LARGE-SIGNAL CHARACTERIZATION OF MILLIMETER-WAVE TRANSISTORS USING AN ACTIVE LOAD-PULL MEASUREMENT SYSTEM

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Abstract- An automated measurement system is described for obtaining the load-pull characteristics of high speed transistors at millimeter-wave frequencies. The method uses "active tuning" to electronically vary the transistor output load impedance. The large-signal characteristics of an 8-by-20-µm permeable base transistor (PBT) have been measured with this method and applied to the design of a 27-mW PBT amplifier at 40.1 GHz.

INTRODUCTION

Load-pull measurement of nonlinear active two-port networks is well known as being a useful technique for characterizing the large-signal properties of microwave transistors. Most of the work, however, has been associated with applications at the lower microwave frequencies. With new three-terminal devices like the permeable base transistor, the high electron mobility transistor, and the heterojunction bipolar transistor emerging as serious contenders for power applications at millimeter-wave frequencies, large-signal characterization must be addressed at EHF.

Conventional load-pull measurement generally requires impedance-transforming tuners to provide a suitable range of output load impedances to the two-port device under test. In this method the transmission line losses between the device under test and the tuner depend on the standing wave pattern in this line. Consequently, the transmission line losses vary with different settings of the tuner. In addition, the tuner loss is itself a function of the tuner settings [1]. Therefore, at EHF, where circuit losses are increased because of the multi-wavelength path between device and tuner, large inaccuracies in a load-pull measurement can result.

At present, many EHF transistors are evaluated by empirical tuning methods which at best provide only a limited description of device performance. In our application, large-signal characterization is performed using "active" load-pull measurement [2], which circumvents the limitations of empirical evaluation methods and lossy tuners. The technique electronically induces a variable output load impedance at the terminals of a transistor, without using impedance tuners.

In this paper we present the first-reported implementation of an active load-pull measurement system at 40 GHz. Results of load-pull measurements on an 8-by-20-µm PBT are presented and applied to a prototype PBT amplifier at 40.1 GHz.

PRINCIPLE OF ACTIVE LOAD-PULL MEASUREMENT

Tuners are not present in the system in an active load-pull measurement. The output load impedance is defined and varied using boundary conditions between incident and reflected power waves at the transistor output port.

In general, a nonlinear two-port in large-signal operation will excite harmonic voltages and currents. The work presented here assumes only fundamental frequency components are present. This is plausible, since higher frequency harmonics will be attenuated by circuit losses. Figure 1 illustrates a simple network describing our implementation of the active load-pull concept. An input matching network is used to 'pre-match' the transistor input. The nonlinear active two-port is then excited at each port by coherent incident wave amplitudes a_1 and a_2 at a specified frequency. Reflected wave amplitudes b_1 and b_2 will exist at the same frequency. The total voltage at and current into the transistor output port are given by

$$I_2 = (a_2 - b_2) / Z_0^{(1/2)} \qquad (1)$$

$$V_2 = Z_0^{(1/2)}(a_2 + b_2) \qquad (2)$$

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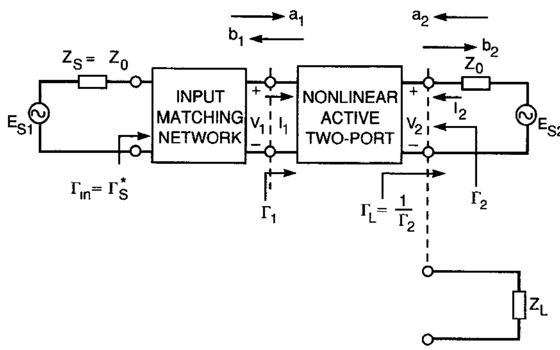

Fig. 1 Simple network for describing the active load-pull measurement concept. Generators E_{S1} and E_{S2} are coherent. The equivalent load impedance is separately denoted in dotted lines.

In these equations Z_0 is positive-real and represents the system characteristic impedance [3]. Using the relation $I_2=Y_2V_2$ and recognizing that the equivalent load admittance Y_L (shown schematically by dotted lines in Figure 1) is given by $Y_L = -Y_2$, we have

$$Y_L = Y_0\,[(b_2/a_2 - 1) / (b_2/a_2 + 1)] \qquad (3)$$

which illustrates that the equivalent load admittance is determined by the ratio of wave variables b_2/a_2.

In order to determine how the ratio b_2/a_2 depends on the incident wave amplitudes, the two-port network can be examined in terms of some "large-signal power parameters" of the nonlinear active two-port under test [4]. The reflection coefficients looking into the nonlinear device can be defined as

$$\Gamma_1 \equiv b_1/a_1 = S'_{11} + S'_{12}\ a_2/a_1 \qquad (4)$$

$$\Gamma_2 \equiv b_2/a_2 = S'_{22} + S'_{21}\ a_1/a_2 \qquad (5)$$

where the **S'**-parameters can be thought of as large-signal two-port parameters which are functions of frequency and input drive. With a pre-matched transistor input, only Γ_2 need be considered. Holding the amplitude of a_1/a_2 constant and varying

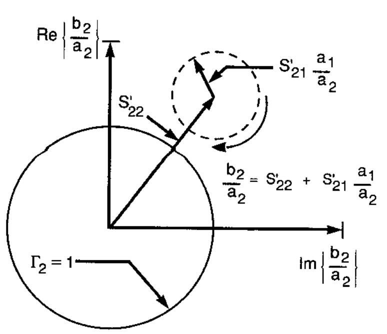

Fig. 2 Circular locus in the Γ_2-Plane resulting from varying the phase between a_1 and a_2 while maintaining the ratio a_1/a_2 constant. The S'-parameters are functions of frequency and input power.

only the phase between a_1 and a_2 results in a circular locus in the output reflection coefficient plane as illustrated in Figure 2. Since no physical termination is placed on the output port, the output reflection coefficient Γ_2 is merely the ratio of wave variables which are associated with a load that has been artificially induced by the excitations a_1 and a_2 [5]. The region in the Γ_2-plane where $|\Gamma_2|>1$ corresponds to equivalent load impedances that provide positive transistor output power. Operation inside the unit circle of the Γ_2-plane cannot be achieved with any passive load.

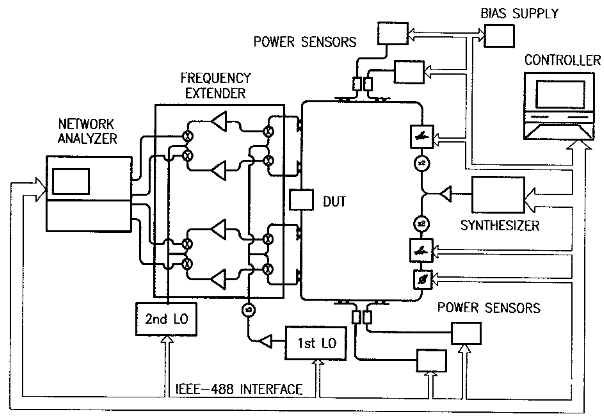

Fig. 3 Block diagram of the EHF active load-pull measurement system.

Implementation of Active Load-Pull at EHF

Figure 3 illustrates the block diagram of our active load-pull system for the 33-to-50-GHz frequency band. The output power, gain, efficiency, and output load impedance are obtained from the measured quantities P_1 (i.e., $|a_1|^2$), P_2 (i.e., $|a_2|^2$), Γ_1, Γ_2, and bias. The system operates by injecting two coherent RF signals simultaneously into the input and output ports of a transistor under test. Varactor doublers, optimized for maximum output power over a selected narrow bandwidth, are used to upconvert to the measurement frequency [6]. The input power P_1 determines the operating drive level. The phase and amplitude of the injected power P_2 establish the equivalent output load impedance presented to the device. The output power from the device P_{out} is obtained from a differential power meter measurement or from the relation

$$P_{out} = P_2\,(|1/\Gamma_2|^2 - 1) \qquad (6)$$

The reflection coefficients Γ_1 and Γ_2 are obtained from two 33-to-50-GHz reflectometers positioned at the input and output ports of the active transistor. A dual-downconversion frequency extender mixes EHF signals down to a 20-MHz IF for processing by a vector network analyzer. The IEEE-488 instrument-control interface bus is used with programmable attenuators and a phase shifter to electronically control the load impedance.

In measurements involving the PBT, the input port is matched prior to load-pull testing to minimize input reflection loss. This process is relatively simple because the input impedance of a PBT is not a strong function of input power.

The measurement system can automatically sweep through a selected range of device bias, input power level, frequency, and output load impedance to generate constant output power and efficiency contours. System calibration is done with standard deembedding techniques and a dry-calorimeter.

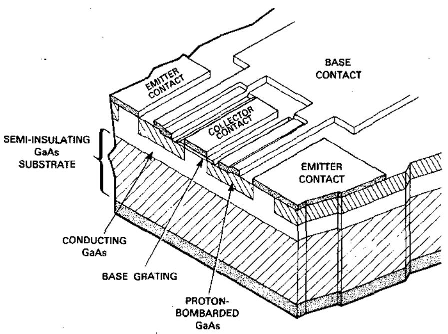

Fig. 4 Cutaway view of a PBT fabricated on a semi-insulating GaAs substrate.

Characterization of a Permeable Base Transistor

The EHF active load-pull measurement system has been used to characterize the large-signal performance of a an 8-by-20-μm PBT fabricated on a semi-insulating GaAs substrate. A cutaway view of the transistor structure is shown in Figure 4.

Figure 5 illustrates the EHF test fixture in which the device was mounted for measurement. The fixture uses wideband MIC-to-waveguide transitions which typically exhibit a minimum input return loss of 15 dB and a maximum back-to-back insertion loss of 1.25 dB in the 34-to-48-GHz frequency band. The

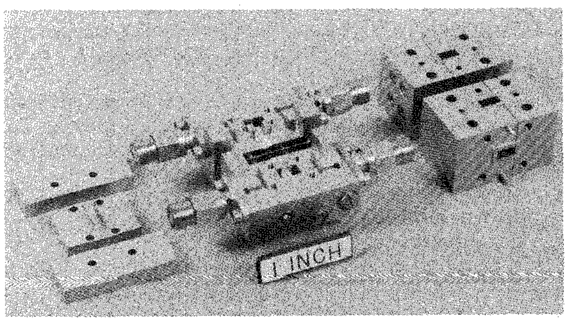

Fig. 5 EHF test fixture used for testing the PBT.

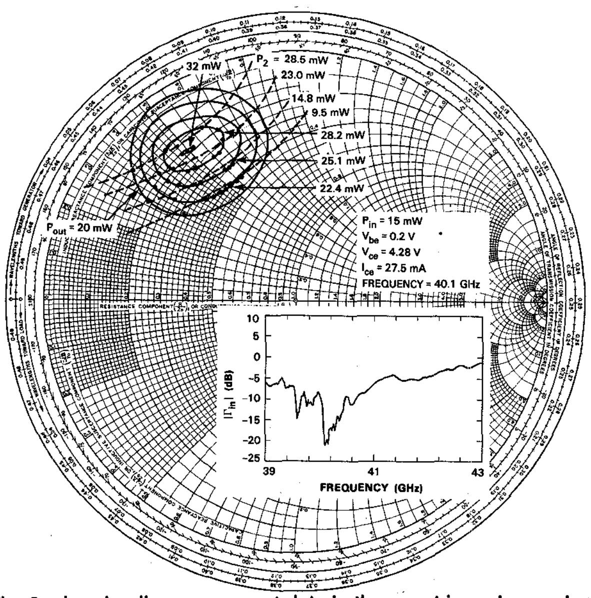

Fig. 6 Load-pull measurement data in the ouput impedance-plane. Contours of constant output power at 40.1 GHz and 15 mW input drive are shown for a 8-by-20-μm PBT. The reflection coefficient magnitude associated with the input matching network is shown in the inset.

device was epoxied onto a 250-μm-thick carrier and packaged in a manner similar to that described in [7].

The constant output power contours for a fixed frequency and input power level are shown in Figure 6. Contours of constant P_2 as a function of phase and the input return loss are also shown. The data points were generated automatically by utilizing algorithms designed to induce selected regions of output load impedances. Results of the characterization are tabulated in Table 1. An output power of 30 mW with 3 dB of associated gain and 12.8% power-added efficiency was predicted.

Design Example of an EHF PBT Power Amplifier

In order to verify the results obtained from the EHF active load-pull measurement system, the information from large-signal characterization was applied to the design of a moderate-power PBT

Table 1

Results From Active Load-Pull Characterization of a 8-by-20 micron PBT

Pin (mW)	Gain (dB)	Pout (mW)	Vce (V)	Ice (mA)	Vbe (V)	Pdc (mW)	Power-Added Efficiency	Collector Efficiency
3.92	6.08	15.89	3.43	47.9	0.88	164.3	7.3%	9.7%
4.92	5.66	18.11	3.90	41.8	0.60	163.1	8.1%	11.1%
6.24	4.84	19.01	3.91	41.8	0.65	163.5	7.8%	11.6%
8.00	3.76	19.01	3.75	36.1	0.42	135.3	8.1%	14.0%
10.02	3.41	21.98	4.08	30.7	0.28	125.2	9.5%	17.6%
12.39	3.24	26.12	4.22	29.7	0.25	125.3	11.0%	20.9%
15.38	2.96	30.41	4.33	27.2	0.19	117.8	12.8%	25.8%

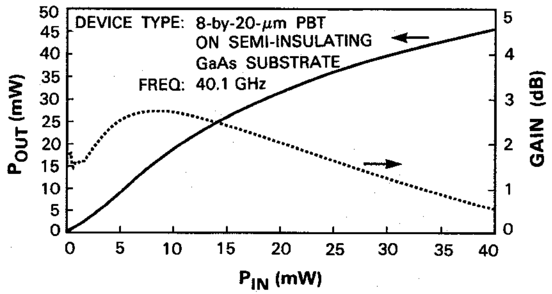

Fig. 7 Measured gain and output power of the prototype PBT amplifier. Circuit losses have been removed from the data.

amplifier at 40 GHz. The device structure was not optimized for power applications. In this example, the optimum output load impedance, bias, and input drive level were selected from load-pull results. Narrowband impedance-matching networks were designed and fabricated on 250-μm alumina MIC substrate. Figure 7 illustrates the achieved output power and associated gain with circuit losses removed. Approximately 27 mW of output power with 2.6-dB associated gain was measured at 40.1 GHz. The power-added efficiency was 12.6%. This result was in good agreement with the load-pull prediction of 30 mW with 3 dB of gain and 12.8% power-added efficiency. Figure 8 illustrates the amplifier output power and gain as a function of

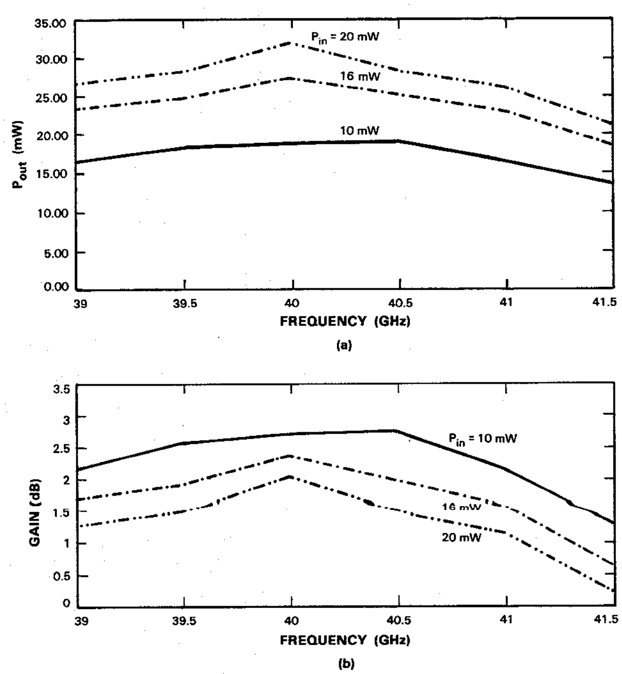

Fig. 8 Measured performance of the PBT prototype amplifier as a function of frequency. Bias was optimized for a given frequency and input power level. (a) Output power for fixed levels of input power. (b) Gain with various input drive levels.

frequency and input power. The bias parameters for each curve were adjusted for optimum performance at the particular frequency and input drive level. No effort was made to optimize the circuit bandwidth.

CONCLUSION

An EHF active load-pull system capable of large-signal characterization of two-port transistor networks at millimeter-wave frequencies has been described. The measurement system circumvents the circuit losses of impedance tuners by providing an equivalent electronically induced output load impedance. The measurement system was successfully applied to the design of a 27-mW PBT amplifier at 40.1 GHz.

To the best of the authors' knowledge, this is the first reported use of active load-pull characterization above 40 GHz. It represents a method for large-signal EHF transistor evaluation that is superior to using empirical tuning.

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REFERENCES

1. M. L. Stevens, "Semiautomatic Load-Pull Measurements of Power GaAs FET's at 21 GHz," *Professional Programs Session Record 4, Electro/82*, Boston, MA, paper 4/3, 1982.
2. Y. Takayama, "A New Load-Pull Characterization Method for Micro-wave Power Transistors," *Digest of Technical Papers, IEEE G-MTT International Microwave Symposium*, Cherry-Hill, NJ, pp. 218-220, 1976.
3. K. Kurokawa, "Power Waves and the Scattering Matrix," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-13, No. 3, pp. 194-202. March 1965.
4. S. R. Mazumder and P. D. van der Puije, "Two-Signal Method of Measuring the Large-Signal S-Parameters of Transistors," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-26, No. 6, pp. 417-420, June 1978.
5. D. C. Yang and D. F. Peterson, "Large-Signal Characterization of Two-Port Nonlinear Active Networks," *Digest of Technical Papers, IEEE MTT International Microwave Symposium*, Dallas, TX, pp. 345-347, 1982.
6. P. W. Staecker and R. W. Chick, "10 to 40 GHz Doubler-Doubler Chain for Satcom Applications," *Microwave Journal*, Vol 28, No. 12, pp. 87-108, December 1985.
7. R. Actis, R. W. Chick, M. A. Hollis, B. J. Clifton, K. B. Nichols, and C. O. Bozler, "Small-Signal Gain Performance of the Permeable Base Transistor at EHF," *IEEE Electron Device Lett.*, Vol. EDL-8, No. 2, February 1987.