"TWO-SIGNAL" METHOD OF MEASURING THE LARGE-SIGNAL S-PARAMETERS OF TRANSISTORS

Dr. P.D. van der Puije
Department of Electronics
Carleton University
Ottawa, Canada

Dr. S.R. Mazumder
Chaire d'Electromagnetisme et d'Hyperfrequences
Ecole Polytechnique Federale de Lausanne
Lausanne, Switzerland

ABSTRACT

Large-signal S-parameters reviewed; of transistors in Class-C employed. S_{12} and S_{21} problems encountered. Novel method concisely developed; based on theory herein presented. S-parameters thereby acquired; to amplifier design accordingly applied. Predicted and measured output power compared. Suitable conclusions duely recorded.

Introduction

Small-signal S-parameter characterization of transistors is well established. Attempts to obtain large-signal S-parameters for transistors have been of limited success especially in cases where the non-linearity is severe such as in Class-C operation.[1-3]

The large-signal parameters S_{11} and S_{21} can be fairly accurately measured since the drive applied to port 1, set up signals in the transistor which closely resemble those that would exist under Class-C conditions. When the drive is applied to port 2 in order to measure S_{12} and S_{22}, the signal as well as the dc bias of the transistor will, in general, be quite different from those that would occur in a Class-C amplifier.

In this paper a new and simple method of measuring the large-signal S-parameters is proposed. This involves the simultaneous application of two signals of the same frequency to the ports of the device.

Theory

An active 2-port to be used in the design of a class-C amplifier may be characterized at a specified power level, bias and frequency by large-signal S-parameters.[1-3]

$$b_1 = S_{11}a_1 + S_{12}a_2 \tag{1}$$

$$b_2 = S_{21}a_1 + S_{22}a_2 \tag{2}$$

where the a's and b's are the wave variables.[6] It is assumed that the S-parameters are constants at the signal power levels represented by $|a_1|^2$ and $|a_2|^2$.

It is convenient to express (1) and (2) in the form:

$$\frac{b_1}{a_1} = S_{11} + S_{12}\frac{a_2}{a_1} \tag{3}$$

$$\frac{b_1}{a_2} = S_{11}\frac{a_1}{a_2} + S_{12} \tag{4}$$

$$\frac{b_2}{a_1} = S_{21} + S_{22}\frac{a_2}{a_1} \tag{5}$$

$$\frac{b_2}{a_2} = S_{21}\frac{a_1}{a_2} + S_{22} \tag{6}$$

From (3) to (6) we observe that if $|a_1|$ and $|a_2|$ are constant, then each of the quantities $\frac{b_i}{a_j}$ (i,j = 1,2) generates a circle in the corresponding $\frac{b_i}{a_j}$ - plane as a function of $\frac{a_2}{a_1}$, the phase angle between a_2 and a_1, as shown in fig. 1. It is also noted, from fig. 1, that the centre of the circular locus of $\frac{b_i}{a_j}$ corresponds to the S-parameter S_{ij}.

Since the quantities $\frac{b_i}{a_j}$ can be measured by a reflection (i=j) or transmission (i≠j) type of measurement by using a Network Analyzer systems, the $\frac{b_i}{a_j}$ - locii can be obtained as a function of the phase angle between a_2 and a_1. Thus the 4 S-parameters can be determined by locating the centres of the $\frac{b_i}{a_j}$ - locii.

Clearly, at a specified power level of $|a_i|^2$, the $\frac{b_i}{a_j}$ - locii will deviate from their circular locus if the S-parameters vary with the phase angle between a_1 and a_2.

The "Two-Signal" Method of Measuring the Large-signal S-parameters

An experimental set-up to measure the $\frac{b_i}{a_j}$ - locii is shown in fig. 2. The system consists of a signal source from which are derived the two input signals a_1 and a_2. The quantities $\frac{b_i}{a_j}$ are measured by reflection (i=j) or transmission (i≠j) type of measurement using the Network Analyzer. The phase

CH1355-7/78/0000-0263$00.75

angle between a_1 and a_2 is varied by the phase shifter. The amplitudes of a_1 and a_2 are adjustable by using the variable attenuators. The adjustment of the amplitude of a_1 is dictated by a required dc collector current (I_c) in the transistor. The amplitude of a_2 can be adjusted to any suitable value. However, it is informative to obtain the $\frac{b_i}{a_j}$ - locii, for a particular collector current I_c, corresponding to a number of values of $|a_2|$. If I_c varies significantly with respect to the phase between a_2 and a_1, then the amplitude of a_1 has to be adjusted to maintain constant I_c and in this case, the $\frac{b_i}{a_j}$ - locii for various values of $\left|\frac{a_2}{a_1}\right|$ are measured. It may be observed that the $\frac{b_i}{a_j}$ - locii, for various values of constant $|a_2|$, will show how the S-parameters vary with respect to the load "mismatches". This observation will be clearer if we regard the different values of a_2 as actually simulating different load reflection coefficients at the output port.[7,11]

The calibration of the reference planes of measurement in fig. 2 is accomplished by the standard method [5] of reflection and transmission measurement using a Network Analyzer.

Results

The $\frac{b_i}{a_j}$ - locii, (i,j = 1,2) for a transistor (NEC2SC1255) under class-C conditions are shown in fir. 3. These locii were generated at 2 GHz, with the dc voltages of V_{CE} = 15 V, V_{BE} = 0V and a dc current through the transistor of I_C = 70 mA which was established by applying the appropriate input power level. From these locii the large-signal S-parameters S_{ij}'s (centres of $\frac{b_i}{a_j}$ - locii) are determined as follows:

$$S_{11} = 0.64 \angle{-154^\circ} \qquad S_{12} = 0.14 \angle{-33^\circ}$$
$$S_{21} = 0.69 \angle{-40^\circ} \qquad S_{22} = 0.86 \angle{-57^\circ} \qquad (7)$$

Conventional Large-Signal S-parameters

The large-signal S-parameters were also measured by the conventional method.[1,5]

These S-parameters, given in (8), were also measured at 2 GHz with V_{CE} = 15 V and V_{BE} = 0V. The dc current through the transistor, I_C = 70 mA, was established by applying sufficient RF power while measuring the parameters S_{11} and S_{21}. While measuring S_{12} and S_{22}, the current I_C was negligibly small. As also mentioned earlier, this measurement condition of the conventional method to measure S_{12} and S_{22} is not meaningful.

The S-parameters were found to be:

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} = 0.64 \angle{-156^\circ} \qquad S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0} = 0.03 \angle{88^\circ} \qquad (8)$$
$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} = 0.69 \angle{-42^\circ} \qquad S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0} = -.06 \angle{-93^\circ}$$

Note the difference in the values of S_{12} and S_{22} in the two methods of measurement.

It is important to mention here that in both cases of measuring the S-parameters given in (7) and (8), the harmonics should be terminated by the same impedances. In the present paper, the second harmonic terminations used were designed by the method reported earlier [8] and were realized in the form of an elliptic function type low-pass filter.[7,10]

Comparison

In order to compare the results of the two methods of measurement, each set of S-parameters were used in the design of an amplifier following the method proposed by Leighton et al.[4] The load impedances for the amplifiers were determined from the points of intersection of the gain circles and the constant P_{out} circle, as shown in fig. 4, drawn on the output plane.

The amplifier, the experimental performances of which are shown in fig. 4., was constructed on microstrip by realizing the source and the load terminations as predicted by using the method reported in.[9] These matching networks were realized using elliptic function type of structures which also simultaneously realized the corresponding second harmonic terminations with which the S-parameters were measured.[7]

From fig.4, it can be seen that the S-parameters measured by the "Two-signal" method predict the performance of the power amplifiers with greater accuracy than those measured by the conventional method. Since in the two measurement systems the values of S_{11} and S_{21} are almost the same, it is reasonable to argue that the more accurate values of S_{12} and S_{22} given by the "Two-Signal" method are responsible for the good agreement between predicted and experimental results.

One major advantage of the "Two-Signal" method is that it is possible to anticipate how good the amplifier design will be by observing the nature of the $\frac{b_i}{a_j}$ - locii. If these depart significantly from a circle, a greater difference between predicted and experimental performance can be expected. In such situations, the optimum design of the amplifier may be accomplished by the method reported earlier.[9]

Discussion and Conclusion

The "Two-Signal" method of characterizing an active 2-port has been proposed and a set-up for measuring the large-signal S-parameters given. The greater accuracy of the "Two-Sighal" method over the conventional large-signal S-parameter measurement method has been demonstrated.

References

1. R.J. Chaffin and W.H. Leighton, "Large-Signal S-parameters Characterization of UHF Power Transistors", Digest of Tech. papers, 1973, IEEE-MTT Int. Microwave Symp., University of Colorado, June 5, 1973.
2. L.S. Houselander et al, "Transistor Characterization by Effective Large-Signal 2-port Parameters", IEEE Journal of Solid State Circuits, April 1970.
3. O. Muller, "Large-Signal S-parameters Measurement of Class-C Operated Transistors", Nachrichtentech Z., October, 1968.
4. W.H. Leighton et al, "RF Amplifier Design with Large-Signal S-parameters", IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-21, No. 12, December 1973.
5. H.P. Application Note No. 117-2, "Stripline Component Measurements with the HP 8410 Network Analyzer", January 1971.
6. K. Kurokawa, "Power Waves and the Scattering Matrix", IEEE Trans. on Microwave Theory and Techniques, March 1965.
7. S.R. Mazumder, Characterization and Design of Microwave Class-C Transistor Power Amplifier, Ph.D. Thesis, 1976, Carleton University, Ottawa, Canada.
8. S.R. Mazumder and P.D. van der Puije, "Characterization of Non-linear 2-ports for the Design of Class-C Amplifiers" IEE Journal on Microwaves, Optics and Acoustics (MOA), vol. 1, No. 4, July 1977, pp. 138-142.
9. S.R. Mazumder and P.D. van der Puije, "An Experimental Method of Characterizing Non-Linear 2-ports and its Application to Microwave Class-C Transistor Power Amplifier Design", IEEE Journal of Solid State Circuits (JSSC), Vol. SC-12, No. 5, October 1977, pp. 576-580.
10. R. Saal and E. Ulbrich, "On the Design of Filters by Synthesis", IRE Trans. on Circuit Theory, Dec. 1958, pp. 284-327.
11. Y. Takayama, "A New Load-pull Characterization Method for Microwave Power Transistors", 1976 IEEE MTT-S International Microwave Symposium, Digest of Technical papers, pp.218-220.

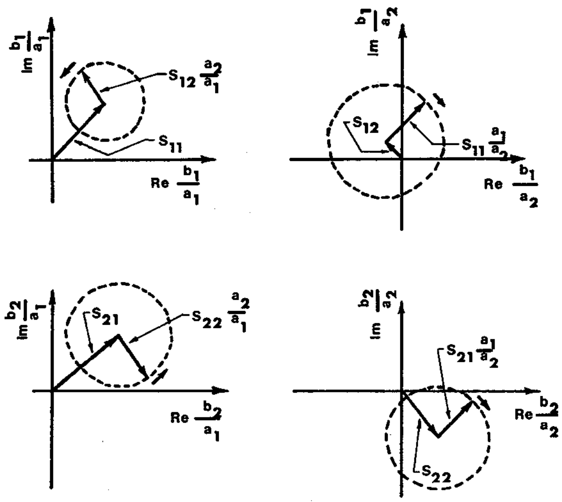

Fig. 1 Circular locii in b_i/a_j - plane as a function of a_2/a_1. Centre of b_i/a_j - locus corresponds to S_{ij}.

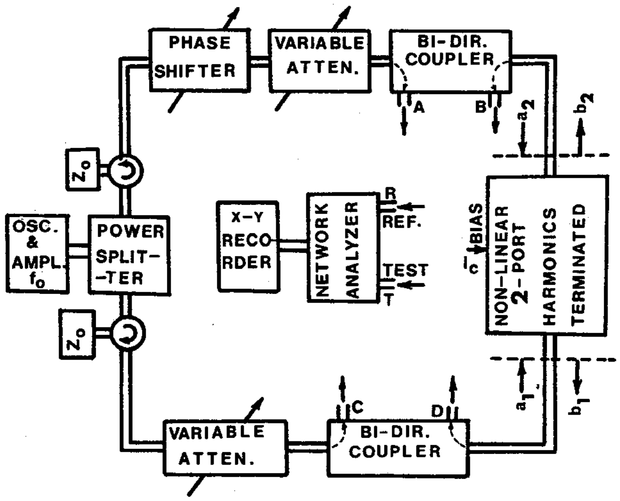

Fig. 2 Large-signal S-parameters measurement set up using 'two-signal' method. Note: to measure the locus of:-

(i) b_1/a_1: connect C to R; D to T; and vary the phase shifter.

(ii) b_1/a_2: connect A to R; D to T; and vary the phase shifter.

(iii) b_2/a_1: connect C to R; B to T; and vary the phase shifter.

(iv) b_2/a_2: connect A to R; B to T; and vary the phase shifter.

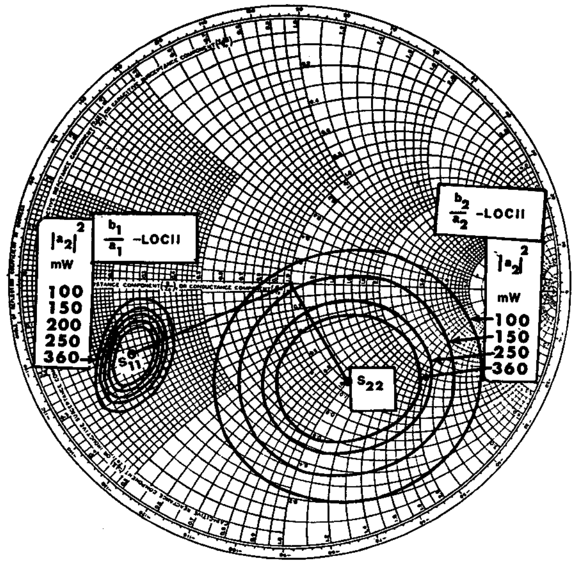

Fig. 3(a) Locii for b_i/a_i; i=1,2, as function of a_2/a_1; for different values $|a_2|^2$ mW. (Transistor NEC 2SC1255). (Note: for b_2/a_2 locus, the outer circle of the Smith chart corresponds to 2.0.)

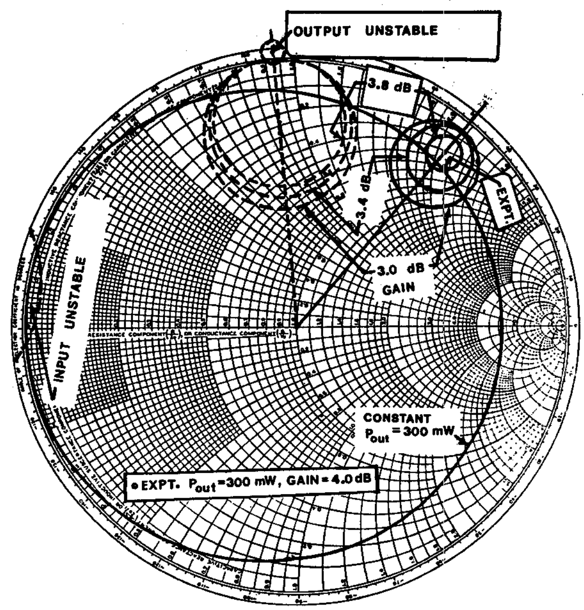

Fig. 4 Amplifier design using S-parameters. Note:
_____ Constant Gain circles corresponding to the S-parameters in (7);
----- Constant Gain circles corresponding to the S-parameters in (8).

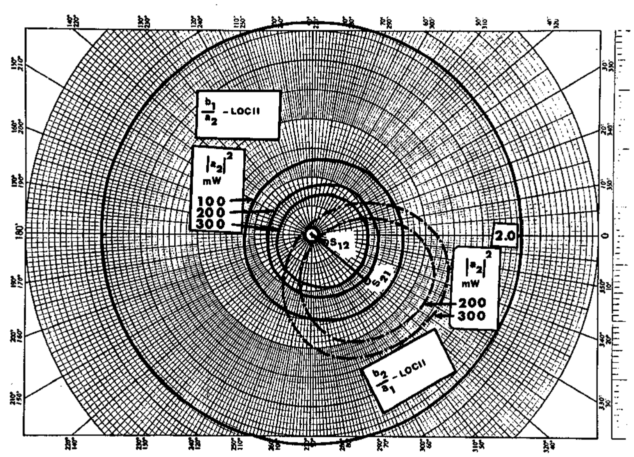

Fig. 3(b) b_1/a_2, b_2/a_1 - locii, as function of a_2/a_1; for different values of $|a_2|^2$ mW. (Transistor NEC 2SC1255)