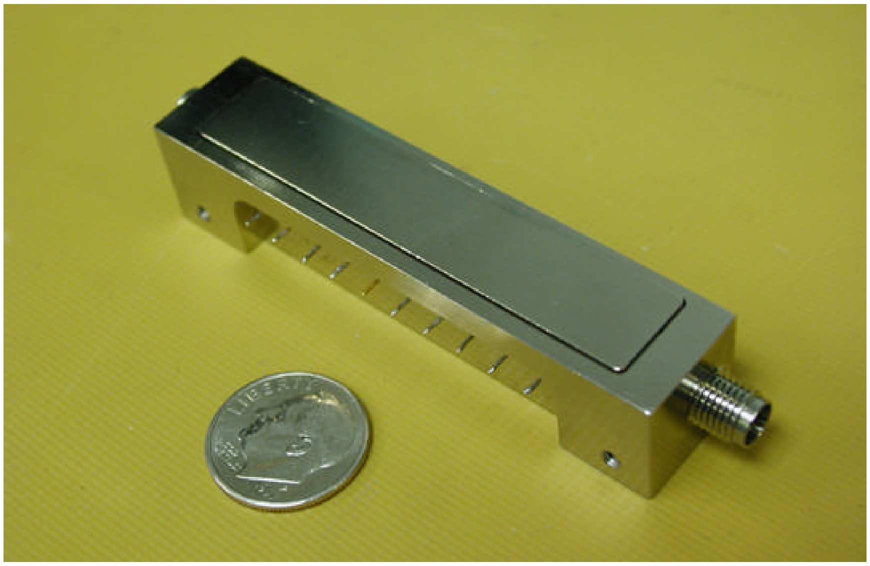

Figure 12 MPM/MMPM linearizer housing

SUMMARY

In the ten years since the introduction of MMW linearizers significant technological advances have been made. MMW Inearizers now are available for both Ka and Q-band. They can now provide near ideal performance and operation over greater than 10 GHz of bandwidth. MMW linearizers have been produced for helix and CC-TWTAs, KPAs and EIKs and a variety of SSPAs. The growing need for linearity and power is making linearization at Ka-band a necessity. A linearized HPA (TWTAs and SSPAs) can deliver more than a 4-fold increase in power capacity for many MMW applications. An increasing need for MMW linearizers in anticipated.

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