# W-BAND ON-WAFER LOAD-PULL MEASUREMENT SYSTEM AND ITS APPLICATION TO HEMT CHARACTERIZATION

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## ABSTRACT

An on-wafer large-signal characterization system has been developed for W-band frequency applications. The system is computer-controlled and employs a high-precision electromechanical W-band tuner. Its application to obtaining constant output power and gain contours as well as power saturation characteristics of submicron InP-based HEMTs is demonstrated at 77GHz and 102GHz.

## INTRODUCTION

Microelectronic devices capable of operation at frequencies of 77GHz and above are necessary for the development of automotive collision-prevention systems and other emerging W-band radar applications [1]. InP-based HEMT is a typical example of device with operation capability at W-band and has been employed for both low noise and high power applications at these frequencies [2,3]. Accurate small-signal as well as large-signal models and good understanding of electrical characteristics is necessary in this frequency range for optimal design of amplifiers and other W-band radar system components. Currently employed techniques are based on either extrapolation of characteristics measured at lower frequencies or on manual testing, which is often limited in range and resolution. The authors have developed an automated W-band on-wafer large-signal characterization system and report for the first time its application to load-pull and power saturation measurements of InP-based HEMTs at 77GHz and 102GHz.

## SYSTEM COMPONENTS

The W-band on-wafer large-signal characterization system consisted of a control computer, electro-mechanical W-band tuner, network analyzer, W-band testset, RF and LO sources, frequency multiplier, and two W-band mixers. The RF source was used to generate a 15-22GHz signal, which was then up-converted by a frequency multiplier to produce the 75-110GHz W-band input signal. The source setup also included an isolator for source isolation and protection, an attenuator for input power control, and an EH-tuner for input matching. The maximum output power of this setup was limited to about -2dBm by the frequency multiplier. A 102GHz Gunn-diode oscillator with the output power of 17dBm was also employed to generate a W-band signal at higher power level and drive the tested devices stronger under large-signal conditions.

A 10-dB waveguide directional coupler was used to monitor the input power ($P_{in}$). Both input and output power were monitored by W-band mixers driven by the LO source, which was phase-locked with the RF source. The benefits from the use of mixers as power meters include frequency selectivity and expanded dynamic range. The schematic of the complete setup is shown in Figure 1.

Load-pull conditions were achieved with the specially developed W-band high-precision computer-controlled FOCUS electromechanical tuner. The control computer measured power, gain, efficiency, and DC-bias as a function of input power and load impedance as set by the load tuner.

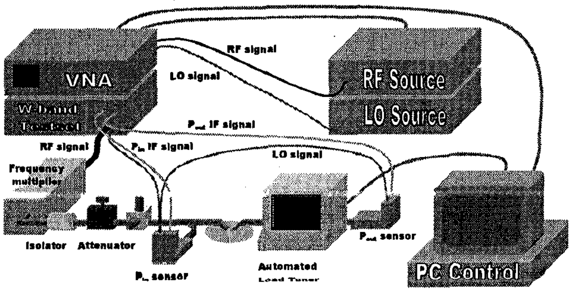

Figure 1. Schematics of an automated W-band on-wafer load-pull measurement system

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The basic approach is similar to that described at a previous report by the authors on electromechanical tuners [4], but includes specially designed tuners for higher frequency of operation and an enhanced software for improved data extraction and handling.

The tuner uses a WR-10 waveguide with a non-contact slug moving in, out, and along the waveguide slot to generate controlled amplitude and phase variations. The vertical resolution of slug movement is 1.5μm and the horizontal step is 3μm. Obtainable VSWR exceeds 10:1, and reaches up to 19:1 in most parts of the 75 to 110GHz band. The tuner has excellent repeatability and is capable of tuning to 600,000 impedance points at 94GHz.

During measurements the W-band tuner, frequency multiplier, and W-band mixers were connected with WR-10 waveguide sections and mounted on an Alessi probe station. On-wafer probing was possible by means of PICO W-band probes.

## SYSTEM CALIBRATION

The purpose of the system calibration is to measure phase shifts and losses between the DUT, load tuner, and power meters in order to obtain measurements corrected to the probe tips. The calibration is performed as follows. First, small-signal network characterization setup for W-band is assembled on a table and calibrated at the waveguide level. Then S-parameters of the "Load Tuner" block are measured and recorded for varying impedance conditions produced by computer-controlled movement of the tuner slug. There are 181 calibration points uniformly covering the Smith chart.

Next S-parameters of "Input Isolation" (input-to-output-port) and "Input Coupler" (input-to-coupled-port) blocks are measured and recorded. It is important to note that although the calibration of "Input Coupler" block required repositioning of the network characterization setup for measurement with ports at oriented 90 degrees, the setup calibration was preserved.

Finally, the W-band network characterization setup is reassembled and calibrated at the waveguide level on the probe station. Then the S-parameters of "Test Fixture" block (W-band microwave probes) are measured. Once all blocks are calibrated, the complete system is assembled in its final configuration. The calibrated part of the setup and the power-flow diagram is shown in Figure 2.

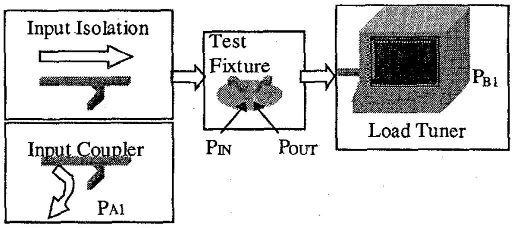

Figure 2. Power-flow diagram of the load-pull system

The value of input ($P_{IN}$) and output power ($P_{OUT}$) at the device level can be calculated from power meter readouts $P_{A1}$ and $P_{B1}$ using the equations below:

$$P_{IN}=P_{A1}+L_{INUT\ COUPLER}-L_{INPUT\ ISOLATION}-L_{LEFT\ PROBE} \quad (1)$$

$$P_{OUT}=P_{B1}+L_{TUNER}+L_{RIGHT\ PROBE} \quad (2)$$

where $L_{IC}$, $L_{II}$, $L_{LP}$, $L_T$, and $L_{RP}$ are the losses in the corresponding blocks. At 77GHz the losses were $L_{IC}$=6.5dB, $L_{II}$+$L_{LP}$=3.7dB, and $L_{RP}$=2.1dB.

$P_{A1}$ and $P_{B1}$ were monitored by the W-band mixers. A W-band power meter was used to measure the conversion losses of the mixers, which were -10.6dB and -8.7dB correspondingly at 77GHz. The values of conversion loss were entered into the computer as correction factors for readouts $P_{A1}$ and $P_{B1}$. In order to verify the calibration, constant loss contours of a through-line were evaluated and demonstrated low distortion and high uniformity as shown in Figure 3. Maximum transmission was found for load conditions close to the center of Smith chart. The losses between the load tuner and DUT decrease the maximum reflection coefficient $\Gamma_L$ visible by the device, and therefore the maximum radius of load-pull contours; $\Gamma_L$ is limited due to the losses in the "Text Fixture" block of the setup.

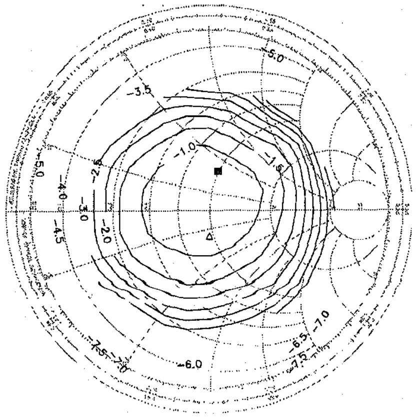

Figure 3. Constant loss contours of a through line

## LOAD-PULL CHARACTERIZATION

The developed system was used to characterize InP-based double-heterostructure HEMTs fabricated at the University of Michigan. The HEMT structure consisted of InGaAs channel (15nm) sandwiched between two InAlAs spacers (3nm), followed by delta-doped planes and two InAlAs barriers. Gates were 0.2μm-long and 2x45μm-wide. Devices demonstrated $g_M$=750mS/mm, $I_{DSS}$=280mA/mm, and $V_{PO}$=-0.7V. Their characteristics permitted operation at W-band and thus evaluation of the developed system, as well as, large-signal features of HEMTs at these frequencies.

*Prior* to load-pull characterization, the network analyzer was set to read input power as "$a_1$" and output power as "$b_1$" wave. Thus, the power gain was automatically calculated as network-analyzer-measured parameter "$S_{11}$", which allowed fast and convenient optimization of measurement conditions. Then the EH-tuner on the source side was manually adjusted to obtain maximum gain. The input power level was controlled by the attenuator and varied between –25dBm and –7dBm.

A power gain of 4.5dB at a low input power ($P_{IN}$= -25dBm) was found under optimum bias conditions ($V_{DS}$=1V, $V_{GS}$=-0.15V, $I_D$=13mA) at 77GHz for load tuner positioned at 50Ω. Load-pull characterization allowed evaluation of constant gain and power contours. The constant gain contour evaluated at the above conditions is shown in Figure 4. The matching load impedance was found at (28.6-j24.1Ω) with associated maximum gain of 5.5dB.

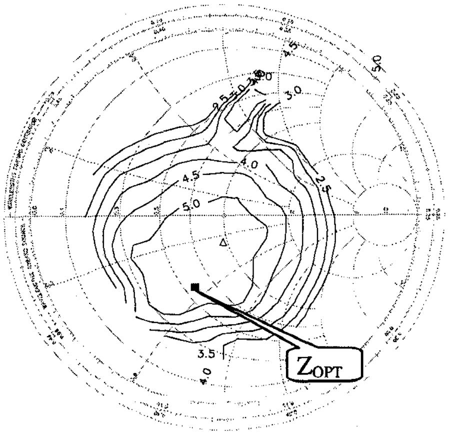

Figure 4. Constant gain contours for $P_{IN}$=-25dBm

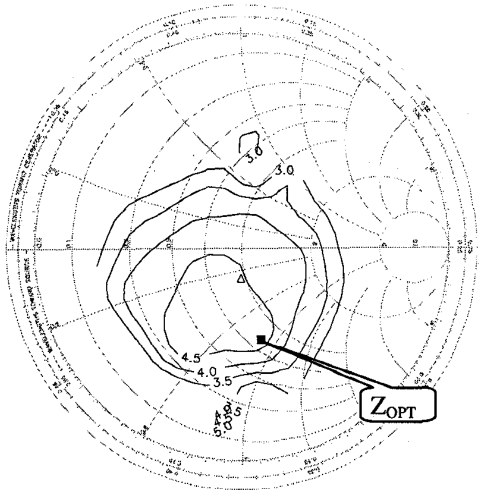

Figure 5. Constant gain contours for $P_{in}$=-7dBm

At a higher input power, gain showed compression while gain and power contours became distorted due to self-biasing effects. When the input power was increased to maximum $P_{IN}$=–7dBm (at DUT level) the optimal load impedance point moved to (39.9-j43.5Ω) and the gain was compressed by 1dB. Contours of constant gain evaluated at $P_{IN}$=–7dBm were distorted as shown in Figure 5.

## POWER SATURATION MEASUREMENTS

The input power available from the setup at 77GHz is limited to -7dBm. A Gunn-diode 102.3GHz oscillator source with 17dBm output power was used to further investigate the $P_{OUT}(P_{IN})$ and $PAE(P_{IN})$ characteristics in these devices. A power gain of 2.4dB was obtained for 102GHz operation at the input power of –4dBm. The biasing conditions were ($V_{DS}$=1.9V, $V_{GS}$=-1V, $I_D$=38mA). For comparison, the same devices were tested in an on-wafer large-signal measurement system with 2-18GHz electromechanical tuners of similar type, and demonstrated power gain of 13dB at $P_{IN}$=-13dBm at 10GHz.

The output power was measured for different input power levels at 77GHz, 102GHz, and 10GHz as shown in Figure 6. It is observed that 1-dB gain-compression occurs for $P_{IN}$=-7dBm at 77GHz and $P_{IN}$=-+1dBm at 102GHz. A comparison of measurements at 10GHz demonstrated compression at $P_{IN}$=-13dBm.

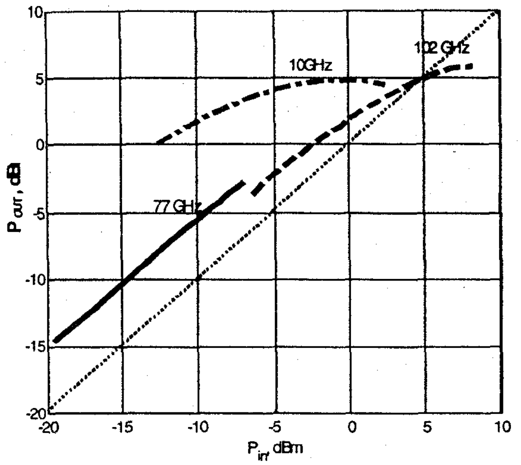

Figure 6. Output power as a function of input power at 10GHz, 77GHz, and 102GHz

Thus, although the gain is reduced at higher frequencies, the saturation is shown take place at higher input power levels, which results in comparable output power levels. However power-added efficiency (PAE) is diminished for higher-frequency operation. PAE was 26% at 10GHz and only about 1% at 102GHz with +3dBm input power for the devices in this study as shown in Figure 7. The PAE at 77GHz was about 2.5% under the maximum power level available from our source and appeared to continue to increase with the input power.

## CONCLUSIONS

Overall, an on-wafer large-signal computer-controlled measurement system using a high-precision electromechanical tuner has been developed at W-band. The system allows load-pull and power saturation characterization of millimeter-wave devices, as necessary for the development of power amplifiers and other components for W-band applications. The system was employed to characterize InP-based HEMTs. The results obtained from the latter studies, although related to non-optimized for this frequency devices, permit system validation by evaluation of constant gain and power contours at 77GHz. A power gain of 5.5dB was found at 77GHz at $P_{IN}$=-25dBm for optimal impedance (28.6-j24.1Ω). When the input power was increased to $P_{IN}$=-7dBm, the gain was compressed to 4.5dB and the optimal impedance moved to (39.9-j43.5Ω). PAE at 102GHz was ~1% for $P_{IN}$=+3dBm. A value of 2.5% was recorded at 77GHz which appeared to increase for power levels close and above $P_{IN}$=-7dBm.

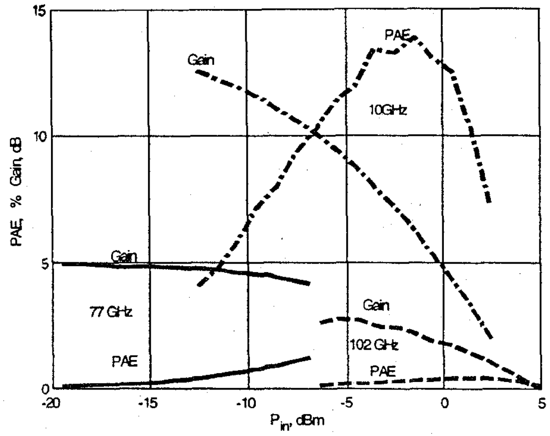

Figure 7. Gain and power-added-efficiency (PAE) as a function of input power at 10GHz, 77GHz, and 102GHz

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