

Wideband Operation of Nonlinear Solid-State Power Amplifiers—Comparisons of Calculations and Measurements

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Calculations of intermodulation (IM) noise and input/output power-transfer characteristics for a number of different nonlinear Solid-State Power Amplifiers (SSPAs) are found to be in very good agreement with measurements. The calculations are based on the measured AM/AM and AM/PM characteristics, and include results of a computer simulation, and analytical results based on modeling the SSPA as an ideal envelope limiter. The results demonstrate that the calculations predict wideband performance characteristics of nonlinear amplifiers for arbitrary input signal configurations and operating conditions, as well as provide a basis for comparison against which anomalous behavior can be identified. Earlier results, in which anomalous behavior of an SSPA was observed to result in significant performance degradation, are discussed in the light of these new results. A simple analytical criterion is developed for evaluating measurements to identify such degradation. The effect of AM/PM conversion is investigated and found to cause significant degradation in IM performance only at low power levels for typical SSPAs. In the vicinity of saturation, and above, the contribution to IM noise due to AM/PM conversion is found to be very small in comparison with that due to the saturating AM/AM characteristic.

I. INTRODUCTION

Two important considerations that arise in the design of nonlinear power amplifiers such as those used in satellite and terrestrial radio

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systems are the input/output power-transfer efficiency, and the amount of intermodulation (IM) noise produced as a function of input and output power levels. The former of these is related to what is termed the power-added efficiency of the device and the latter is a measure of its range of linearity. An earlier paper presented some results of analyses of these aspects of a nonlinear multistage Solid-State Power Amplifier (SSPA) under wideband excitation.¹ The results revealed a significant discrepancy between the calculated and measured power-transfer characteristics of the SSPA. In particular, measured output power levels in the vicinity of saturation were found to require approximately 3 dB more input power above predicted values based on AM/AM and AM/PM measurements. Ideally, the measured single-tone AM/AM and AM/PM characteristics of a nonlinear amplifier uniquely specify how it will perform in operation with wideband signals. The results of Ref. 1, however, have shown that anomalous cases—in which the single-tone measurements are not sufficient for predicting measured wideband behavior—can occur, with significant degradation in performance. It is therefore necessary to have a basis for comparison against which measurements of wideband power-transfer efficiency, IM performance, and possibly other performance criteria can be evaluated. In following up these initial results, the techniques originally developed in Ref. 1 have been extended and applied to a number of additional nonlinear SSPAs with newly measured performance data.² As we will see from the results presented below, calculations of this kind provide such a basis for any arbitrary input signal configuration and, essentially, any set of operating conditions.

Numerical results are obtained by means of computer simulation and an analytical closed-form expression for the wideband power-transfer characteristics. In the analysis, the multicarrier signal is assumed to be Gaussian, which is a very good approximation for the signals of interest here. In all cases it is assumed that the devices under consideration are memoryless or instantaneous. The initial results in Ref. 1 were obtained for a multistage SSPA, referred to as MS-1. The additional SSPAs for which comparisons of calculations and measurements have been made include a single-stage SSPA, referred to as SS-1, of which six such stages were employed in MS-1, another multistage SSPA, referred to as MS-2, which also employed six SS-1's, and three additional multistage SSPAs.

In all cases, measured and calculated results presented below for these SSPAs are in very close agreement, differing for the most part by fractions of a decibel. This demonstrates that the methods presented herein can be used to accurately determine what the operating characteristics of nonlinear SSPAs under wideband excitation should

be, and that they are sufficiently reliable to reveal anomalous behavior and to help pinpoint the sources of such anomalies. Specifically, the anomalous behavior of MS-1 was identified by comparison of the measured power-transfer characteristics with calculated values. Furthermore, the good agreement between measurements and calculations for SS-1 and MS-2 shows that, in general, the transistors employed in MS-1 can be expected to perform as predicted both singly as well as in a multistage configuration. Thus, the anomalous behavior observed with MS-1 has been clearly identified as being a peculiarity of the particular device. Possible reasons for this include one or more malfunctioning individual stages, and peculiarities in the overall design configuration, including possible saturation of early stages.

In the above discussion we have used the term "anomalous behavior" to indicate an observed discrepancy between measurements and predictions based on AM/AM and AM/PM characteristics. It is of interest to consider possible connections between predictable performance and optimal design. Kaye, George, and Eric have conjectured, but not proved, that, from the point of view of minimizing IM noise as a function of output power, the optimum nonlinear power amplifier has AM/AM characteristics that exhibit exact linearity up to the saturation level, with constant power output thereafter, and zero AM/PM conversion.³ These characteristics are referred to as those of an Ideal Envelope Limiter (IEL). Reference 4 proves part of Kaye, George, and Eric's conjecture, namely that AM/PM conversion can only degrade, never improve, IM performance for multicarrier input signals. Since, in practice, some degree of AM/PM conversion can be expected, it is of interest to investigate how the shape of the AM/PM characteristic affects the extent of the degradation.

For SSPA's, the AM/PM measurements examined thus far indicate that the phase shifts at low power levels are relatively small (i.e., a few degrees), and increase very gradually up to saturation. At this point they abruptly begin to increase much more rapidly, reaching perhaps 25 to 30 degrees a few decibels above saturation; an example of such a characteristic is presented below. The larger and more rapidly increasing phase shifts at and above saturation, however, are less important to the overall IM performance than the phase shifts at lower power levels (e.g., ~6 to 10 dB back-off). This has been determined by calculating the IM performance of the SSPA with and without AM/PM conversion, which is easily done in the computer simulation. It is found near saturation that the AM/AM characteristic dominates the IM production to the extent that the difference with and without AM/PM conversion is of the order of 1 dB or less. On the other hand, for low power levels, because the AM/AM characteristic seen by the signal is effectively much more linear, relatively small

phase variations can make a very significant difference in IM performance—up to 6 dB is observed here. This indicates that, assuming that some degree of AM/PM conversion cannot be avoided, the design goal would be to have it as small as possible below saturation, while in the vicinity of saturation and above, much greater leeway in the shape of the characteristics could be tolerated. This could be of practical significance in the design of networks for compensating for AM/PM conversion. That is, the results indicate that it is more important to compensate for the small, slowly varying phase shifts below saturation than for the large, rapidly varying phase shifts at and above saturation, where the compensation is presumably more difficult and where requirements on the performance of phase-compensation networks could be relaxed with little degradation in IM performance.

With regard to the ideal AM/AM characteristics, to date no violations or counter examples to Kaye, George, and Eric's conjecture seem to have been found. AM/PM conversion has no effect on input/output total power-transfer characteristics.⁴ Furthermore, based on comparisons of measurements with eq. (6), below, it is found that, excluding anomalous cases, SSPAs exhibit power-transfer characteristics that are nearly identical to those of an IEL, which under Kaye, George, and Eric's conjecture can be considered optimal. Thus, it should be possible for the AM/PM to be adjusted or compensated as necessary for minimum IM noise without affecting or sacrificing ideal power-transfer efficiency. With the use of eq. (6), a simple analytical criterion is developed for evaluating the extent to which SSPA wideband power-transfer measurements meet this ideal performance.

Section II summarizes the analytical results relevant to this work, including the optimal power-transfer characteristics of an IEL. Section III describes the computer simulation, Section IV compares measurements and calculations, and a summary of results and conclusions is presented in Section V.

II. SUMMARY OF ANALYTICAL RESULTS

The multicarrier signals of interest here can, to a very good approximation, be represented as bandpass Gaussian noise in the form

$$n(t) = x(t)\cos \omega_0 t + y(t)\sin \omega_0 t, \quad (1)$$

where ω_0 is the filter center frequency. Equation (1) is the narrowband representation of Gaussian noise, in which the low-pass functions $x(t)$ and $y(t)$ are required to be slowly varying with respect to ω_0 . In the cases of interest (e.g., satellite communications), the bandwidth of $x(t)$ and $y(t)$ is nominally 40 MHz and f_0 is 4 GHz, satisfying this requirement by a very large margin. Equation (1) can also be written as

$$n(t) = r(t)\cos(\omega_0 t + \theta(t)), \quad (2)$$

where $r(t) = (x^2(t) + y^2(t))^{1/2}$ is the envelope, and $\theta(t) = \tan^{-1}y(t)/x(t)$ is the phase. Since $x(t)$ and $y(t)$ are Gaussian, $r(t)$ has a Rayleigh distribution:

$$\frac{r}{\sigma^2} e^{-r^2/2\sigma^2}, \quad (3)$$

where $\sigma^2 = E(x^2(t)) = E(y^2(t))$ is the input-signal power.

The output of the nonlinearity will include an infinite number of harmonics of ω_0 . We are interested only in the principal zone, including only the first harmonic and a neighboring frequency range sufficiently wide to encompass all the IM noise produced (~ 200 MHz) (see Section III). For an instantaneous system, the principal-zone output can be written as:

$$A(r)\cos(\omega_0 t + \theta(t) + v(r)), \quad (4)$$

where $A(r)$ and $v(r)$ vary in time as $r(t)$, and, as functions of r , represent the AM/AM and AM/PM characteristics of the nonlinearity.

As Ref. 4 shows, the total output power in the principal zone is just $1/2\langle A^2(r) \rangle$, independent of $v(r)$. For all the SSPAs studied, the AM/AM characteristics very closely resemble those of an IEL and excluding anomalous cases, the power-transfer characteristics are also found to be essentially identical to those of an IEL. To calculate the output power for an IEL, referring to Fig. 1 we write:

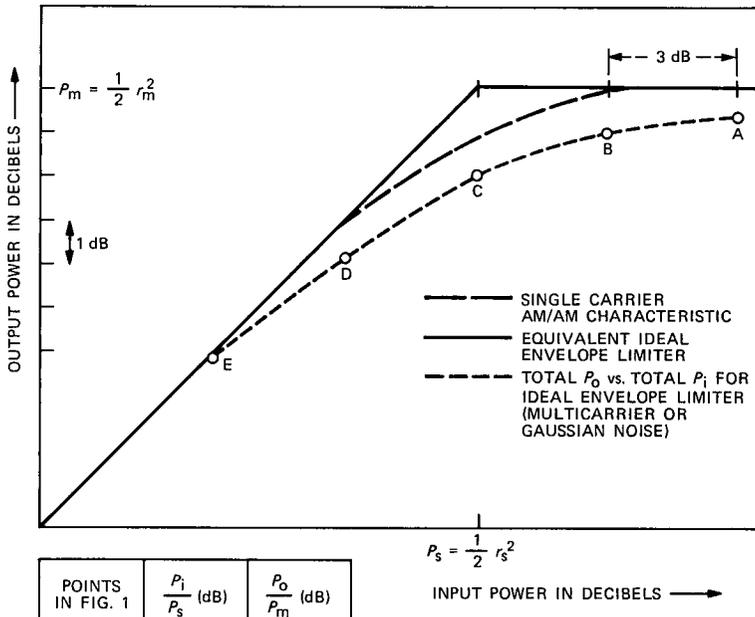
$$E\left(\frac{1}{2} A^2(r)\right) = \int_{r \leq r_s} E(A^2(r)/2)P(r)dr + \int_{r > r_s} E(A^2(r)/2)P(r)dr, \quad (5)$$

where r_s is the value of the input envelope r necessary to drive the limiter into saturation and $P(r)$ is given by (3). In the saturated region, $r > r_s$, we have $A(r) = r_m$, the maximum saturated value of the output envelope, and in the linear region, $r \leq r_s$, we have $A(r) = kr$, where the constant k is r_m/r_s . Under these conditions the integrals in (5) are easily evaluated and, denoting the output power, $1/2\langle A^2(r) \rangle$, as P_0 , and $P_s = 1/2r_s^2$, $P_m = 1/2r_m^2$, it is found that

$$P_0 = P_m \frac{1 - e^{-P_s/P_i}}{P_s/P_i}, \quad (6)$$

where in (6) we have redesignated the input power as P_i .

Equation (6) provides a convenient means for quickly evaluating SSPA wideband power-transfer measurements in order to determine whether the device is performing as it should. As diagrammed in Fig. 1, the IEL equivalent to a given SSPA is defined by extending the linear and saturated portions of the AM/AM characteristic to the point of



POINTS IN FIG. 1	$\frac{P_i}{P_s}$ (dB)	$\frac{P_o}{P_m}$ (dB)
A	+6	-0.53
B	+3	-1.04
C	0	-1.99
D	-3	-3.64
E	-6	-6.01

Fig. 1—SSPA AM/AM characteristics with equivalent IEL and IEL power-transfer characteristics.

intersection that defines P_s and P_m . Using these values of P_s and P_m , the theoretically correct values of P_0 as given by (6) can be easily plotted by noting that, starting with a value of P_i 6 dB above P_s and stepping down in 3-dB increments to 6 dB below P_s , the corresponding values of output power are very nearly 0.5, 1, 2, 3.6, and 6 dB below P_m ; the exact values are given in the table insert in Fig. 1. Using this method, measurements of power-transfer characteristics for a number of SSPAs are compared in Section IV to theoretical values and found to be in almost exact agreement, which demonstrates the usefulness of this approach. It should be noted that this method is not valid for traveling-wave tubes, which do not have IEL-like AM/AM characteristics.

III. COMPUTER SIMULATION

Figure 2 presents a block diagram of the computer simulation used in these analyses, and Ref. 1 gives a description of the calculation

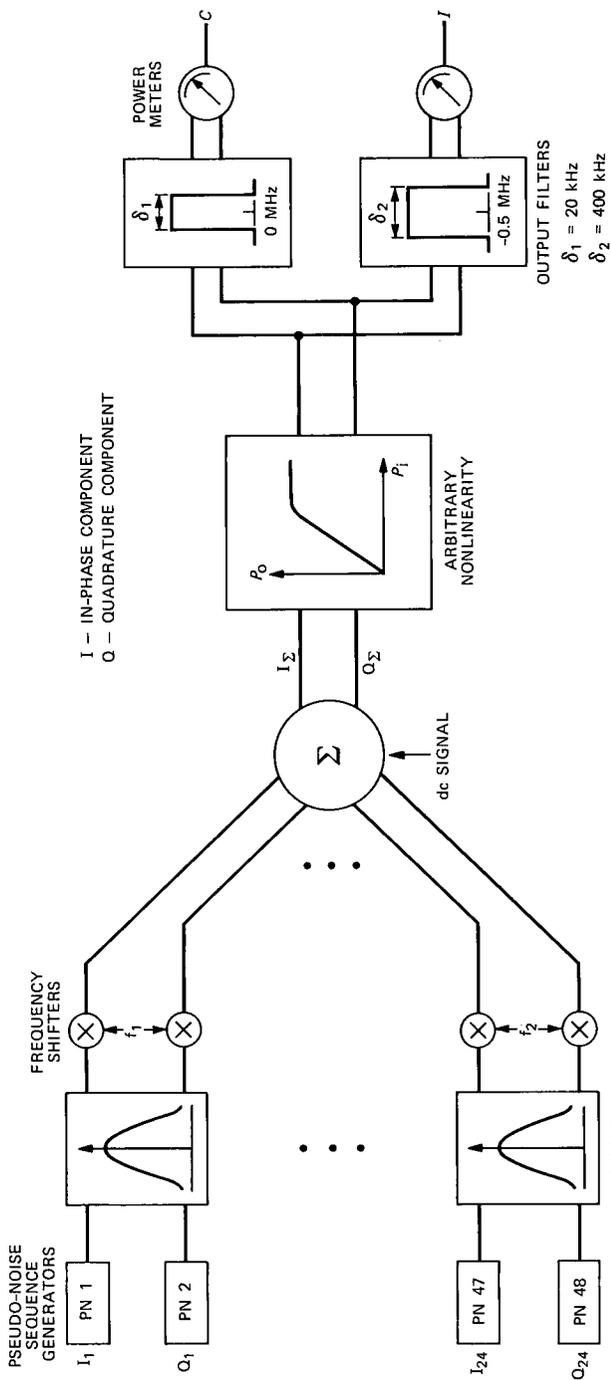


Fig. 2—Block diagram of simulation.

procedures. In the laboratory measurements, the input waveform consisted of 24 equal-power, filtered, Quadrature Phase-Shift Keying (QPSK) signals spaced on either side of an unmodulated carrier at band center (4 GHz) by the frequency increments shown in Table I (from Ref. 2). The power in the unmodulated tone was adjusted at the input to be equal to that of a single QPSK signal.

In simulating this waveform, a complex baseband formulation was employed. The simulated input consists of the outputs of 48 (24 pairs of) independent, equal-power, Pseudo-Noise (PN) sequence generators. The outputs of each pair of generators are formed into a complex number, which, in the baseband formulation, represents a QPSK signal, with the real part representing the in-phase component and the imaginary part, the quadrature component. Each QPSK signal is then passed through a four-pole Butterworth filter with a 3-dB (positive-frequency) bandwidth of 0.5 MHz. This is essentially the same filtering employed at the output of each QPSK signal generator in the 24-channel laboratory test set. The pulse duration employed in the simulation is 1.3 μ s, corresponding to 0.772×10^6 symbols/s, or a DS-1 rate of 1.544×10^6 bits/s.

After filtering, each QPSK signal is shifted in frequency on either side of zero by the same increments used in the measurements (see Table I). The 4-GHz carrier in the laboratory measurements is represented in the simulation by a dc signal adjusted in power to be equal at the input to a single QPSK signal. The spectrum of the input signal employed in the simulation is shown in Fig. 3.

This signal is then input to the nonlinear system under consideration. The nonlinearity is specified by entering tables of the measured AM/AM and AM/PM values into the program to which the simulation fits continuous curves. An example of the spectrum at the output of the nonlinearity, for input power in the vicinity of saturation, is presented in Fig. 4. For evaluating IM performance, the laboratory

Table I—Frequencies used in simulation

Channel	Frequencies (MHz)	Channel	Frequencies (MHz)
-12	-16.65	1	1.40
-11	-15.33	2	2.70
-10	-14.03	3	4.03
-9	-12.70	4	5.33
-8	-11.40	5	6.63
-7	-9.35	6	7.95
-6	-8.05	7	9.25
-5	-6.73	8	11.30
-4	-5.43	9	12.60
-3	-4.13	10	13.93
-2	-2.80	11	15.23
-1	-1.50	12	16.55
0	0		

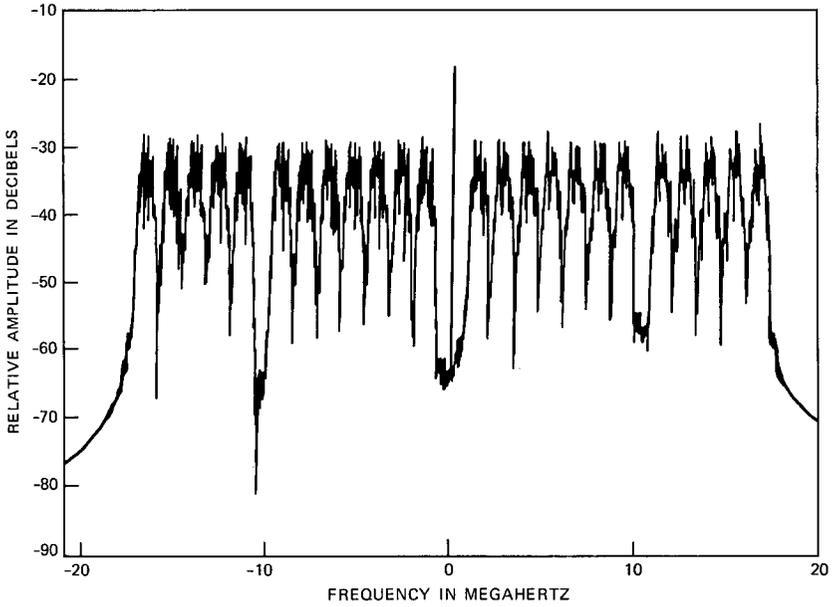


Fig. 3—Input signal spectrum showing 24 T-1 signal plus unmodulated tone at band center.

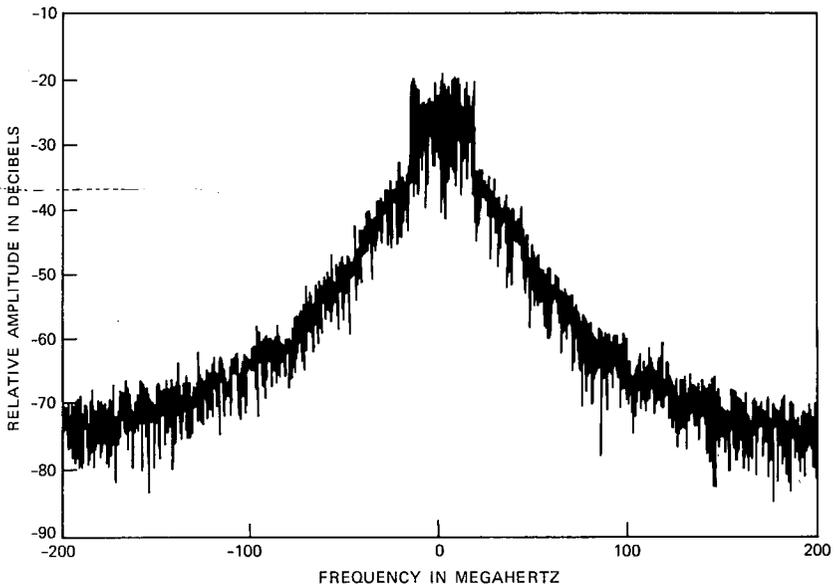


Fig. 4—MS-2 output spectrum with amplifier saturated.

measurements employed a narrowband filter in the notch at 4-GHz for measuring the output unmodulated carrier power, and a number of narrowband filters located in the notch between the 4-GHz carrier and the neighboring QPSK signals for measuring IM power; the individual IM-power measurements were averaged. Correspondingly, the simulation employs a narrowband filter at zero frequency for measuring unmodulated output dc power, and a filter for measuring IM power centered between zero and -1.5 MHz.

For determining power-transfer characteristics, the total output power, including all the IM as well as signal power, is the measured quantity. Figure 4 shows that the saturated output power becomes negligible outside of ± 100 MHz, indicating that terms higher than fifth order are negligible in describing the nonlinearity. In any case, we are safe in assuming that a filter bandwidth of, say, 200 MHz will be sufficient for measuring total output power. This procedure was followed in the computer calculations and in the laboratory measurements in which the bandwidth of the detector used to measure total output power was nominally 300 MHz.

IV. COMPARISONS OF MEASUREMENTS AND CALCULATIONS

In plotting the laboratory data, the procedure adopted was to normalize the measurement by dividing the average measured IM power by the noise bandwidth of the filter, thereby obtaining IM power per 1-Hz frequency interval. Denoting this as I and the output unmodulated carrier power as C , the results were plotted as C/I , in dB-Hz, vs. output power, in dBm. In practice, the quantity of interest is the ratio of signal power to IM power in any given band, S/N_{IM} . Since the signal and IM spectra are essentially flat, this is equal to the ratio of the signal and IM spectral densities, and for a large number of equal-power carriers equally spaced by Δ Hz we have:

$$\frac{S}{N_{\text{IM}}} = \frac{C}{I\Delta} \quad (7)$$

For these data, eq. (7) can be used with Δ set equal to the nominal intercarrier spacing of 1.5 MHz.

Results of the computer calculations are also plotted in terms of C/I . In measuring IM power, an eight-pole Butterworth filter with 400 kHz, 3-dB bandwidth was used; the measured noise bandwidth in this case was 420 kHz. The bandwidth was chosen to be as wide as possible, in order to allow for averaging, and also to be able to fit into the notch in between the unmodulated dc tone and the QPSK signal at -1.5 MHz. In measuring the power in the dc tone at the output of the nonlinearity, an eight-pole Butterworth filter with a 20-kHz, 3-dB bandwidth was used, which was similar to that used in the laboratory

measurements. The following subsections discuss the results for the different devices studied.

4.1 Single-stage SSPA, SS-1

This single-stage SSPA used the same transistor as that used in the multistage MS-1 and MS-2 SSPAs. In this case, AM/PM characteristics for the particular amplifier that was studied were not available. A set of AM/PM characteristics typical of this type of single-stage amplifier is presented in Fig. 5, in which the phase shifts are seen to be very small. For this reason, as will be seen, unavailability of the exact set of AM/PM characteristics for this device had a negligible effect on the results. Calculations of C/I vs. output power are presented in Fig. 6 along with the measured values. For the three largest values of output power, which correspond to input saturation, 3- and 6-dB input back-off (~ 35 -, ~ 34 -, and ~ 32 -dBm output power), the calculated values differ from the measurements by the order of tenths of a dB. For the lowest point—13-dB input back-off, ~ 26 -dBm output power—the measurement included significant thermal noise, which contributed to the difference of 2.5 dB from the calculated value. For the point at 10-dB input back-off (29-dBm output power), the difference is 1.5 dB, which may also include some nonnegligible effects of thermal noise.

In considering C/I performance, it is of interest to determine how much of the IM noise is due to AM/PM conversion, which is easily done in the simulation by setting AM/PM equal to zero. In this case

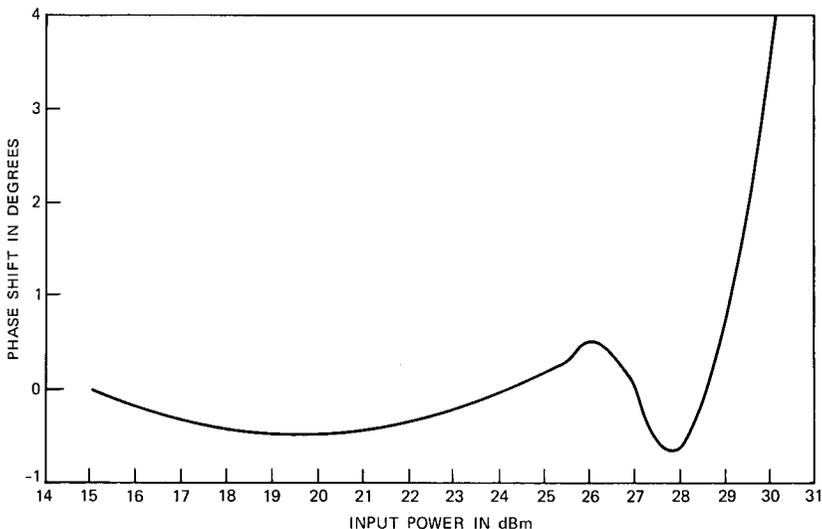


Fig. 5—Typical AM/PM characteristics for single-stage SSPA.

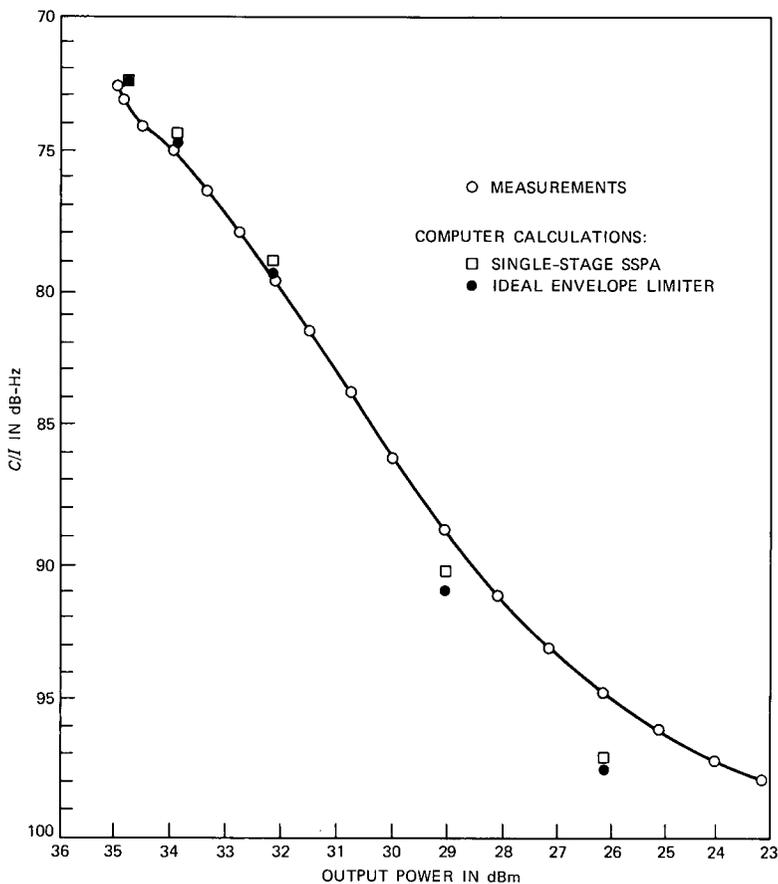


Fig. 6— C/I for single-stage SSPA.

the AM/AM characteristics were modeled as those of the equivalent IEL, which is a very good approximation. The results for the IEL are also presented in Fig. 6 and seen to be only slightly different from those of the single-stage SSPA *with* AM/PM conversion, which demonstrates that phase shifts of the magnitude of those in Fig. 5, below saturation, are essentially negligible, and that the sharp increase in slope and larger phase values at and above saturation are also negligible in comparison with the effect of the saturating AM/AM characteristic.

The AM/AM characteristics used in the calculation of C/I in Fig. 6 are presented in Fig. 7, along with measurements and calculations of total power in vs. power out, and a plot of (6). The computer calculations are seen to fall exactly on the curve of measured values, with the exception of the point at saturation where the difference is ~ 0.2 dB.

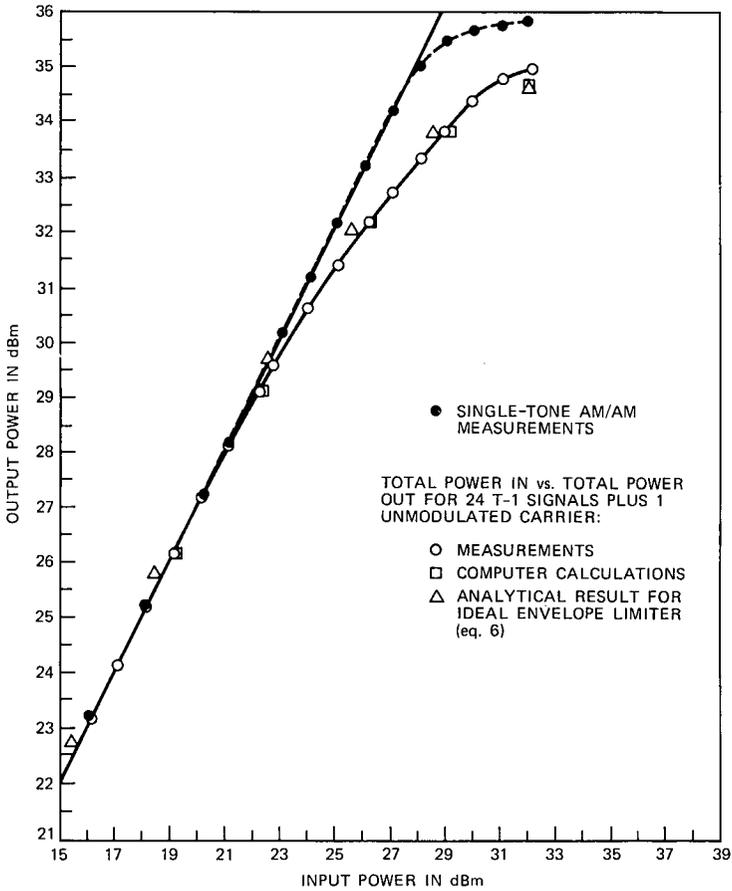


Fig. 7—AM/AM measurements and total power-transfer characteristics for single-stage SSPA.

The IEL power-transfer characteristics of (6) are also seen to be within tenths of a decibel of the measurements and the computer calculations.

4.2 Multistage SSPA, MS-2

Figure 8 presents calculated and measured values of C/I . For input saturation, 3-dB input back-off and 6-dB input back-off (~ 36 -, ~ 35 -, and ~ 34 -dBm output power), the differences are fractions of a decibel. The largest difference is at 10-dB input back-off (~ 31 -dBm output power), where the difference is ~ 1 dB. In this case the thermal noise in the measurements was negligible, as evidenced by the falloff in C/I below ~ 27 -dBm output power. The computer calculations have

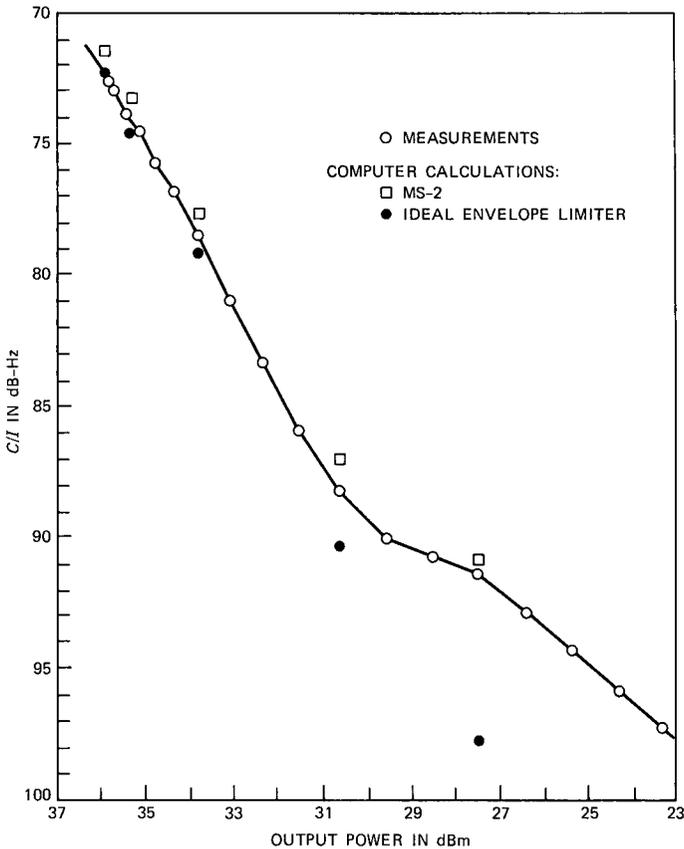


Fig. 8— C/I for MS-2.

reproduced the irregular shape of the measured C/I curve in this region.

The source of this irregular shape was determined to be the somewhat irregular AM/PM characteristics for MS-2 shown in Fig. 9. As shown, the phase shift increases and then decreases somewhat in between -27 - and -21 -dBm input power. When the AM/PM was set equal to zero, the flattening in the C/I curve between 31 and 27 dBm output power disappeared, as shown by the equivalent IEL results in Fig. 8.

We also note that although the phase shifts are largest and vary most rapidly near and above saturation (~ -22 -dBm input power, ~ 37 -dBm output power) (see Fig. 10), their effect on production of IM noise in Fig. 8 is of the order of 1 dB or less. However, although the phase shifts are much smaller and slower varying for low power levels, the differences between the C/I values for MS-2 with AM/PM

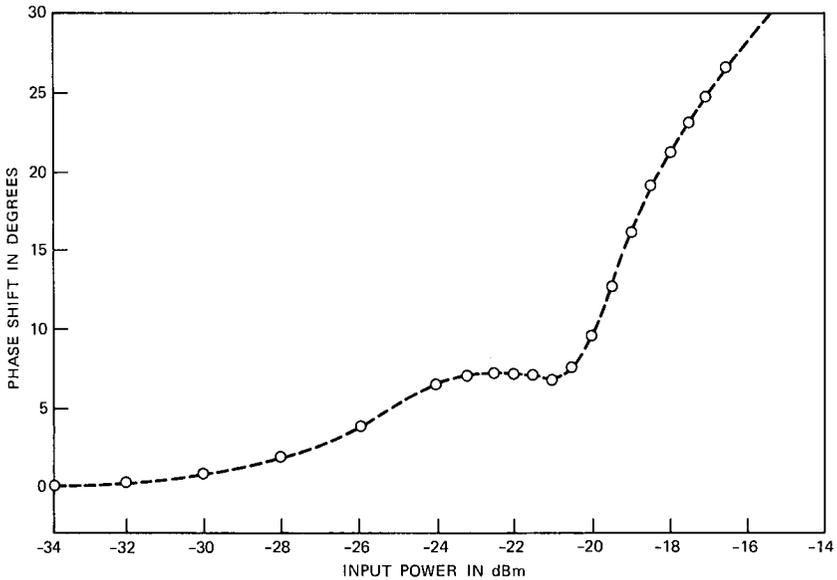


Fig. 9—AM/PM measurements for MS-2.

and the equivalent IEL, with zero AM/PM, are much larger (e.g., ~ 6 dB at ~ 27.5 -dBm output power). The reasons for this, in terms of the relative importance of the AM/AM and AM/PM characteristics as a function of input power level, and the implications in terms of SSPA design and AM/PM compensation, have been discussed in Section I.

The AM/AM characteristics for MS-2 are presented in Fig. 10, along with measurements and calculations of total power in vs. power out and a plot of (6). As for the single-stage SSPA, the differences between measurements, computer simulation results, and results based on (6) are negligible. It is of interest to note that the slope of the AM/AM characteristics differs slightly from strict linearity in the gain-expansion region near saturation, which evidently has a negligible effect.

For the remaining three multistage SSPAs that were studied, AM/PM measurements were not available and C/I calculations not possible. The comparisons were therefore restricted to total power in vs. power out. In these cases the laboratory measurements were compared with calculated values using the five-point approximation method discussed at the end of Section II. Differences between calculated and measured values were found to be negligible; in the interest of brevity, plots of these results are not presented. For convenience we present in Fig. 11 the earlier result for MS-1 from Ref. 1, showing

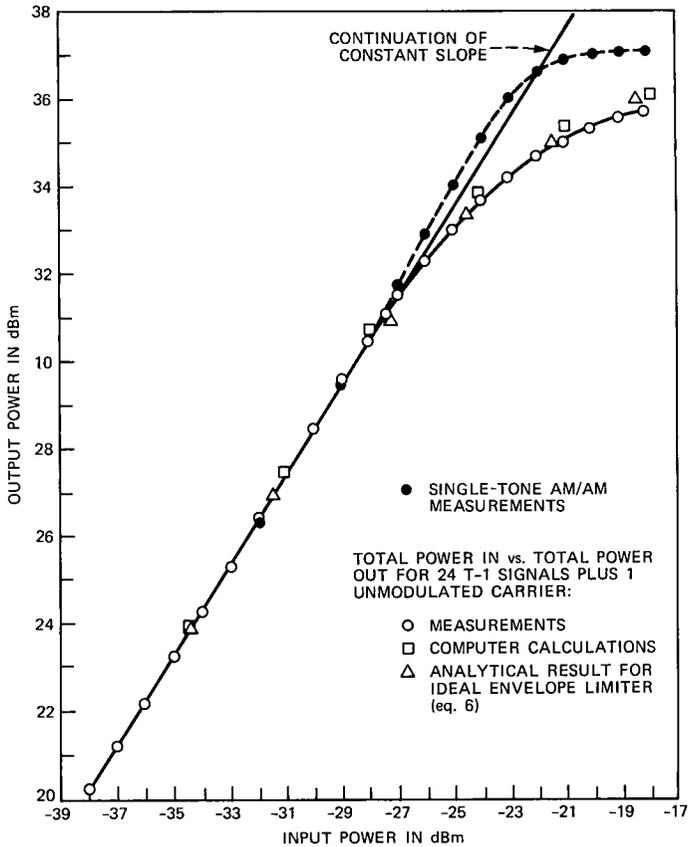


Fig. 10—AM/AM measurements and total power-transfer characteristics for MS-2.

the significant discrepancy between calculated and measured power-transfer characteristics. The significant body of data in which almost exact agreement between measurements and calculations has been obtained clearly indicates that the MS-1 device represents an anomalous case.

V. SUMMARY AND CONCLUSIONS

A number of SSPAs have been studied, for which very good agreement has been observed between calculated and measured wideband power-transfer characteristics and IM noise performance. The calculations include results of a computer simulation developed for this purpose, with which any arbitrary input signal and any set of operating conditions can be investigated, and an analytical result that describes the wideband power-transfer characteristics of typical SSPAs. In all

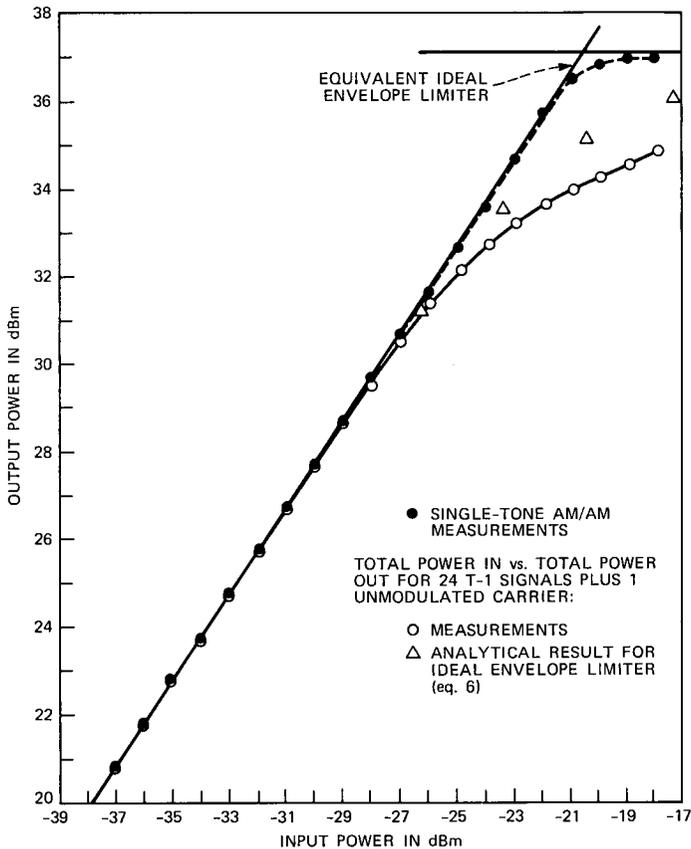


Fig. 11—AM/AM measurements and total power-transfer characteristics for MS-1, showing power-transfer anomaly.

these calculations, the devices are characterized by their measured AM/AM and AM/PM characteristics; for power-transfer calculations AM/PM is, of course, irrelevant.

The number of cases in which agreement has been obtained demonstrates the usefulness of calculations of this kind as means for predicting the performance of nonlinear power amplifiers, as well as for providing a tool with which possible anomalous behavior can be identified. Such behavior, in which the single-tone AM/AM and AM/PM measurements are not sufficient for characterizing the operation of the amplifier under wideband excitation, which can result in severe performance degradation, can, in the case of power-transfer anomalies, be identified by comparing measured data with results predicted by (6). An example of anomalous behavior, in which a

significant degradation in power-transfer efficiency was identified by means of comparison with theoretical predictions, has been discussed.

SSPAs in nonanomalous cases have been shown to generally exhibit power-transfer characteristics essentially identical to those of an ideal envelope limiter which, under the conjecture of Kaye, George, and Eric, are optimal. Part of Kaye, George, and Eric's conjecture has been proved; namely, that AM/PM conversion can only degrade, never improve, IM performance. It has been shown that degradation due to AM/PM conversion is significantly more severe at low power levels than in the vicinity of saturation where, based on available AM/PM measurement data, the phase shifts are much larger and more rapidly varying; the reasons for this have been discussed. This could be of practical importance in the design of compensation networks for AM/PM conversion, since requirements on network performance at saturating power levels could be relaxed with little degradation in IM performance.

Power-transfer characteristics are independent of AM/PM conversion. Ideally, this independence could permit the AM/PM characteristics to be adjusted or compensated to maximize IM performance without sacrificing ideal power-transfer efficiency. Using an analytical expression for power transfer in an IEL, a simple criterion has been developed for evaluating measurements to determine whether ideal power-transfer efficiency has been achieved.

VI. ACKNOWLEDGMENT

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