A QUASI-LINEAR APPROACH TO THE DESIGN OF MICROWAVE TRANSISTOR POWER AMPLIFIERS

K.L. Kotzebue
Department of Electrical Engineering and Computer Science
University of California
Santa Barbara, CA 93106

ABSTRACT

A simple graphical technique similar to the conventional Linvill technique has been developed which specifies the added-power circuit efficiency of a microwave transistor power amplifier with arbitrary load termination. Experimental verification of this approach has been obtained with a 1 W BJT amplifier operating at 1.3 GHz.

INTRODUCTION

It has been recently shown that the large-signal behavior of a microwave bipolar junction transistor can be adequately characterized by a set of large-signal y parameters[1,2]. As part of the verification of this characterization, it was necessary to develop design criteria for the terminations which optimize the large-signal performance of such a transistor when used as a power amplifier. As indicated in Ref. 1, the added-power circuit efficiency of an amplifier is maximized (for a given transistor operating point) when the load termination is given by

$$Y_L = -\left[y_{22} + \frac{y_{21}}{A_{opt}}\right] \tag{1}$$

$$\text{where } A_{opt} = \frac{-(y_{21} + y_{12}^*)}{2g_{22}}. \tag{2}$$

The corresponding input admittance is then given by

$$Y_{in} = y_{11} + y_{12}\,A_{opt}. \tag{3}$$

While Eqs. (1), (2) and (3) are adequate for many design purposes, it also would be desirable to have a theory which shows contours of constant added power in a fashion similar to experimentally obtained load-pull data. Such a design theory has been developed and experimentally verified with a 1 W BJT amplifier operating at 1.3 GHz.

THE DESIGN TECHNIQUE

The approach is a modification of the well-known graphical technique originated by Linvill and Schimpf[3]. However, instead of determining contours of constant power gain, in the present approach contours of constant added power are obtained.

The added power, P_a, is defined as the difference between the output RF power and the input RF power:

$$P_a \equiv P_{out} - P_{in}. \tag{4}$$

A normalized added power, p_a, is defined as

$$p_a \equiv \frac{4P_a g_{22}}{|y_{21}|^2\,|V_1|^2} \tag{5}$$

where V_1 is the amplitude of the RF voltage at the input of the transistor.

In the (x,y) coordinate system which is used in the conventional Linvill chart representation[4,5], the following expression involving the normalized added power may be derived:

$$\left[x + \left|\frac{y_{12}}{y_{21}}\right|\right]^2 + y^2 = 1 + \left|\frac{y_{12}}{y_{21}}\right|^2 - \frac{2}{C}\left|\frac{y_{12}}{y_{21}}\right| - p_a \tag{6}$$

$$\text{where } C \equiv \frac{|y_{21}y_{12}|}{2g_{11}g_{22} - \mathrm{Re}(y_{21}y_{12})}$$

Equation (6) thus defines a family of circles of constant added power. The centers of all circles are identical, located at

$$x_o = -\frac{y_{12}}{y_{21}}, \quad y_o = 0 \tag{7}$$

with radii given by

$$r = \left[1 + \left|\frac{y_{12}}{y_{21}}\right|^2 - \frac{2}{C}\left|\frac{y_{12}}{y_{21}}\right| - p_a\right]^{1/2} \qquad (8)$$

The maximum value of added power will occur when the radius is equal to zero. The result, as obtained from eq. (8), is

$$(P_a)_{max} = |V_1|^2 \frac{|y_{21}|^2 + |y_{12}|^2 + 2\mathrm{Re}(y_{21}y_{12}) - 4g_{11}g_{22}}{4g_{22}} \qquad (9)$$

which is in agreement with the value given in Ref. 1.

As in a conventional Linvill analysis, the circles defined by eqs. (7) and (8) are plotted on a Smith chart oriented for an admittance representation. Also, as in a conventional Linvill analysis, the x-axis is oriented at the angle θ with respect to the horizontal axis, given by

$$\theta = -\arg(-y_{21}y_{12}) \qquad (10)$$

The conversion between Linvill chart coordinates and values of load terminations is also conventional. Thus, if the values of real and imaginary components as read off the Linvill chart are given by g_o+jb_o, then the corresponding load termination is given by

$$Y_L = g_{22}g_o + j(g_{22}b_o - b_{22}) \qquad (11)$$

The physical interpretation of a circle defined by eqs. (7) and (8) is that it represents a contour of constant added power for a given value of input voltage, V_1. Under conditions of amplifier saturation, such a circle will also represent a useful contour of constant added-power circuit efficiency.

EXPERIMENTAL RESULTS

For the experimental investigation of this design approach, the CTC D1-28Z bipolar junction transistor was selected. This transistor is rated at 1 watt output at 960 MHz with V_{CC} = 28 V. The actual frequency used in the experimental evaluation was 1.3 GHz, where the measured maximum collector efficiency was 50% when biased to I_C = 100 mA, V_{CE} = 20 V.

The large-signal y parameters were directly measured on a conventional network analyzer which incorporated a near-short-circuit at the output reference plane[2]. Such a direct measurement technique is necessary, for conventional s parameters cannot be mathematically transformed to the required y parameters with sufficient accuracy because of the transistor's nonlinear behavior. The amplitudes of the RF voltages at which the y parameters are measured are determined with the aid of eq. (9). A useful simplification is to measure y_{22} and y_{12} at a peak RF amplitude somewhat lower than the bias voltage. Such a large amplitude is reasonable since we are interested in amplifier operation near saturation. Also, great precision in the RF voltage swing is not needed since y_{22} and y_{12} are found to be relatively weak functions of the output voltage swing, V_2. In this particular case, since the bias voltage was 20 V, y_{22} and y_{12} were measured at an RF voltage of 16 V peak. (Pulsed measurement techniques were required because of the large power dissipations involved.) With the values of y_{22} and y_{12} thus obtained, y_{11} and y_{21} are measured over a range of values of V_1, and the theoretical added power calculated from eq. (9). An appropriate value of V_1 is that which maximizes the added power. Again, great precision in amplitude of the RF voltage, V_1, is not necessary since the maximum is usually broad and the y parameters do not vary greatly with amplitude when V_1 is large. In the present case, such considerations indicated that the most appropriate value of V_1 was 4.5 V rms. This value of V_1 resulted in a predicted value of P_a of 660 mW. The values of the large-signal y parameters so obtained are given below:

$$y_{11} = .025 - j.052 \text{ mho}$$

$$y_{12} = -.0076 - j.0080 \text{ mho}$$

$$y_{21} = -.053 - j.0051 \text{ mho}$$

$$y_{22} = .016 + j.042 \text{ mho}$$

The added-power Linvill chart representation for this set of y parameters is shown in Fig. 1, with three contours of constant added power shown. These three contours represent values of added power which are 1 dB, 2 dB, and 3 dB below the maximum value, with the maximum added power occurring at the center of the circles. The points labeled A, B, and C represent three different load terminations which were experimentally investigated. Each load termination was preset and then experimentally adjusted as required. The load termination for design A was optimized for maximum added power, while the load terminations for designs B and C were adjusted to yield saturated added power approximately 1 dB below that which was measured for design A.

Figure 2 shows a comparison between the predicted load terminations and the experimentally measured terminations for each design. The agreement is considered to be good. The maximum measured added power for this transistor was 630 mW, yielding an added-power circuit efficiency of 31.5% and a collector efficiency of 50%. The quite good agreement between the predicted and actual values of added power should be considered as somewhat fortuitous since the theoretical result is a fairly sensitive function of all the measured quantities used to characterize the transistor. In general, $\pm$ 20% agreement between the experimental and theoretical values of P_a should be expected.

Another important aspect of this design approach is that it is possible to show contours of constant power gain as well as contours of constant added power; hence the designer can see at a glance how power gain and circuit efficiency are interrelated. The contours of constant power gain are obtained from a conventional Linvill analysis; Fig. 3 shows such a Linvill chart representation. Note that the transistor is potentially unstable, with C = 1.1. From the graphical construction we determine that design A should have a power gain of 5.3 dB, design B a power gain of 4.3 dB, and design C a power gain of 6.8 dB.

These gains should be achieved at the value of V_1 appropriate to the large-signal y parameters used in the construction of the Linvill chart. Since this value of V_1 was chosen to approximately maximize the added power, we need to investigate amplifier performance near the point of maximum added power. Figure 4 is a plot of the experimentally measured added power for each design. The points on the curves indicated by the arrows are the points where the experimental amplifiers have the power gains predicted by Fig. 3. Once again the agreement between theory and experiment is good, for we see that for each design the predicted value of power gain does indeed occur close to the actual maximum added power.

ACKNOWLEDGEMENT

This work was sponsored by the National Science Foundation under Grant GK-15612.

REFERENCES

1. K.L. Kotzebue, "Microwave-transistor power-amplifier design by large-signal y parameters," Elec. Lett., vol. 11, pp. 240-241, May 29, 1975.

2. K.L. Kotzebue, "The use of large-signal y-parameters in high frequency transistor circuit design," Proceedings Ninth Annual Asilomar Conference on Circuits, Systems, and Computers, November 1975.

3. J.G. Linvill and L.G. Schimpf, "The design of tetrode transistor amplifiers," Bell Syst. Tech. J., vol. 35, pp. 813-840, 1956.

4. J.G. Linvill and J.F. Gibbons, Transistors and Active Circuits, McGraw-Hill, 1961.

5. R. Spence, Linear Active Networks, Wiley-Interscience, 1970.

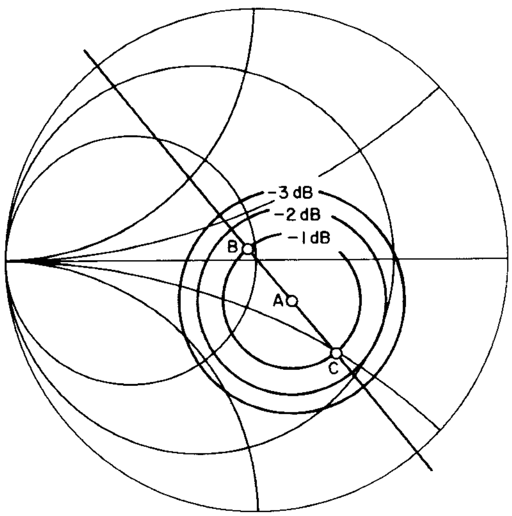

Fig. 1 The added-power Linvill chart for the 1.3 GHz transistor, showing three contours of constant added power and three designs which were experimentally investigated.

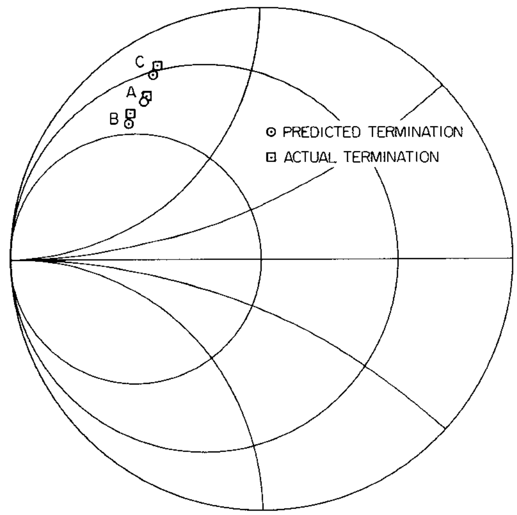

Fig. 2 A Smith chart admittance representation showing the comparison between the predicted and actual load terminations for the three designs of Fig. 1.

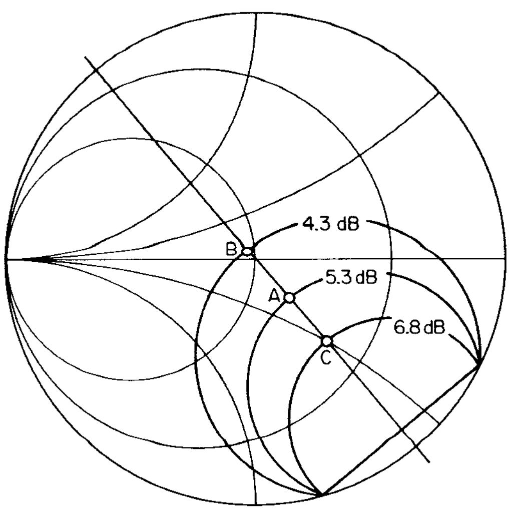

Fig. 3 A conventional Linvill chart for the 1.3 GHz transistor showing the contours of constant power gain for the three designs of Fig. 1.

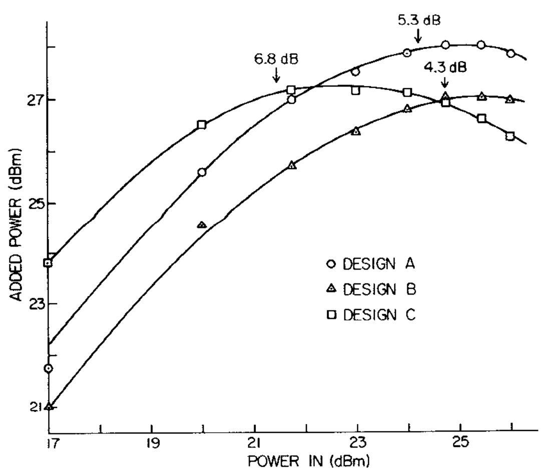

Fig. 4 Experimentally measured added power as a function of input power for the three designs of Fig. 1.