# A New On-Wafer Large-Signal Waveform Measurement System with 40 GHz Harmonic Bandwidth

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## Abstract

A novel on-wafer large-signal waveform measurement system with 40 GHz harmonic frequency range using a microwave transition analyzer is presented. Potential applications are illustrated by the measurement of the harmonic amplitude and phase spectra of the reflection and transmission response of a 0.3 $\mu$m InGaAs pseudomorphic HEMT under X-band sinusoidal stimulus.

## Introduction

Large Signal Waveform Measurements "on-wafer" with a fundamental frequency range up to X-band in conjunction with harmonic frequencies in the millimeter wave range are expected to be of increasing importance for many practical purposes. In the literature,only a few setups restricted to a much lower fundamental frequency range are described [1,2]. These approches are restricted to coaxial reference planes. A more generalized setup which is applicable to coaxial and in fixture measurements with harmonic frequency range up to 20 GHz has been published earlier by the authors [3]. In this paper, an on-wafer waveform measurement system with an extremely improved harmonic frequency range of 40 GHz is presented. The new microwave transition analyzer (MTA) hp 71500A is used as fundamental and harmonic receiver. The potential applications are e.g.: large signal FET model verification, direct model parameter extraction (as proposed in [4]) which is expected to be sensitive to the available bandwidth, the investigation of nonlinear effects with respect to e.g. frequency multiplier realization, and component characterization, e.g. MMIC amplifier harmonic load-pull. As an example, the harmonic magnitude and phase spectra of the reflection and transmission response of a 0.3 $\mu$m InGaAs pseudomorphic HEMT under X-band sinusoidal stimulus are measured.

## Measurement Setup

The block diagram of the measurement setup is depicted in fig. 1. The system stimulus for calibration and measurement is a 50 GHz synthesizer hp 83650A. The generator feeds a modular, in-house built testset consisting of a large signal reflectometer using directional couplers, the transmission return path with bias tee, and the reflection/transmission switch for the two-channel receiver. The key feature of this hardware is, that the coaxial testset reflectometer and the transmission return port are connected directly to the wafer probes of port 1 and 2 via coax elbows. The reflectometer is mounted on top of the probe arm. This configuration avoids the use of cables between the coaxial testset and the wafer probes, yielding the full hardware performance of the coaxial testset. Optimum hardware directivity and match are of special importance with large signal measurements because the zigzag reflections between the DUT and source and load cannot be eliminated by the correction algorithm for reason of the nonlinearity of the DUT - the error correction leads only to a precise description of the real, actual device operating conditions.



The measurement receiver is the microwave transition analyzer hp 71500A which appeared recently. In the setup described here, it substitutes the VNA and Sampling oscilloscope which were used as fundamental and harmonic receivers in the setup after [3].In comparison to the scope, the MTA cuts a significant amount of measurement time and yields the same dynamic range of the harmonic measurement without averaging. The measurement time can be optimized to the same order as it would be required by a VNA in "harmonic sweep" mode. Additionally, the measurement setup is simplified because there is no trigger circuitry as in the case of the sampling oscilloscope.

The 40 GHz frequency range of the present configuration is mainly limited by the sampling aperture of the MTA and the testset reflectometer hardware. The currently available power level at the DUT on wafer reference plane is the source power of the synthesizer minus 3 or 6 dB attenuation

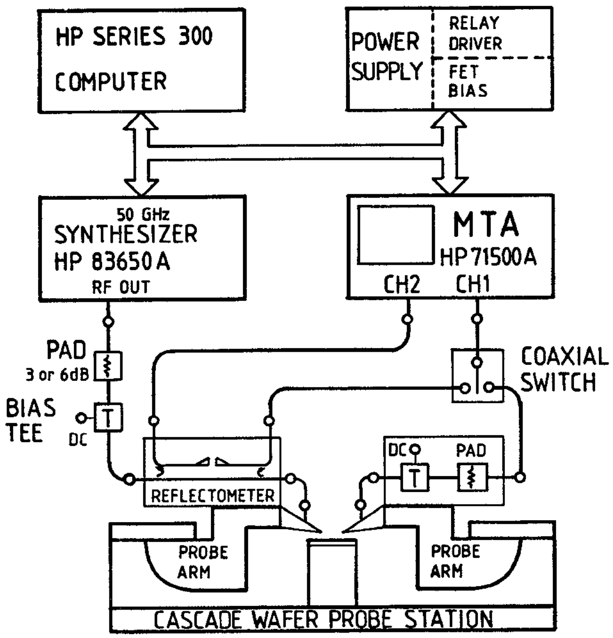


Fig. 1 Block diagram of the on-wafer measurement system

of the RF input PAD (see fig. 1), and additional cable and reflectometer losses which sum up to about 2.0 to 2.5 dB at X-band frequencies, so that the maximum RF power at the DUT is about 8 to 9 dBm at 10 GHz.

The setup was realized as a fully automatic system under remote control of an external computer, enabling the two-port calibration and error correction routines, which are not supported by the firmware of the MTA.

### System Calibration

A two-step calibration procedure is applied. For this purpose, the probe heads and the components of coaxial testset are separated from each other. In the first step, the system calibration with respect to the coaxial reference planes of the reflectometer and the transmission return path is performed. This calibration is based upon the well-known TMSO procedure [5,6] for one-path two-port network analyzer systems. Additional measurements are required to evaluate the amplitude and phase tracking of the directional couplers and the receiver tracking errors for fundamental ratio and harmonic measurement. In [3], the latter are the complex ratio tracking of the VNA and the sampling aperture of the oscilloscope channels. This receiver description is directly applicable to the MTA as a combined fundamental and harmonic receiver. The separation of fundamental and harmonic tracking is justified by the different internal settings and operating conditions of the MTA (vector voltmeter and harmonic analysis mode).

In the second step, the wafer probe heads (including elbows and adapters) are treated as the halves of a non-coaxial test fixture in a formal manner. The probes are calibrated on the hp 8510B 40 GHz VNA system using the "THLR" fixture calibration method published earlier by the authors [7]. Instead of the sliding load which is used at higher frequencies in this method, the fixed load is applied over the entire frequency range. The "THLR" method evaluates the S-parameters of the wafer probes. With the error parameters of the receivers and the coaxial test system and the S-parameters of the probe heads, the raw measurement data obtained in the receiver reference planes can be transformed to the wafer probe reference planes of the DUT. This error correction algorithm yields a precise determination of the four wave spectra being present at the DUT, which is a complete description of its actual operating conditions.

### Verification

The results of the verification measurements can be summarized as follows:

A coaxial offset short and an offset thru (both not being calibration standards) yield an error-corrected uncertainty which is comparable to that of an hp 8510/8516 40 GHz VNA system (typical values for the offset short are 0.15 dB and 3.5 degrees).

The accuracy which is obtained from the two-step calibration of the wafer probes using the "THLR" method is comparable to the results of e.g. the LRM one-step method. In this case, the accuracy was again checked with the measurement of high reflecting and transmitting objects which were not used in the calibration sequence.

The reflection response of a Schottky diode as a nonlinear DUT was measured with and without additional offset between the coaxial reference planes of the DUT and the reflectometer test port. The deviations in the amplitude and phase spectra versus fundamental frequency (fig. 2) describe the influence of zigzag reflections between DUT and source. The harmonic phase spectra are normalized to the fundamental phase value. Harmonic phase values in the vicinity of 0 or 180 degrees describe the resistive nonlinear behaviour of the diode which is due to its small parasitic and junction capacitance and indicate that the omission of the sampler phase tracking error is justified up to 40 GHz with the MTA as harmonic receiver.

The dynamic accuracy of the waveform measurement system has been checked with a short connected to the coaxial reference plane. This results in an "harmonic noise floor" of about 50 dBc up to 8 GHz and ca. 45 dBc up to 12 GHz

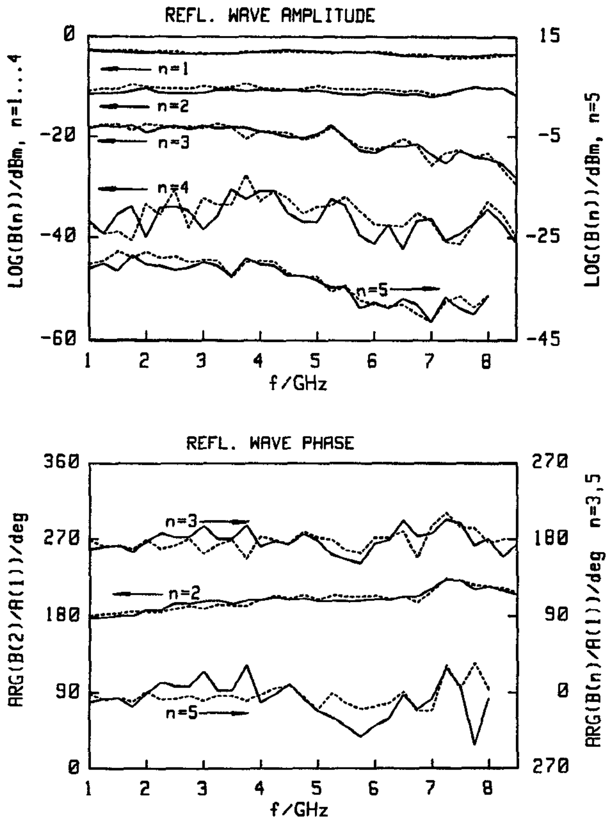


Fig. 2 Schottky diode verification measurement

fundamental frequency on both channels, without the application of averaging or noise filtering. These values mate to the typical specifications of the MTA and are comparable to the values which have been achieved with the 50 GHz oscilloscope system hp 54124T using 128 averages on the time domain traces. The significant advantage of the MTA is that it saves at least 90% of the measurement time of the oscilloscope.

## Measurements

An InGaAs/GaAs pseudomorphic HEMT (0.3$\mu$m x 100$\mu$m gate geometry) manufactured by the Fraunhofer-Institute for Applied Solid State Physics, Freiburg, was measured in the fundamental frequency range from 8 to 12.5 GHz with input power levels from -3 to +9 dBm. For better interpretability of the frequency-swept harmonic amplitude and phase spectra, an automatic power leveling algorithm using reflection error correction for the fundamental spectral component was applied. This iterative procedure adjusts the fundamental stimulus power for each measurement point within $\pm$0.25 dB deviation from the desired value for high reflecting DUTs, yielding a significant improvement in the equivalent source match seen by the input port of the DUT. Fig. 3 displays the magnitude and phase spectra of the reflected wave for four different power levels. The harmonic phase spectra are again normalized to the fundamental phase value. The harmonic phase traces are in the vicinity of $\pm$90 degrees, indicating a reactive nonlinear behaviour which is related to the gate-source capacitance of the FET, which is approximately 0.2 pF for zero gate bias, due to the small gate geometry of the device. This small capacitance is only well-accessible in the waveform measurement with fundamental frequencies at least in X-band.

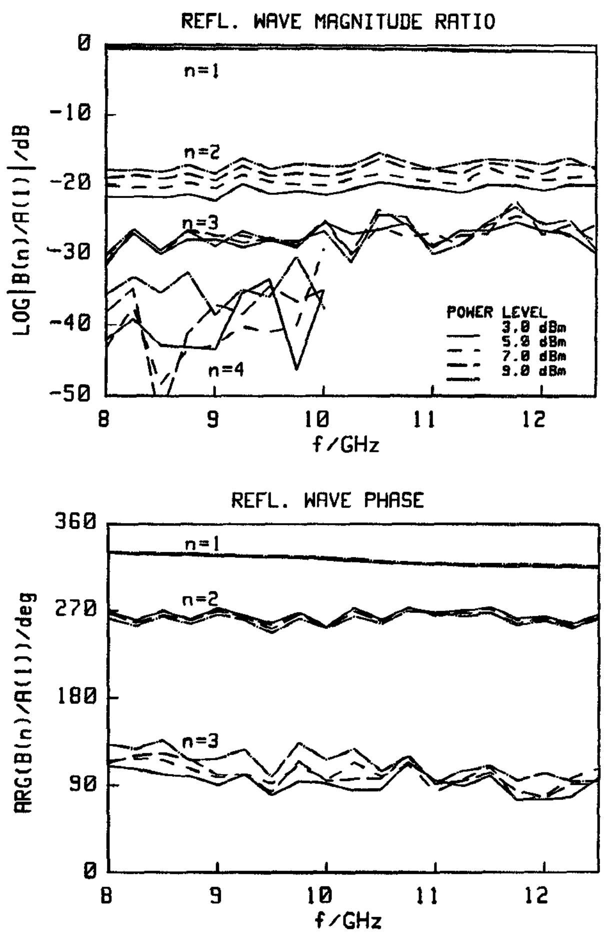


Fig. 3 Reflection magnitude and phase response of 0.3 $\mu$m InGaAs PM HEMT versus fundamental frequency

Fig. 4 depicts the time domain representation of the output voltage at 10 GHz fundamental frequency for different input power levels, with four harmonics included (DC bias point: Vgs=-0.65 V, Vds=2 V). With the highest power level, a 10% to 90% risetime and falltime of 15.5 ps is observed.

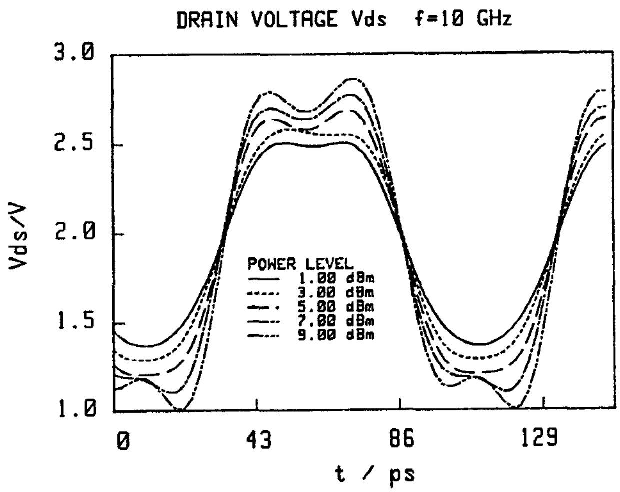


Fig. 4 Drain Voltage of InGaAs PM HEMT for 10 GHz fundamental frequency

## Conclusion

The described reflection and transmission response of a pseudomorphic HEMT illustrates the necessity for millimeterwave large-signal waveform measurement systems, for example with respect to pulse shaping circuits etc. for gigabit logic applications. A subsequent potential application of the system described in this paper could be (e.g.) the characterization of a FET as a logic inverter. For this purpose, an harmonic bandwidth of at least 40 GHz is required in conjunction with X-band repetition frequencies and modern FETs with about quarter micron gate lengths. Another future application may be the on-wafer harmonic load-pull and/or source-pull test of transistors and amplifiers with respect to maximum output power or efficiency and optimized harmonic behaviour, which will lead to a double reflectometer coaxial hardware and calibration concept.

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