Accurate on-wafer power and harmonic measurements of mm-wave amplifiers and devices

Accurate On-Wafer Power and Harmonic Measurements of MM-Wave Amplifiers and Devices

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Abstract. A novel integrated test system that accurately measures on-wafer S-parameters, power levels, load-pull contours and harmonics over 1 to 50 GHz is presented. The capabilities and accuracy are demonstrated by measuring the power at the fundamental frequency and four harmonic frequencies of a 50 GHz traveling wave amplifier and the load-pull contours of a MODFET at 30 GHz.

I. Introduction

On-wafer testing has become essential for the development and manufacturing of MMICs. S-parameter measurements are well established, but better solutions to power and harmonic testing are needed. This paper presents an integrated test system that accurately measures on-wafer S-parameters, power levels, harmonics, load-pull contours and large-signal input reflection coefficients over a broad band (1-50 GHz).

The conventional solution for power and harmonic measurements with power meters and a spectrum analyzer has several drawbacks at mm-wave frequencies [1]. The measurements are only scaler corrected. There are no 1 to 50 GHz spectrum analyzers available and external mixing is band limited. Broadband power meter measurements can be inaccurate because of harmonics or high levels of noise (e.g., 20-40 GHz TWT amplifier produces 4 dBm noise power). The power and S-parameters are usually measured on different systems. Our system overcomes these limitations and measures power and S-parameters with single contact measurements and integrated hardware. There are two keys to this system: first, the network analyzer samplers are used as frequency selective power meters with large dynamic ranges, second, all measurements are vector corrected to the DUT reference planes.

The capabilities of this innovative system are demonstrated with results for a 50 GHz traveling wave amplifier (TWA) and mm-wave MODFETs.

II. Test Set Description

The components of a conventional test set have been rearranged for power measurements. A block diagram of the system is shown in Fig. 1. The test system consists of (1) four broadband couplers mounted directly on the wafer prober, (2) a 50 GHz four-channel frequency converter, (3) a 50 GHz and a 26.5 GHz synthesizer (4) PIN and mechanical switches and (5) a vector network analyzer and controller. The system shown in Fig. 1 is limited to 40 GHz at present by the mechanical switches. The switches are removed for 50 GHz operation and the 26.5 GHz source and active load are connected manually. A 2-50 GHz MMIC amplifier provides broadband input power of more than 18 dBm.

The network analyzer measures the error-corrected two-port S-parameters of the DUT with three samplers. Sampler a_1 is only used for locking. Sampler a_2 measures both a_1 and a_2. The a_2 PIN switch is set by the network analyzer port drive. In S-parameter mode, the a_2 and port-drive PIN switches track each other. S_{11} and S_{21} are re-defined as b_1/a_2 and b_2/a_2 respectively. The PIN switches are repeatable. The quality of on-wafer calibrations is the same as those made with a conventional test set.

The system measures power with a 90 dB dynamic range. In a conventional test set the power range is limited to 30 dB by phase locking. In this system power can be changed by adding attenuation before the input amplifier without changing the power to the a_1 locking sampler or influencing the calibration. Consequently devices and amplifiers with a wide range of power can be characterized without a new calibration.

For power measurements the port-drive PIN switch is not controlled by the test set; a relay fixes it to port 1 drive. The network analyzer measures the input reflection coefficient (one-port S_{11}) and the load reflection coefficient (one-port $1/S_{22}$). The raw a_1 and b_2 powers are measured and vector corrected. The net input power, the net output power and the associated gain are then calculated.

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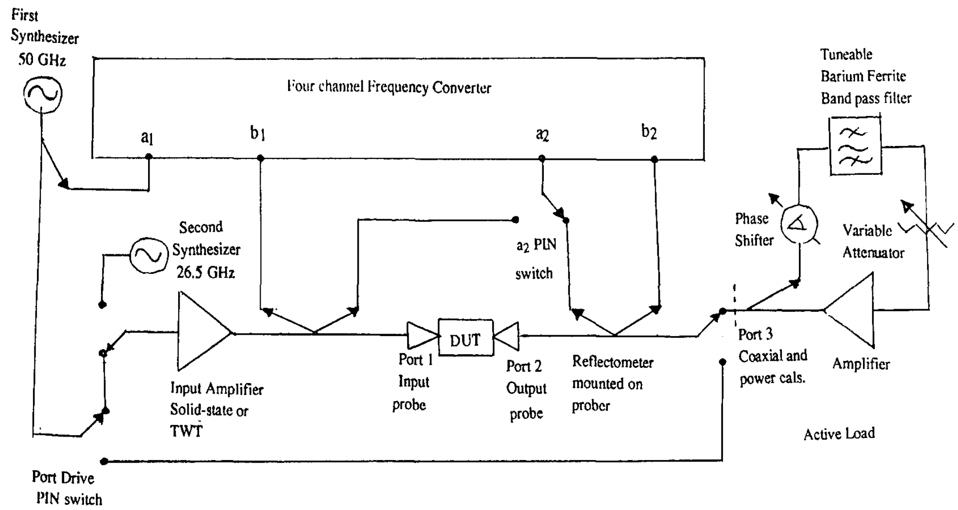

Fig. 1 Block diagram of system for measuring S-parameter, power and harmonics.

For harmonic measurements, the test set is locked to sampler a_1 at the harmonic frequency with the first (50 GHz) synthesizer, while driving the DUT at the fundamental frequency with the second (26.5 GHz) synthesizer [2]. Unlike other harmonic measurement test sets [3], no filtering is needed in our system because the samplers act as frequency selective power meters. The number of harmonics measured is limited only by the bandwidth of the test set. The harmonic power levels are vector corrected to the DUT reference plane by a broadband calibration. The load reflection coefficients at the different harmonic frequencies are also measured. Therefore, in addition to tuning the load at the fundamental frequency, the loads at the harmonic frequencies could be tuned for class B or F amplifiers [4,5].

This test set configuration minimizes the significant losses of broadband coaxial components at mm-wave frequencies. It provides the maximum power level at the probe tips by minimizing the number of components between the input amplifier and the probe. For example at 30 GHz the loss between the "1 Watt" TWT input amplifier and the probe tip is 4.2 dB and 26.5 dBm can be delivered to the probe tip. Mounting the reflectometer on the prober also provides the best reflectometer raw performance because it minimizes the losses between the probe and the reflectometers. The raw directivity at the probe tips is 7 dB at 50 GHz. A conventional test set typically has 0.6 meters of cable between the probe and reflectometer which reduces the 50 GHz raw directivity by 4 dB. This test set is easily re-configured because it has an open architecture. For example, attenuators can be added before the frequency converter samplers, or the input drive amplifier can be changed from solid state to high power TWT.

The maximum output power and load pull contours of devices are measured on-wafer at mm-wave frequencies with this system. An active load is mandatory at mm-wave frequencies to reach high reflection coefficients at the probe tip because cable and probe losses are high. We present the first mm-wave active load. The active load loop consists of a TWT amplifier, variable attenuator, phase shifter and a tunable barium ferrite filter, as shown in Fig. 1. The active load can produce a unity reflection coefficient at the probe tips at 35 GHz for a DUT with an output power up to 25 dBm. The test system simultaneously measures the load presented to the device output at the probe tips and the net output power.

III. Calibration

A single set of broadband calibrations are used for S-parameter, power level and harmonic measurements. The calibration technique is a special application of the QSOLT calibration theory [6] for S-parameters with a new error correction algorithm for load pull and harmonic measurement [7].

There are three steps in the calibration. First a 1 port calibration is made on-wafer at port 1. Second, the probes are connected with a thru, then coaxial standards are measured at port 3 (see Fig. 1) with both reflectometers. This QSLOT calibration gives 1-port calibrations at ports 2 and 3. Third, power is measured coaxial

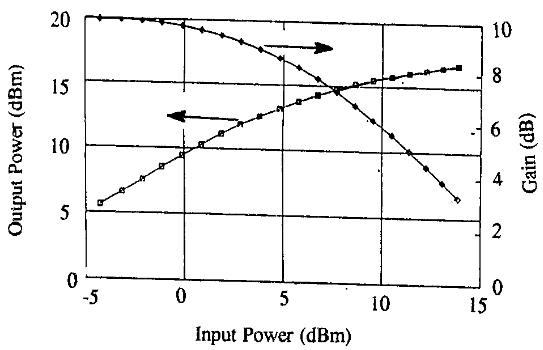

Fig. 2 Output power and gain versus input power for a 1 to 50 GHz TWA at 8.82 GHz.

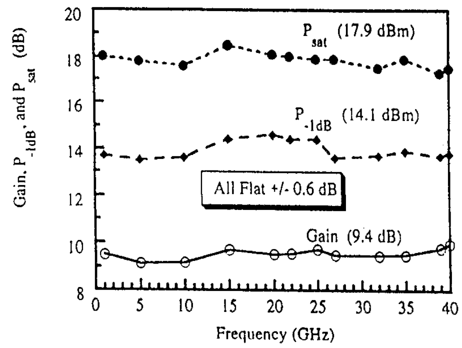

Fig. 3 Gain, -1 dB power and saturated power of a 1 to 50 GHz TWA versus frequency.

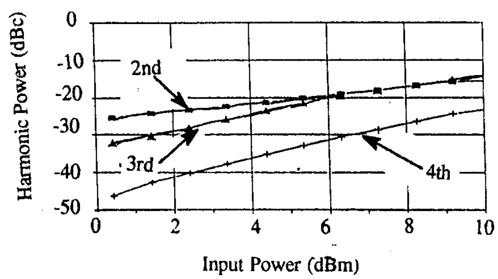

Fig. 4 Harmonic powers in dBc versus input power for a 1-50 GHz TWA at a fundamental frequency of 8.82 GHz.

power meter at port 3 and with the b_2 sampler. b_2 can then measure the power at port 3. The error model between port 2 and port 3 is calculated from the port 2 and 3 calibration coefficients. The power at the probe tip (port 2) is then measured by the b_2 sampler using the error model. With this calibration vector corrected, incident and reflected powers are measured on-wafer at both probe tips. The calibration does not require breaking the path between a probe and its reflectometer, or an on-wafer power sensor. No additional calibration is necessary to measure the harmonic power levels [2].

The control software quickly re-configures the system and provides the appropriate calibrations necessary for the many different measurement options. The operator can make any measurement at a single frequency (e.g., load pull) within the entire broad band calibration frequency range (e. g, 1 to 50 GHz in 0.5 GHz steps). The only limitations are the bandwidths and maximum powers of the input amplifier and the active-load. The system can sweep power for determining the saturated power and the power at -1 dB gain compression of an amplifier, as shown in Fig. 2. Power characterization at many frequencies is fast because several frequencies are measured during the same power sweep.

IV. Experimental Results

The high level of accuracy of the vector-corrected measurements was demonstrated by measuring consistent gain -1 dB power and saturated power for a 50 GHz traveling wave amplifier [8] over a frequency range of 1 to 40 GHz. The results are shown in Fig. 3. All the parameters are constant +/- 0.6 dB across the band for the 12 frequency points. Some variation in the power parameters of the amplifier is expected because the passive load impedance varied with frequency and variations of similar magnitude are seen in the simulated S_{21} and in the S_{21} measured with 2-port correction. The measurement of harmonics is demonstrated for the 50 GHz TWA in Fig 4. Four harmonics were measured simultaneously for a fundamental frequency of 8.82 GHz.

The measurements show the third harmonic crossing the second at high input power. This behavior is consistent with large-signal simulations.

The system's ability to characterize devices for power at mm-wave frequencies was demonstrated with 0.25 um pseudomorphic MODFETs. The devices were tuned for maximum added power at 30 GHz with an the active load. A plot of input power and gain versus output power is shown in Fig. 5. The gain, -1 dB power and saturated power were determined from this plot. The load-pull contours were measured with the active load, as shown in Fig. 6. The contours have the elliptical shape typical for FETs [9]. The contours shown in Fig. 6 demonstrate that the active loads produces high reflection coefficients at the probe tip.

Mixers could also be characterized with this system because the drive and measured frequencies do not have to be the same. This system is able to make a wide variety of small- and large-signal characterizations from low frequencies to mm-wave frequencies on wafer with a single contact.

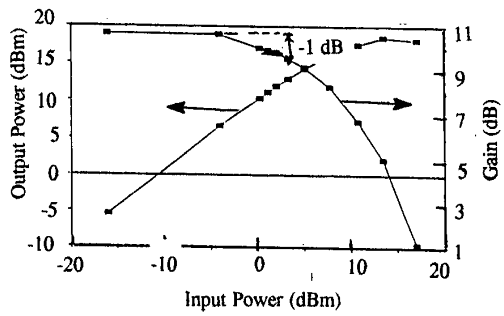

Fig. 5 Output power and gain of a 0.25 um MODFET versus input power at 30 GHz.

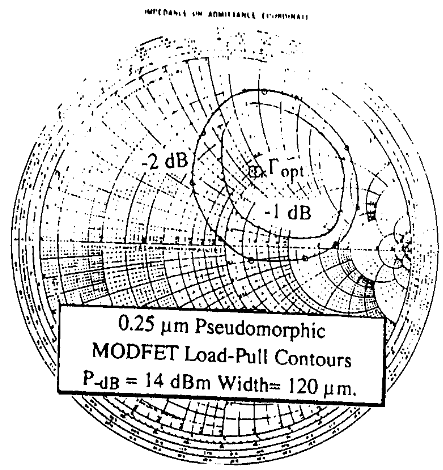

Fig. 6 Load-pull contours of a 0.25 um MODFET at 30 GHz.

V. CONCULSIONS

A new integrated S-parameter, power, load-pull and harmonic test is presented. It provids fast, accurate measurements on-wafer for characterizing and testing mm-wave devices and integrated circuits. The usefulness and accuracy of this system is demonstrated with results for 50 GHz TWA and mm-wave MODFETs.

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