REFERENCES

[1] C. L. Kory and J. A. Dayton, Jr., "Accurate cold-test model of helical TWT slow-wave circuits," *IEEE Trans. Electron Devices*, vol. 45, pp. 966–971, Apr. 1998.
[2] R. T. Longo, *IEDM Tech. Dig.*, 1984.

Computer Simulation of Intermodulation Distortion in Traveling Wave Tube Amplifiers

Richard G. Carter, Wolfgang Bösch, Vishnu Srivastava, and Giuliano Gatti

***Abstract*—The intermodulation performance of a helix TWT was computed using a large-signal disc model with two, three and eight correlated carriers and also using the program IMAL which models a generalized nonlinearity described by its single carrier transfer characteristics. The results obtained by both methods showed good agreement. The inter-modulation performance of a TWT for both correlated and uncorrelated carriers can therefore be predicted from its single-carrier transfer characteristics if they do not change significantly over the frequency range of interest.**

I. INTRODUCTION

Contemporary communications satellites use an array of channel amplifiers whose frequency bands are set by the system hardware before the satellite is launched. This has the disadvantage that the system cannot subsequently be reconfigured to meet changing needs during the lifetime of the satellite. A possible solution to this problem is to use broad-band traveling wave tube amplifiers (TWTAs) in a Butler matrix [1] to provide a single broadband amplifier capable of handling all the downlink traffic. A system using such an amplifier could be reconfigured to carry a variety of carriers having different powers and bandwidths in frequency domain multiplex. The amplifier would need to have a dc to RF conversion efficiency exceeding 50% without the generation of unacceptable levels of intermodulation distortion to be a viable alternative to existing narrow band amplifiers with efficiencies of up to 70%.

The individual carriers used in space communication systems are normally phase modulated using a scheme such as QPSK. If it is assumed that the modulating signals are random, it follows that all possible phase relationships between the carriers occur with equal probability. Thus, the instantaneous carrier power can be greater than, or less than, the mean power according as the carriers combine constructively or destructively. For two carriers, this situation can be modeled using unmodulated signals since all possible phase combinations occur with equal probability during one complete cycle of the difference frequency of the carriers. For three, or more, carriers, however, it is necessary to employ Monte-Carlo methods to achieve the results required.

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An examination of the peak power distribution computed for ten equal carriers shows that the instantaneous power covers a range of -20 dB to $+10$ dB relative to the mean power. There is a high probability that the instantaneous power level is 3 dB or more above the mean. If an idealized amplifier, whose am/am curve is linear up to saturation and constant thereafter, were supplied with ten equal phase-modulated carriers it would be necessary to set the mean input power 10 dB below saturation to avoid all nonlinear effects. The result would be that the mean output power would be 10 dB below the saturated output power, and the efficiency would be reduced to 10% of the saturated efficiency. This loss of efficiency is unacceptable in amplifiers for space applications because it leads to increases in the size and weight of the amplifier and of the waste energy that must be dissipated as heat. The challenge for the TWT designer is, therefore, to design a tube that can be operated as close as possible to saturation whilst achieving specified levels of inter-modulation distortion. This task requires the ability to predict the inter-modulation performance of each design using computer simulations.

II. MODELING THE MULTICARRIER PERFORMANCE OF A TWT

It is well known that the performance of a TWT under large-signal conditions can be modeled by a Lagrangian analysis in which the electron beam is represented by an assembly of discs, or rings, of charge whose motion is tracked under the influence of the RF field of the helix. These models assume a sinusoidal input signal. The computer program LSM, developed jointly by CEERI and Lancaster University includes multiple input signals, signal harmonics and intermodulation products provided that a base frequency can be defined which is the highest common factor of all the signal frequencies present [2], [3]. The model includes details of the electron beam, and the propagation constant and interaction impedance of the helix slow-wave structure at each frequency as a function of axial position in the tube. It can therefore be used to investigate the effects of changes in the design of the TWT on its intermodulation performance with correlated, unmodulated, carriers. It is also possible to study the effects of changing the phase relationships between the carriers by varying the input data. Although it would be possible, in principle, to simulate TWT performance with multiple, uncorrelated, carriers using this method, the computer time required is generally too great.

An alternative approach, which is much less time consuming, is to model the TWT as a generalized nonlinearity described by its single-carrier transfer characteristics. The program IMAL was developed at ESTEC for this purpose [4]. Basically, IMAL utilizes an input signal defined in the frequency domain. An initial random phase value is assigned to each spectral line and the spectrum is converted into the time domain using the inverse fast Fourier transform (IFFT). As we are interested in the intermodulation falling in the amplifier band, the bandpass input signal is then converted to a complex lowpass equivalent one (complex envelope) and this is distorted using the nonlinear characteristics of the microwave amplifier. A linear interpolation routine is used to distort the signal and it is then transformed back to the frequency domain (FFT) to obtain the desired characteristics. In general the phases of the spectral lines in a multicarrier signal are statistically independent. Hence the output spectrum has to be averaged over many different random phase settings of the input signal. For standard nonlinear amplifier responses, convergence is generally obtained after 50 to 500 interations. This approach is valid only for quasi-memoryless nonlinear systems, but a well designed microwave amplifier normally falls within this category. It assumes that the transfer characteristics do not vary appreciably over the frequency range to be studied.

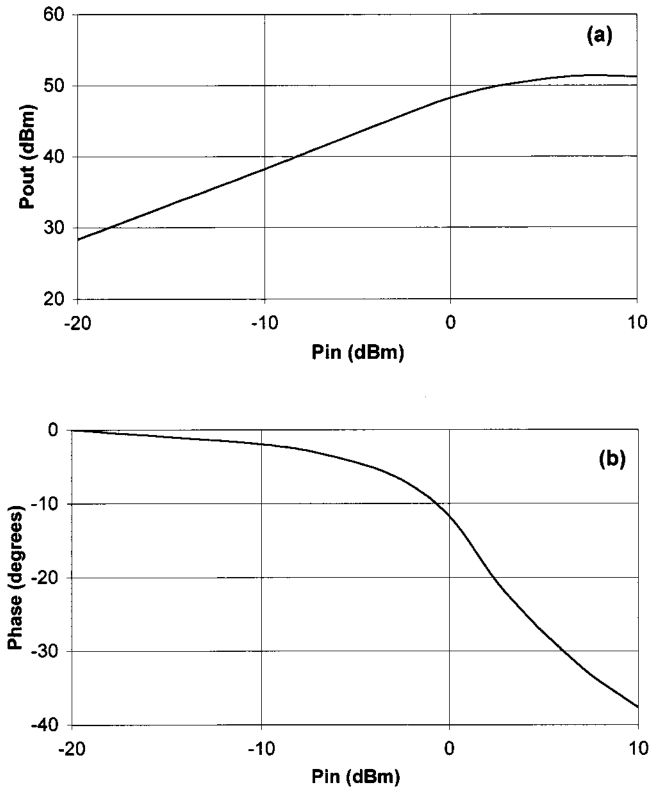

Fig. 1. Single carrier transfer characteristics (a) AM/AM and (b) AM/PM.

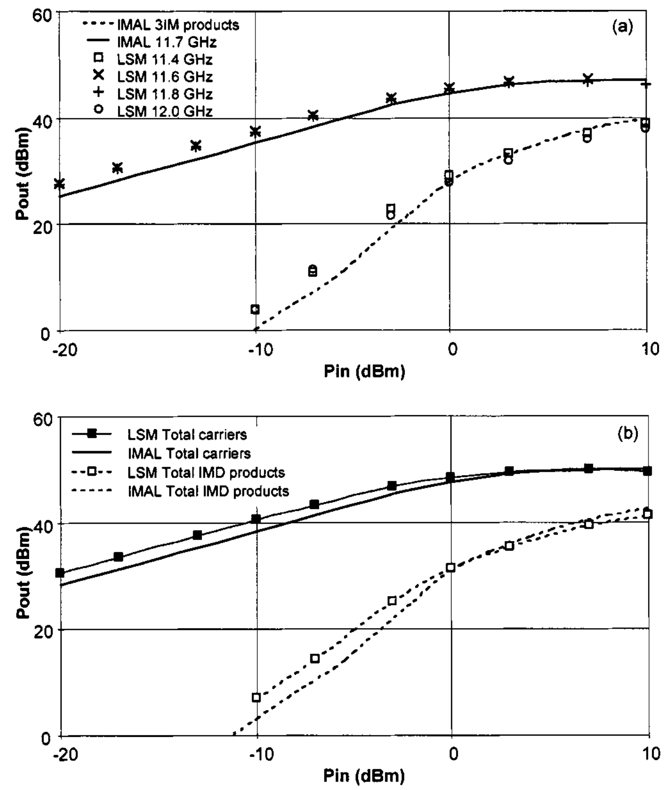

Fig. 2. Comparison between LSM and IMAL results for two carriers.

III. Comparison Between IMAL and LSM

Detailed analysis of the nonlinearity of a TWT reveals complex behavior in which the trajectories of individual electrons may cross over each other so that their positions and velocities are no longer single-valued functions of the RF phase at which they entered the tube. Such crossovers normally begin to occur at approximately the input signal level for which the transfer characteristics are perceptibly nonlinear. It is not self-evident, therefore, that the nonlinear performance of a TWT can be represented adequately by an analysis based on its single-carrier transfer characteristics. A comparison was made between results obtained using IMAL and LSM for three cases:

- two equal carriers;
- three equal carriers with phases varied in 60° steps;
- eight equal carriers.

The TWT simulated comprised a single section without attenuators or variations in the helix pitch. Its single-carrier transfer characteristics are shown in Fig. 1(a) and (b). The AM/AM curve varied only slightly over the band from 10.7 to 12.7 GHz and the variation of phase at saturation was about 10° over the same band.

A. Two Carriers

The performance of the TWT was simulated using LSM with two carriers, their harmonics and the third-order inter-modulation products. Three tests were carried out using pairs of carriers centered on 11.7 GHz with separations of 200, 400, and 600 MHz. The results obtained were very similar in all three cases and any differences could be attributed to variations of the transfer characteristics (especially the AM/PM curves) with frequency. The same simulation, with the exception of the harmonics, was carried out using IMAL. The results obtained by the two methods are compared in Fig. 2(a) and (b). It can be seen that there is close correspondence between these two figures. The LSM results show slight separations between the curves for the two carriers and the two third-order intermodulation products because of the frequency variation in the transfer characteristics.

B. Three Carriers

Calculations were carried out using LSM with three equal carriers at frequencies of 11.4, 11.6, and 12.0 GHz and intermodulation products at 11.2, 11.8, and 12.2 GHz. The relative phases of the carriers were varied in steps of 60° to make a total of 36 cases. It was found that the total carrier power varied between 49.3 dB and 49.6 dB over the range of relative phases investigated. The variation of the total power in the intermodulation products was between 34.0 dB and 37.0 dB. Results were obtained using IMAL for the same phase relationships and Fig. 3(a) and (b) shows the comparison between the two sets of results for correlated carriers and for the average of the 36 phase combinations. It can be seen that there is a close correspondence in both cases. IMAL was also used to generate results for random phase variations and these were found to differ from the case with thirty-six variations by only about 0.1 dB.

C. Eight Carriers

Finally, results were computed for eight correlated carriers at intervals of 200 MHz in two groups of four with a gap of 400 MHz between them. Intermodulation products were computed in the gap between the two groups and 200 MHz below and above the complete set. The same case was computed using IMAL and the results are shown in Fig. 4. The two sets of results are in good agreement with each other and the differences can be attributed mainly to the frequency variation of the transfer characteristics. It will be noted that the IMAL results show a separation between the carriers at high drive levels. This is caused by interference from intermodulation products whose frequencies coincide with those of the carriers. It will also be noted that the intermodulation product falling in the gap between the two groups of carriers has an amplitude 2 to 3 dB higher than those at the edges.

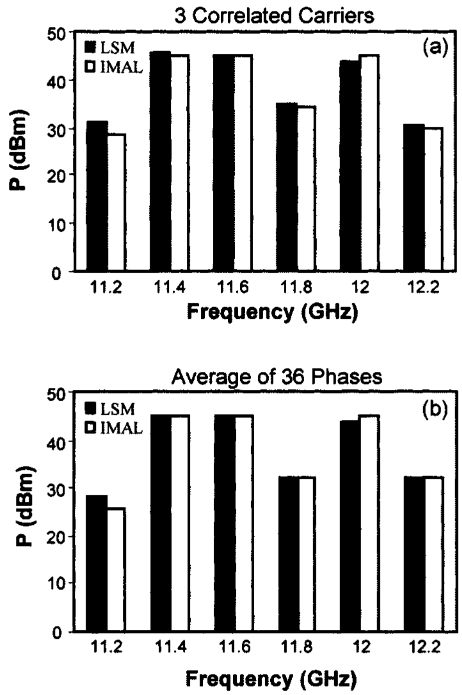

Fig. 3. Comparison between LSM and IMAL results for three carriers (a) correlated carriers, and (b) average of 36 phase combinations.

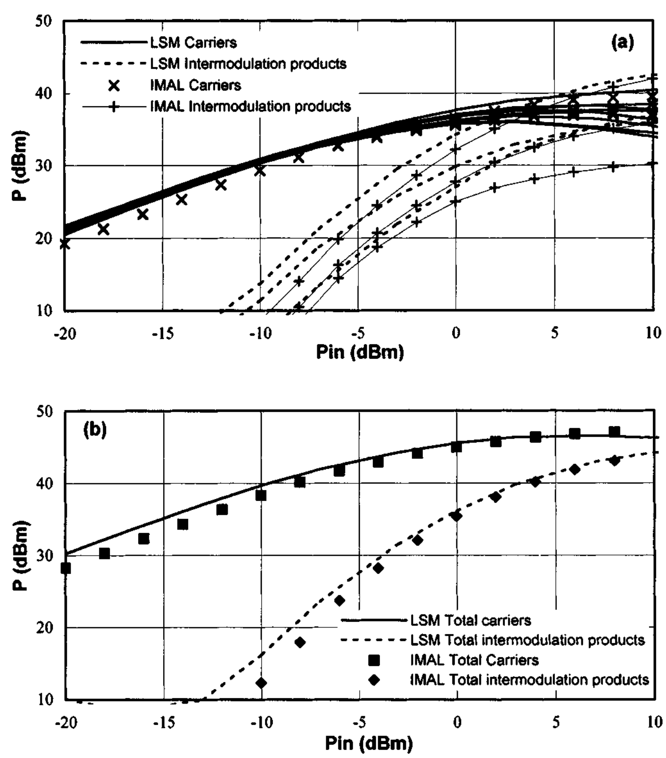

Fig. 4. Comparison between LSM and IMAL results for eight correlated carriers.

IV. Conclusions

The results presented have shown that there is good agreement between the two methods for the cases considered. The differences are attributable to the frequency dependence of the transfer characteristics of the TWT. It is concluded that the nonlinear performance of a TWT can be computed from its single frequency transfer characteristics and that the results are valid over any frequency band for which these do not vary greatly. It can also be concluded that the task of designing a TWT with a specified linearity can be reduced to that of ensuring that it has the necessary transfer characteristics.

References

[1] D. Banks, "A Ku-band Butler matrix amplifier using TWTA's," in *Proc. Space TWT's 1994 Workshop*, The Netherlands, May 18–20, 1994, ESA WPP-072.

[2] V. Srivastava and S. N. Joshi, "Improved nonlinear model for multi-signal analysis of helix TWTs," in *Proc. Inst. Elec. Eng. H*, vol. 139, 1992, pp. 129–134.

[3] R. G. Carter, P. Wang, and V. Srivastava, "Computer-aided design tools for space TWTs," in *Proc. Space TWTA's 1994 Workshop*. Noordwijk, The Netherlands, May 18–20, 1994, ESA WPP-072.

[4] G. Gatti *et al.*, "IMAL-2 a simulation software for inter-modulation analysis of power amplifiers," in *XRM Tech. Notes*. The Netherlands: ESTEC, June 4, 1996, vol. V.

Development of a Low Voltage Power Booster TWT for a Q-Band MMPM

John Kennedy and Carl Colombo

***Abstract*—Compact millimeter wave amplifiers with output powers ranging from around 20 to 100 W are required for a number of important military and commercial applications. This paper describes the design of a miniature, low voltage, vacuum power booster TWT for a Q-band (40–45 GHz) millimeter wave power module (MMPM).**

At a design voltage of 7.7 kV and a maximum current of 120 mA, an output power goal of greater than 40 W of CW rf output power has been established for the Q-band TWT. Beam confinement is provided using an optimized samarium cobalt PPM stack. Circuit losses at millimeter wavelengths are minimized using a novel wire-wrapped, T-shaped BeO rod support structure. Output power is transmitted through a 0.051 cm. thick alumina ceramic output window. High overall device efficiency is achieved through the use of a 3 stage depressed collector.

A recently completed engineering prototype produced 51 W of CW power at 41 GHz. Experimental overall device efficiency was 34.5%. These results will be described, as well as ongoing work to further improve overall device performance.

I. Introduction

Millimeter wave power modules (MMPMs) are complete microwave amplifiers which include a low gain helix TWT, a high gain solid state driver amplifier (SSA), and a high density electronic power conditioner (EPC), contained in a single compact, lightweight package. Due to their small size and weight they are useful for a variety of terrestrial and airborne applications. Subsequently, the helix TWT must be capable of operating in situations where the power resources may be quite limited. Size, weight, and efficiency are factors that drove the design of the present Q-band TWT to operate at a voltage of less than 10 kV.

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