Multitone Power and Intermodulation Load–Pull Characterization of Microwave Transistors Suitable for Linear SSPA's Design

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***Abstract*— In this paper, an experimental load–pull characterization of microwave transistors operated under N-tone excitations $(2 \leq N \leq 32)$ is presented. Such characterization is very useful to investigate the linearity of high-power amplifiers via intermodulation distortion analysis. All the measurements were carried out using a newly developed multiline measurement system which uses an arbitrary waveform generator (AWG) to generate the spectrum of any N desired tones and a microwave transition analyzer (MTA) as a vector receiver. The measured intermodulation rejection (IMR) behavior, as the number of tones increases, is compared with previously published theoretical results. Constant output power contours and IMR contours in the $\Gamma_L(f_0)$ plane for different number of tones are presented and discussed. The dependency of the IMR on the biasing conditions and the carriers' phase distribution is also investigated.**

***Index Terms*—Intermodulation, linearity, load–pull, multitone, phase distribution, transistor.**

I. Introduction

In MOBILE communications, highly efficient and linear power amplifiers with high intermodulation rejection (IMR) are needed for personal handy-phone systems. To efficiently design the desired linear amplifier, investigation of the linearity of its amplification component, the transistor, is essential. Intermodulation-distortion (IMD) analysis is a good way to explore the nonlinear behaviors in microwave and millimeter-wave amplifiers [1], [2]. It is an important parameter that indicates the nonlinearity performance of transistors. IMD analysis is relatively well studied, theoretically and experimentally, under two-tone excitations [3], [4]. This was performed on both bipolar and field-effect transistors. Good results were obtained for equally leveled tone inputs. However, the IMD characterization and analysis under $N (N > 2)$ tone excitations are not yet well investigated [5]. This issue has been discussed in few publications. Theoretical works on IMD in a multisignal environment were reported in [6], [7]. In those references, equations were provided to calculate the IMR and the intercept point levels for different operating conditions. Nevertheless, those equations have not been verified by experimental results. A new instrumentation has recently been introduced to test the intermodulation distortion under multitone excitation with optimal phase relationship [8]. This paper focuses on device IMD characterization with different multitone phase distribution, biasing, and loading conditions. For this purpose, a new multitone load–pull measurement system is developed [9].

The previously reported measurement systems [3], [4] were developed for two-tone excitations only, where two separate signal generators were employed. One of the limitations of those systems is that if the number of tones increases, the complexity of the system augments due to the required large number of signal generators. The new proposed measurement system reduces the complexity by using an arbitrary waveform generator (AWG) and a simple mixer to generate the spectrum of any desired N tones. With this technique, the use of many signal generators and signal synchronization problems are avoided. The other novel experiment technique is the use of a wide-band microwave transition analyzer (MTA, dc to 40 GHz) as a receiver of all the reflected and incident signals to the device-under-test (DUT). An experimental validation of the theoretical intermodulation analysis results which essentially gives the required power backoff to maintain a constant IMR for excitations having different number of tones is provided. The degradation of the IMR as the number of tones increases is also described. The other main part in this paper is the load–pull measurements on a GaAs MESFET in multitone environment. Constant output power and IMR contours are illustrated for different number of tones. The results of the effects of the phase distribution of the tones and the biasing conditions are given. One can then optimize the IMR of a certain transistor with an optimal loading and class of operation.

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II. The New Measurement System

To perform accurate load–pull measurements in a multisignal environment, it is important to first generate a very clean spectrum of the N-tone excitation to be applied to the transistor. For such a task, an AWG generator (HP8770A), a mixer, and a filter are used. Fig. 1 shows a block diagram of the whole measurement system. The AWG generates the desired number of tones with desired frequency spacing, power

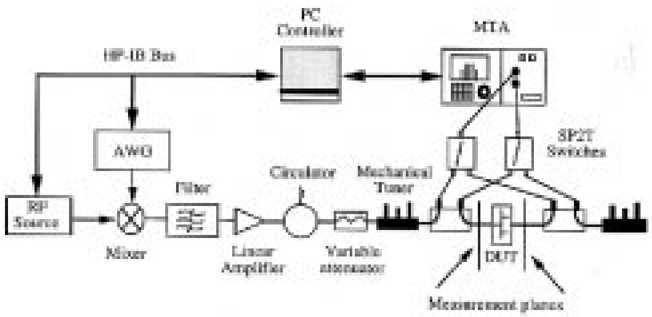

Fig. 1. Multitone load–pull measurement setup.

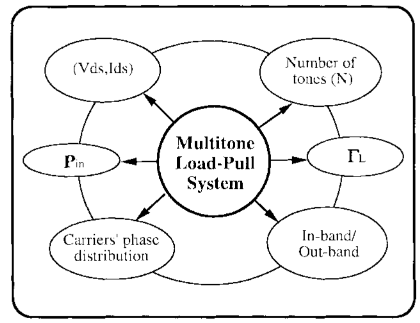

Fig. 2. Parameter variation options in the measurement system.

level, and phase distribution. The phase distribution of the tones can be either random, uniform, or fixed by the user. Using such an instrument reduces the complexity of the system as the number of tones increases, and the synchronization problem between the tones is avoided. The other indispensable instrument used in the setup is the MTA (HP70820), which acts as a network analyzer with its home-designed test set.

The mixer is used to up-convert the base-band signal generated by the AWG around the microwave operating signal available from the microwave synthesizer connected to the other input of the mixer. With this configuration, the mixer acts as an up-converter. The selective narrow-band filter inserted at the output of the mixer is used to pass only the principal N-tone spectrum. The multitone signal at the output of the filter is obtained with an IMR of −55 dBc. The filtered spectrum is then amplified by a linear amplifier to reach the desired power level. The variable attenuator is used to perform a power sweep and the mechanical tuner is used to adjust the input reflection coefficient for maximum power transfer to the transistor.

The incident and reflected waves at the input and output of the transistor are sampled by two dual couplers with small coupling factors (−20 dB). These sampled waves are received and measured by the MTA via a switching stage. The output mechanical tuner is used to perform a passive loading. Due to the insertion losses in the tuner, the maximum reflection coefficient magnitude reached is 0.9.

The data acquisition from the MTA, the system calibration, and the switches control are performed via an HP-IB bus using a 486 PC. Considerable effort has been made to develop the software tool for instrument control, data processing, and result visualization. This was accomplished using the HP Vee-Test software.[1]

A. System Calibration

To de-embed the measured raw data taken by the MTA to the reference measurement planes of the transistor, the SOLT (short-open-load-thru) technique [10] is used. For power corrections, the measuring ports have been calibrated with an independent powermeter. Other calibration techniques (e.g., thru-reflect line (TRL) [11]) will be included in the future to improve the system flexibility and precision, and to extend the system to perform on-wafer measurements.

[1] *HP-Vee Advanced Programming Techniques & HP-Vee Reference*. Hewlett-Packard, 2nd ed., Jan. 1995.

B. Possible Measurement Options

With the present system, one can perform many kinds of multitone measurements. This flexibility is obtained by varying some independent parameters of the system. The parameters that can be varied are:

- the input power;
- the number of tones;
- the carriers' phase distribution;
- the load impedance;
- the biasing conditions;
- the IMR measurement mode (in-band/out-band).

All the possible variation options of these parameters are shown in Fig. 2. Performing measurements by varying these independent parameters will generate a complete database which would be useful in the development of different charts for a given transistor with given nonlinear characteristics.

III. Experimental Validation of Theoretical IMR Results

This section presents the first part of the experimental results obtained for a MESFET (ACK0151P) having a 1-dB compression point at $P_{1\mathrm{dB}} = 23$ dBm. This is done to validate the theoretical intermodulation distortion analysis results reported in [7]. It consists of the evaluation of IMR degradation as the number of tones increases, as well as the required backoff level in the input power to maintain a certain constant IMR. All the measurements were carried out for input signals having 2, 4, 8, 16, and 32 tones, with 100-kHz spacing between tones. The MESFET was biased at $V_{\mathrm{ds}} = 10$ V and $I_{\mathrm{ds}} = 100$ mA for class A operation. Load–pull measurements were made to determine the optimum load for maximum output power. This load was found to correspond to $\Gamma_L = 0.58\angle 172^{\circ}$. Using the MTA, the input reflection coefficient, the absorbed input power per tone, the output reflection coefficient, the output power per tone, and the third-order IMR of the transistor were measured. For each number of tones, the IMR parameter was measured for an input power sweep up to the 1-dB compression region of the transistor. Such measurement was repeated for ten random phase distributions of the carriers. The experimental results presented here correspond to the two extreme cases of the phased distribution among the ten cases considered—one is the best case and the other is the worst case.

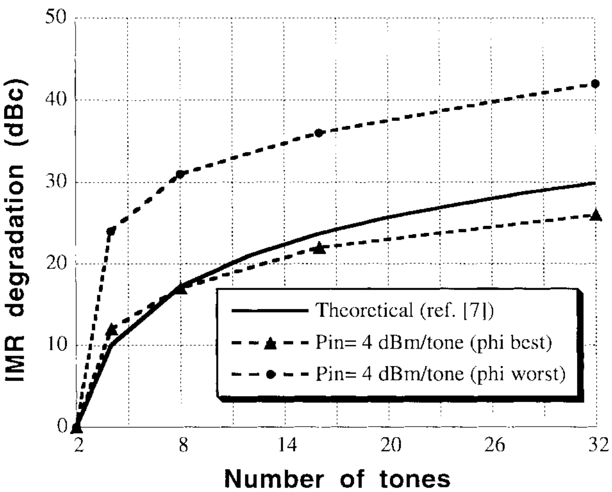

Fig. 3. IMR degradation with constant input power per tone.

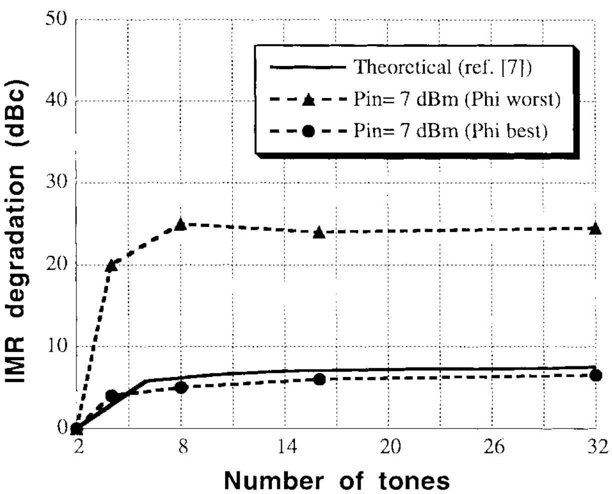

Fig. 4. IMR degradation with constant total input power.

Fig. 3 shows the theoretical (reported in [7]) and the measured IMR degradation as the function of the number of tones for a constant input power level per tone ($P_{\mathrm{in/tone}} = 4$ dBm). One can see that there is an acceptable agreement between the measurements and the theory, and the theoretical IMR degradation falls in the range between the best and the worst cases. The deviation observed is due to the fact that the theoretical curve reported in [7] is an average of many curves corresponding to different carriers' phase distributions.

Fig. 4 illustrates a comparison between the measured and the theoretical [7] IMR degradation as a function of the number of tones for the same total input power level ($P_{\mathrm{in/total}} = 7$ dBm). The total input power is calculated by using

$$P_{\mathrm{in/total}} = P_{\mathrm{in/tone}} + 10 \times \log(\mathrm{N}) \qquad (1)$$

where N is the number of tones. Again, the theoretical IMR degradation falls in the range defined between the best and the worst cases of the carriers' phase distribution.

It can be concluded from these results that the phase distribution of the carriers has a strong influence on the transistor IMR. It is also shown that there is a difference up to 20 dBc between the IMR degradation values of the two extreme cases. Therefore, in multichannel operation, the power characteristics of amplifiers strongly depend on the behavior of the carrier signal of each channel. It is also shown that IMR degradation tends to achieve a constant value when increasing the number of tones.

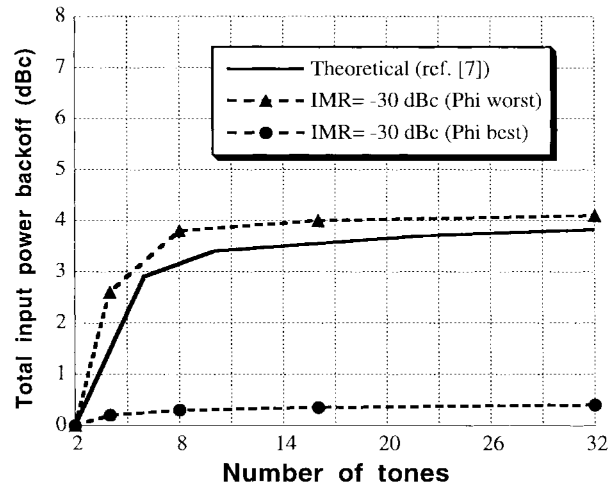

Fig. 5. Required power backoff to maintain constant IMR.

Fig. 5 shows the measured and theoretical [7] total input power backoff required to maintain a constant IMR. Again, the theoretical results fall in the range bounded by the two presented phase-distribution cases. It is also important to notice that for a certain phase distribution of the carriers, a backoff in the total input power is not needed to maintain a constant IMR. This is illustrated in Fig. 5, for the best case of random carriers' phase distribution, the power backoff required is very small (around 0.2–0.4 dB). This is very important in the design of highly efficient linear amplifiers, where the transistor used has to be operated near its compression region to achieve the desired high power-added efficiency.

IV. Load–Pull Measurement Results

This second part of the characterization consists of varying the load impedance of the transistor to generate contour curves of large-signal characteristics of the transistor, such as output power and IMR, for different number of tones. Here, only measurements corresponding to two-zone and eight-tone exciting signals are presented. The first tone is fixed at $f_1 = 2.015$ GHz, the other remaining tones are equally spaced relative to each others by 100 kHz ($f_2 = 2.0149$ GHz,$\cdots$). The phase distribution of the tones is taken random, and the transistor was biased for class A operation ($V_{\mathrm{ds}} = 10$ V and $I_{\mathrm{ds}} = 100$ mA).

Figs. 6 and 7 show the constant output power contours (in dBm) per tone in the $\Gamma_L(f_0)$ plane for cases $N = 2$ and $N = 8$ tones, respectively. One can observe that the optimal load for maximum output power is located in the same region of the Smith chart for the two cases. The same observation is obtained for the other cases of 4, 16, and 32 tones. From these results, one can conclude that the transistor loading is almost independent of the number of tones with a certain phase distribution. It is theoretically known that, for a given

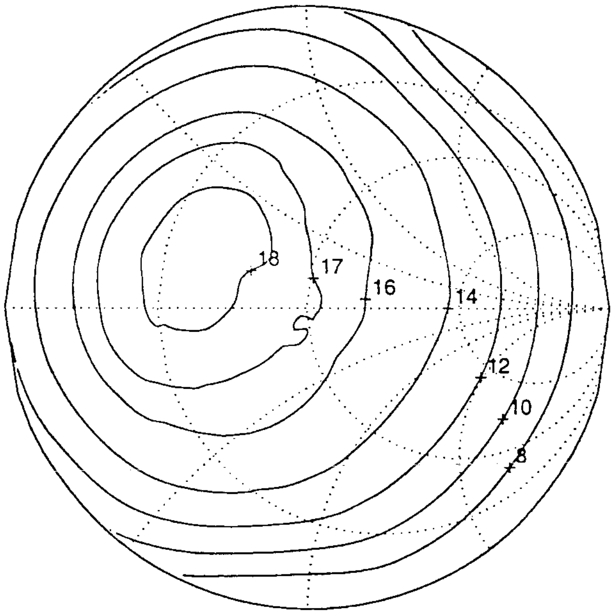

Fig. 6. Constant output power contours per tone in the $\Gamma_L(f_0)$ plane ($N = 2$ tones).

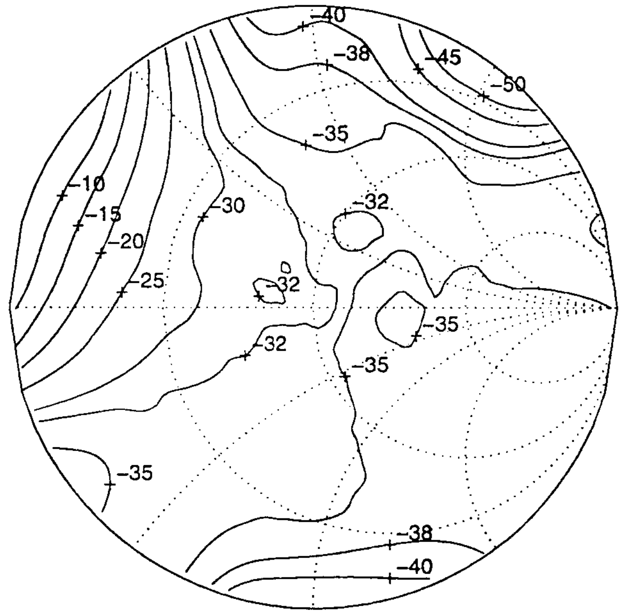

Fig. 8. Constant IMR contours in the $\Gamma_L(f_0)$ plane ($N = 2$ tones).

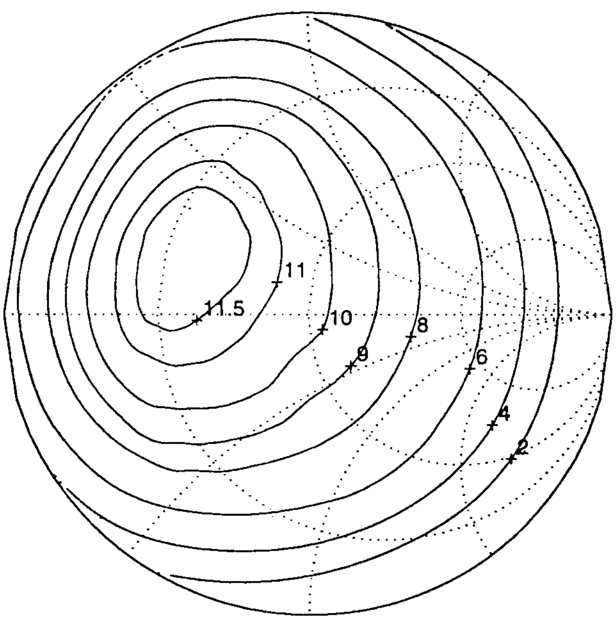

Fig. 7. Constant output power contours per tone in the $\Gamma_L(f_0)$ plane ($N = 8$ tones).

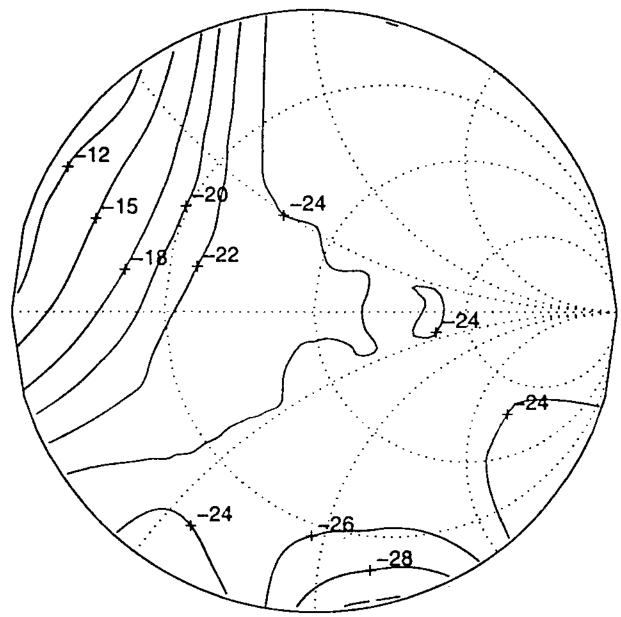

Fig. 9. Constant IMR contours in the $\Gamma_L(f_0)$ plane ($N = 8$ tones).

total-output power level, the output power level per tone of a N-tone signal is 3 dB higher than the power level per tone of a $2N$-tone signal. This is experimentally validated here in Figs. 6 and 7, where the power contour levels of the two-tone case (Fig. 6) is around 6.5 dB higher than the power contour levels of the eight-tone case (Fig. 7) in the entire Smith chart. This is acceptable since the theoretical power level's difference between two- and eight-tone cases is 6 dB (eight tones $2 \times 2 \times 2$ tones, which lead to $3 + 3$ dB). These results indicate that the accuracy of the measurements using the measurement system is within 1 dB.

The constant outband IMR contours (in dBc) in the $\Gamma_L(f_0)$ plane for the cases $N = 2$ and $N = 8$ tones are shown in Figs. 8 and 9, respectively. It can be seen that for a given load there is an IMR degradation as the number of tones increases.

From these two kinds of contours, one can make a tradeoff between the output power and the IMR for a given phase distribution, to select optimal transistor loading conditions. This tradeoff can be improved by investigating the effects of other independent parameters, such as the carriers' phase distribution and transistor operator class on power and IMR characteristics.

V. Effect of Carriers' Phase Distribution

The phase distribution of tones is a spectrum containing the absolute phase values of all the carriers of the signal. This

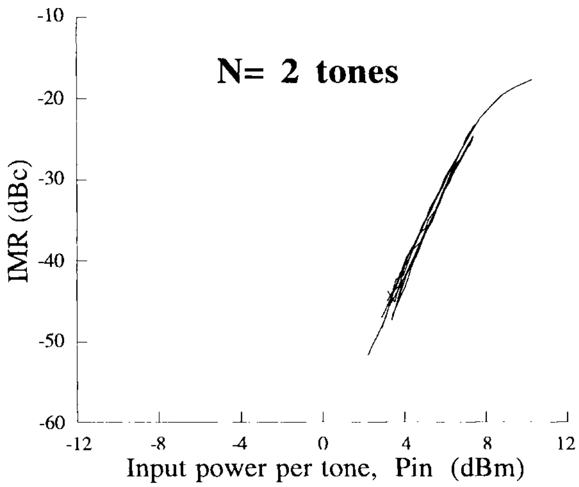

Fig. 10. Effect of carrier's phase distribution on IMR ($N = 2$ tones).

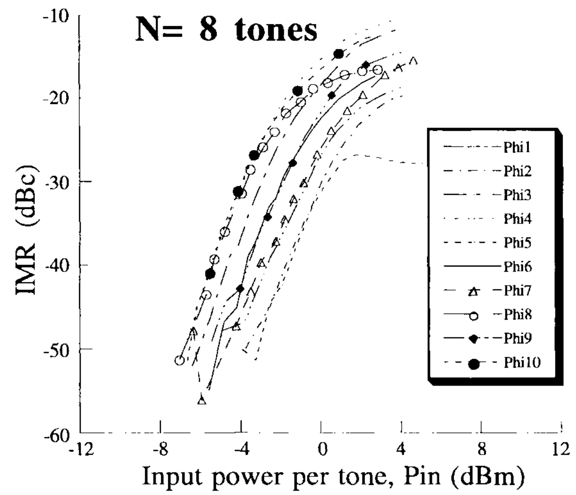

Fig. 11. Effect of carriers' phase distribution on IMR ($N = 8$ tones).

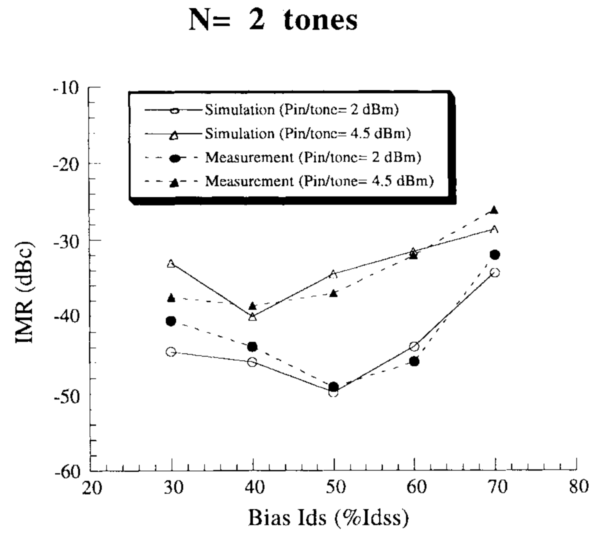

Fig. 12. Effect of biasing conditions on IMR ($N = 2$ tones).

parameter has a significant effect on the total signal, which can be characterized by its time-domain waveform envelope. Depending on the shape of the input signal envelope, the large-signal transistor characteristics may considerably vary, which affects its performances. This was observed in the measurements carried out on the GaAs MESFET mentioned above.

To illustrate such an effect, the transistor IMR was measured at different random phase distributions. Figs. 10 and 11 show IMR levels, for ten random phase distributions, as a function of input power per tone for two- and eight-tone input signals, respectively. It can be shown that the phase distribution effect on the IMR becomes more significant as the number of tones is increased. For $N = 8$ tones (Fig. 11), an IMR level variation of 15–20 dBc, between two different phase distribution cases, can be reached at a given and constant input power level per tone. This is due to the fact that the shape of the envelope of the input signal waveform is strongly affected by the phases of the tones. Thus, the peak power value is strongly dependent on the phase distribution of the N tones. However, for $N = 2$ tones (Fig. 10), the phase distribution effect on the IMR level is negligible. This leads to the conclusion that the shape of the total signal envelope is not considerably affected by the variation of the absolute phases of a two-tone signal.

VI. Effect of Class of Operation

It is well known that the small-signal and large-signal performances of a microwave transistor depend on the applied biasing conditions. As will be seen in the following results, an interesting behavior of the IMR as a function of the dc drain current is obtained.

In this measurement option, the carriers' phase distribution is kept uniform for all performed operating classes (identical absolute phase for each tone). The transistor is loaded with the optimal impedance for maximum output power ($\Gamma_L = 0.58\angle 172°$). The IMR measurements are performed at seven bias points: from 30% $I_{\rm dss}$ to 70% $I_{\rm dss}$ with a 10% step, where $I_{\rm dss}$ is the saturation transistor drain current. The measurement results are obtained by performing an input power sweep at each bias point for $N = 2$ and eight tones.

The slope of the obtained IMR variation as a function of the dc drain current $I_{\rm ds}$ changes at a certain bias point depending on the applied input power. This experimental result is not readily explainable. To further investigate this experimental observation, multitone harmonic-balance simulations [12] were performed using an HP-MDS.[2] For this purpose, a large-signal model for the investigated MESFET is extracted using the Curtice cubic model [13], dc, and S-parameter measurements.

Figs. 12 and 13 present a comparison between the measurement and simulation results of the behavior of the IMR as a function of the drain current $I_{\rm ds}$ for two different input power levels per tone, for $N = 2$ and 8 tones, respectively. One can see that the measurements and the simulation are in an acceptable agreement in term of the IMR levels and mainly in term of the IMR variation slope. Discrepancies between

[2] HP85150 Microwave Design System (MDS). *Building and Analyzing Circuits.* Hewlett-Packard, May 1990.

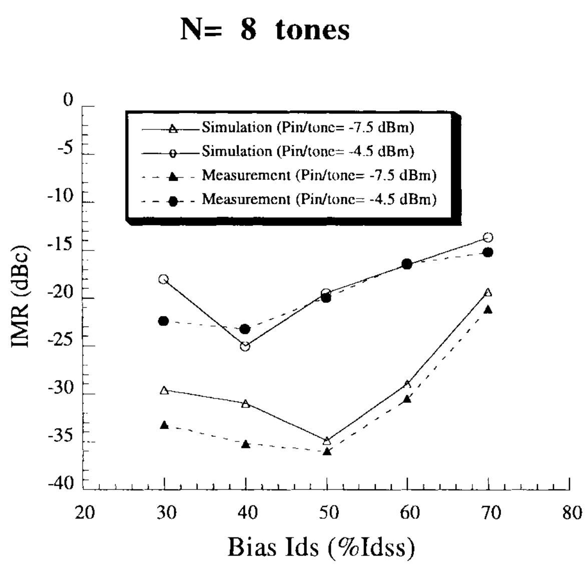

Fig. 13. Effect of biasing conditions on IMR ($N = 8$ tones).

measurement and simulation results are increasing when biasing the transistor toward its pinch-off region, particularly for $N = 8$ tones (Fig. 13). This may be due to the extracted model accuracy at that region.

It can also be observed that in a small-signal operating mode (low input power level), the optimal IMR is obtained in class A operation (50% $I_{\rm dss}$). Around this point, toward the clipping and pinch-off regions, the IMR is degraded. In the large-signal operating mode (near/or in the compression region), the IMR degradation increases with the drain current increasing and tends to maintain constant value at high $I_{\rm ds}$. It is important to notice that the phase distribution was taken uniform (all the tones have the same phase), and the authors expect a similar conclusion for the random carriers' phase distributions. The same observations were obtained for the other N-tones testing ($N = 4$, 16, and 32).

The biasing conditions are, therefore, another parameter to take into account in optimizing power and linearity performances of amplifiers.

VII. Conclusion

In this paper, a new multitone load–pull measurement system for microwave transistor characterization in a nonlinear operating mode was presented. Many possible measurement options can be performed using the new system to generate a large-signal multitone database useful for accurate transistor characterization. Some previously published theoretical results on the degradation of the IMR as a function of the number of tones are experimentally validated using such a measurement system. It was particularly observed that for a certain carriers' phase distribution, an input power backoff is not needed to maintain constant IMR as the number of tones increases. Load–pull measurement results of both the power and the IMR were presented, showing transistor performance at different number of tones. The effects of the carriers' phase distribution and biasing conditions were also discussed. The effect of biasing conditions was experimentally studied and compared to the simulation results. It was concluded that these two parameters—carriers' phase distribution and biasing conditions—affect the transistor performance in terms of linearity. In other words, the IMR is strongly dependent on the carriers' phase distribution and biasing conditions, mainly when the number of tones is increased.

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References

[1] S. A. Maas, *Nonlinear Microwave Circuits.* Norwood, MA: Artech House, 1988.
[2] S. M. Perlow, "Third-order distortion in amplifiers and mixers," *RCA Rev.*, vol. 37, pp. 234–266, June 1976.
[3] C. Tsironis, "Two-tone intermodulation measurements using computer-controlled microwave tuner," *Microwave J.*, vol. 32, pp. 161–161, Oct. 1989.
[4] F. M. Ghannouchi, G. Zhao, and F. Beauregard, "Simultaneous load–pull of intermodulation and output power under two-tone excitation for accurate SSPA's designs," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 929–934, June 1994.
[5] J. Jacobi, "IMD still unclear after 20 years," *Microwaves RF*, pp. 119–126, Nov. 1986.
[6] J. G. Freed, "Equations provide accurate third-order IMD analysis," *Microwaves RF*, pp. 75–84, Aug. 1992.
[7] M Leffel, "Intermodulation distortion in a multi-signal environment," *R. F. Des.*, pp. 78–83, June 1995.
[8] L. Cellai and A. Greco, "Optimal phase relationship aids IM testing," *Microwaves RF*, pp. 56–61, July 1996.
[9] R. Hajji, F. Beauregard and F. M. Ghannouchi, "Multi-tone characterization for intermodulation and distortion analysis," in *Proc. 1996 IEEE-MTT-S Symp.*, San Francisco, CA, June 17–21, pp. 1691–1694.
[10] G. P. Locatelli, "De-embedding techniques for device characterization," *Alta Freq.*, vol. 57, no. 5, pp. 267–272, June 1988.
[11] M. A. Maury, Jr., S. L. Mar., and G. R. Simpson, "TRL calibration of vector automatic network analyzers," *Microwave J.*, vol. 30, no. 5, pp. 387–382, May 1987.
[12] K. S. Kundert and A. S. Vincentelli, "Simulation of nonlinear circuits in the frequency domain," *IEEE Trans. Computer-Aided Design*, vol. CAD-5, pp. 521–535, Apr. 1986.
[13] W. R. Curtice, "GaAs MESFET modeling and nonlinear CAD," *IEEE Trans Microwave Theory Tech.*, vol. MTT-36, pp. 220–230, Feb. 1988.

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