"Two-Signal" Method of Measuring the Large-Signal S-Parameters of Transistors

SHAMSUR R. MAZUMDER, MEMBER, IEEE, AND P. D. VAN DER PUIJE

Abstract—In this paper, large-signal S-parameters are reviewed, and transistors of Class-C are employed. Problems are encountered in obtaining large-signal parameters S_{12} and S_{21}. A novel method is concisely developed, based on theory presented herein. The acquired S-parameters are applied to amplifier design accordingly. The predicted and measured output power are compared, and suitable conclusions are duly recorded.

I. 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 nonlinearity 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 one sets up signals in the transistor which closely resemble those that would exist under Class-C conditions. When the drive is applied to port two 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.

II. Theory

An active two-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

Manuscript received August 9, 1977; revised September 30, 1977.

S. R. Mazumder is with the Chaire d'Electromagnétisme et d'Hyperfréquences, Ecole Polytechnique Féderale de Lausanne, Lausanne, Switzerland.

P. D. van der Puije is with the Department of Electronics, Carleton University, Ottawa, Ont., Canada.

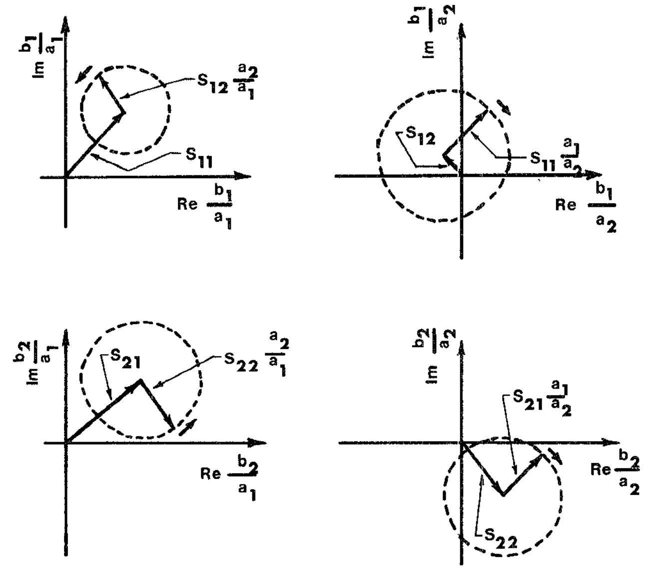

Fig. 1. Circular loci in b_i/a_j plane as a function of $\angle a_2/a_1$. Center of b_i/a_j locus corresponds to S_{ij}.

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

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

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

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

From (3) to (6), we observe that if $|a_1|$ and $|a_2|$ are constant, then each of the quantities b_i/a_j $(i,j=1,2)$ generates a circle in the corresponding b_i/a_j plane as a function of $\angle a_2/a_1$, the phase angle between a_2 and a_1, as shown in Fig. 1. It is also noted from Fig. 1 that the center of the circular locus of b_i/a_j corresponds to the S-parameter S_{ij}. Since the quantities b_i/a_j can be measured by a reflection $(i=j)$ or transmission $(i \neq j)$ type of measurement by using a network analyzer system, the b_i/a_j loci can be obtained as a function of the phase angle between a_2 and a_1. Thus the four S-parameters can be determined by locating the centers of the b_i/a_j loci.

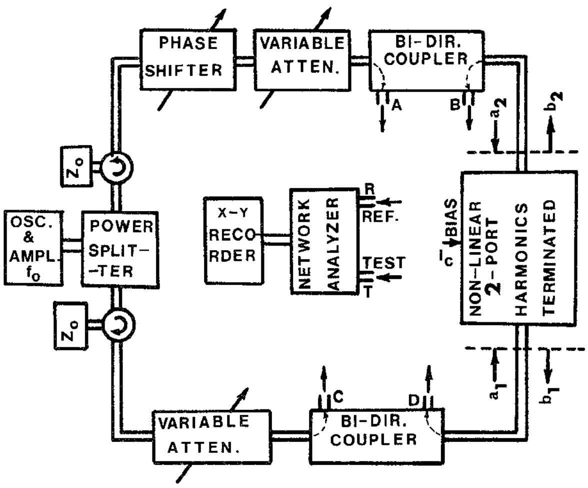

Fig. 2. Large-signal S-parameters measurement setup using "two-signal" method. (Note: To measure the locus of
(i) b_1/a_1: connect C to R, D to T, and vary the phase shifter;
(ii) b_1/a_2: connect A to R, D to T, and vary the phase shifter;
(iii) b_2/a_1: connect C to R, B to T, and vary the phase shifter;
(iv) b_2/a_2: connect A to R, B to T, and vary the phase shifter.)

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

III. The "Two-Signal" Method of Measuring the Large-Signal S-Parameters

An experimental setup to measure the b_i/a_j loci 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 b_i/a_j are measured by reflection $(i=j)$ or transmission $(i \neq j)$ type of measurement using the network analyzer. The phase 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 b_i/a_j loci, 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 b_i/a_j loci for various values of $|a_2/a_1|$ are measured. It may be observed that the b_i/a_j loci, for various values of constant $|a_2|$, will show how the S-parameters vary with respect to 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.

IV. Results

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

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

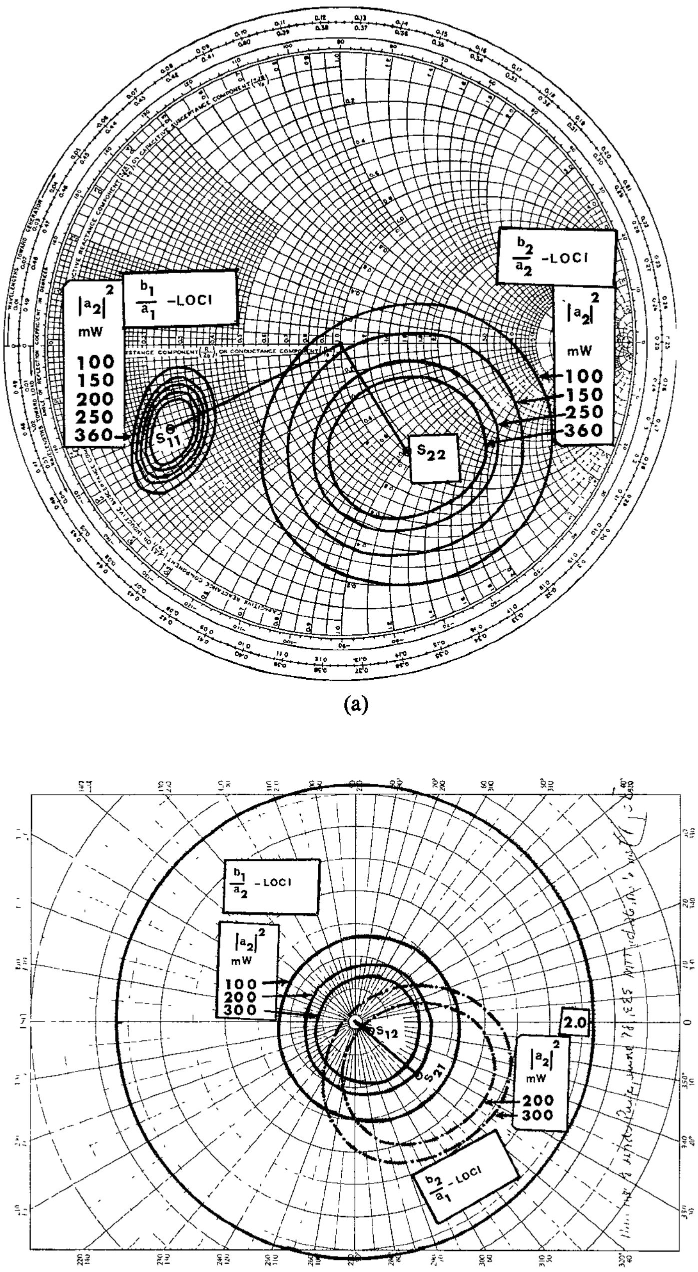

Fig. 3. (a) Loci for b_i/a_i; $i=1,2$, as function of $\angle(a_2/a_1)$, for different values $|a_2|^2$ mW (Transistor NEC 2SC1255). (Note: for b_2/a_2 locus, the outer circle of the Smith chart corresponds to 2.0.) (b) $b_1/a_2, b_2/a_1$ loci, as function of $\angle a_2/a_1$, for different values of $|a_2|^2$ mW (Transistor NEC 2SC1255).

V. 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 $V_{BB}=0$ V. 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

$$S_{11}=\left.\frac{b_1}{a_1}\right|_{a_2=0}=0.64\angle-156^\circ$$

$$S_{12}=\left.\frac{b_1}{a_2}\right|_{a_1=0}=0.03\angle 88^\circ$$

$$S_{21}=\left.\frac{b_2}{a_1}\right|_{a_2=0}=0.69\angle-42^\circ$$

$$S_{22}=\left.\frac{b_2}{a_2}\right|_{a_1=0}=0.96\angle-93^\circ. \quad (8)$$

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].

VI. Comparison

In order to compare the results of the two methods of measurement, each set of S-parameters was 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.

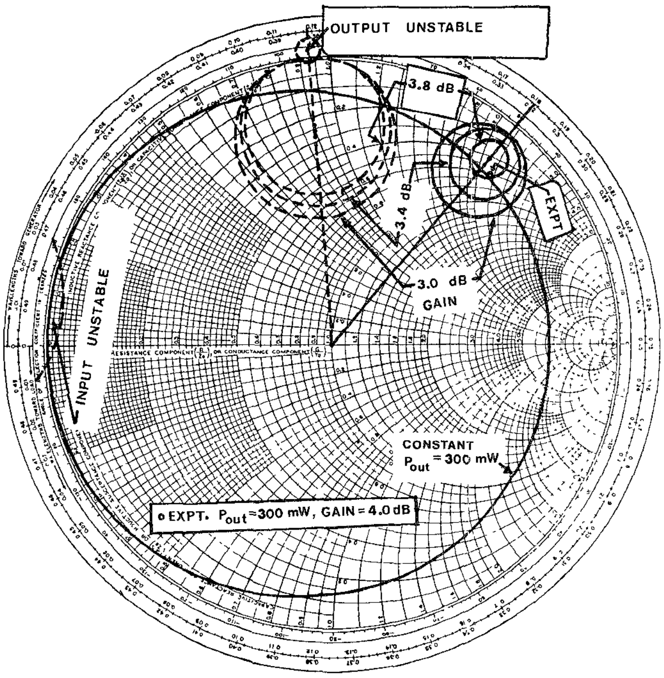

Fig. 4. Amplifier design using S-parameters. (Note: ______ constant gain circles corresponding to the S-parameters in (7), - - - - - - constant gain circles corresponding to the S-parameters in (8).)

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 b_i/a_j loci. 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].

VII. Discussion and Conclusion

The "two-signal" method of characterizing an active two-port has been proposed and a setup for measuring the large-signal S-parameters given. The greater accuracy of the "two-signal" 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," in *Digest of Tech. Papers, Proc. 1973 IEEE MTT Int. Microwave Symp.*, Univ. Colorado, Boulder, June 5, 1973.

[2] L. S. Houselander *et al.*, "Transistor characterization by effective large-signal 2-port parameters," *IEEE J. Solid-State Circuits*, Apr. 1970.

[3] O. Müller, "Large-signal S-parameters measurement of Class-C operated transistors," *Nachrichtentech Z.*, Oct. 1968.

[4] W. H. Leighton *et al.*, "RF amplifier design with large-signal S-parameters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, Dec. 1973.

[5] "Stripline component measurements with the HP 8410 network analyzer," *H. P. Application Note No. 117-2*, Jan. 1971.

[6] K. Kurokawa, "Power waves and the scattering matrix," *IEEE Trans. Microwave Theory Tech.*, Mar. 1965.

[7] S. R. Mazumder, "Characterization and design of microwave

Class-C transistor power amplifier," Ph.D. dissertation, Carleton Univ., Ottawa, Canada, 1976.
[8] S. R. Mazumder and P. D. van der Puije, "Characterization of non-linear 2-ports for the design of Class-C amplifiers," *IEE J. Microwaves Optics Acoust.*, vol. 1 no. 4, pp. 138–142, July 1977.
[9] —, "An experimental method of characterizing non-linear 2-ports and its application to microwave Class-C transistor power amplifier design," *IEEE J. Solid-State Circuits*, vol. SC-12, pp. 576–580, Oct. 1977.
[10] R. Saal and E. Ulbrich, "On the design of filters by synthesis," *IRE Trans. Circuit Theory*, pp. 284–327, Dec. 1958.
[11] Y. Takayama, "A new load-pull characterization method for microwave power transistors," in *Digest Tech. Papers, 1976 IEEE MTT-S Int. Microwave Symp.*, pp. 218–220.

Cavity Stabilization and Electronic Tuning of a Millimeter-Wave IMPATT Diode Oscillator by Parametric Interaction

HIROSHI OKAMOTO, MEMBER, IEEE, AND MUTSUO IKEDA

***Abstract*—A new technique is proposed by which both noise reduction and electronic tuning of a millimeter-wave solid-state oscillator can be realized by injecting an arbitrary low-frequency (several hundred megahertz or beyond) signal to the oscillator element which is provided with an additional high-Q cavity.**

This method has much wider tuning bandwidth than that of the conventional subharmonic injection locking technique.

Presented are both experimental results and some theoretical interpretations by using an IMPATT diode oscillator.

I. Introduction

INJECTION LOCKING is a conventional circuit technology to reduce sideband noise and to give electronic tunability to solid-state oscillators. Three types of injection locking methods have been developed by now. They are as follows.

1) Fundamental-wave injection locking [1]—Here, the frequency of the injection signal f_{inj} is nearly equal to the free-running oscillation frequency f_O to be locked.

2) Subharmonic injection locking [2]—Here, f_{inj} is nearly equal to $(1/n)\cdot f_O$, where n is an integer larger than unity.

3) Sideband-wave injection locking [3]—Here, two injection signals are used, one of which is a low-frequency signal $f_{inj,\,1}$, and the other a signal with frequency $f_{inj,\,2} \doteqdot f_O \pm f_{inj,\,1}$.

The first and the third techniques have wider locking bandwidth (i.e., tuning bandwidth) than the second, when compared for a particular gain. With increasing frequency, however, it becomes more difficult to realize a low-noise injection signal source with frequency nearly equal to that of the oscillator to be stabilized.

The advantage of the second technique is that a low-frequency signal can be used for injection. But unfortunately, the tuning bandwidth becomes narrower when the order of multiplication n is increased. In one example of the subharmonic injection locking of an 8.5-GHz IMPATT diode oscillator, it was reported [2] that the available tuning bandwidth is 1 MHz or less when n is equal to 9 and the locking gain is 0 dB.

In order to overcome these difficulties, a new technique is proposed here, which is an extended version of the injection locking technique to a parametrically interacting system. This method has the following two advantages.

1) The frequency of the injection signal can be selected somewhat arbitrarily (at several hundred megahertz or beyond). We can, therefore, use an injection signal whose frequency is much lower than that of the solid-state oscillator to be stabilized. This makes it rather easy to realize the injection signal source.

2) The tuning bandwidth is much wider than that provided by subharmonic injection locking. The bandwidth is comparable to that obtainable with fundamental-wave and sideband-wave injection locking methods.

Experimental results on a millimeter-wave IMPATT diode oscillator are presented in this paper, along with some analytical discussions.

II. Mechanism

The frequency planes shown in Fig. 1 illustrate the mechanism of the new technique discussed here.

Assume an IMPATT diode oscillator is oscillating freely at f_O. This is shown in Fig. 1(a). The frequency f_O is

Manuscript received August 22, 1977; revised December 20, 1977.
The authors are with the Musashino Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation, Musashino-shi, Tokyo 180, Japan.

0018-9480/78/0600-0420$00.75 © 1978 IEEE