

W-BAND NOISE FIGURE MEASUREMENT DESIGNED FOR ON-WAFER CHARACTERISATION

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ABSTRACT

The first fully automated noise and S-parameter measurement bench is reported for W-band on-wafer characterisation. A calibration procedure is described that allows the receiver reference plane to be accurately moved to the probe tip.

1. INTRODUCTION

The absence of accurate on-wafer noise parameter measurements at W-band is currently inhibiting MMIC and subsystem design. The paper presents the first reported automated combined on-wafer noise and S-parameter measurement system to work at these frequencies together with an improved calibration sequence to accurately move the receiver reference plane from a waveguide port to the probe tips.

The conventional cold-source measurement technique [1] is supplemented with a new procedure to determine the S-parameters of the connection between the DUT and the receiver. This section cannot be measured in any conventional manner since one end is terminated in a co-planar wafer probe and the other in waveguide. The S-parameters of this section are therefore extracted from many one-port measurements using a de-embedding technique with a series of different loads presented at the waveguide

termination. These loads are generated by an automated W-band tuner, included in the receiver module, illustrated in Figure 1. A photograph of the complete measurement bench is shown in Figure 2.

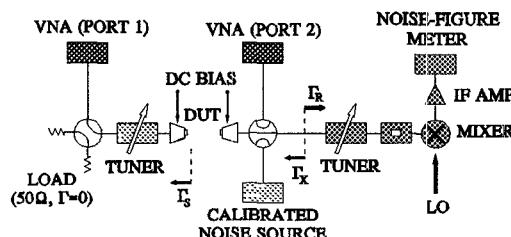


Figure 1 Combined S-parameter & noise figure measurement bench

The measurement technique also corrects fully for the mismatch effects occurring between the noise source, DUT and receiver. The available gain and mismatch factor for both the 'hot' and 'cold' noise source states are calculated, thus eliminating the assumption of identical noise source reflection coefficients. The change in noise source reflection coefficient between the 'hot' and 'cold' states is shown to introduce errors of up to 0.25dB in receiver noise figure, Figure 3.

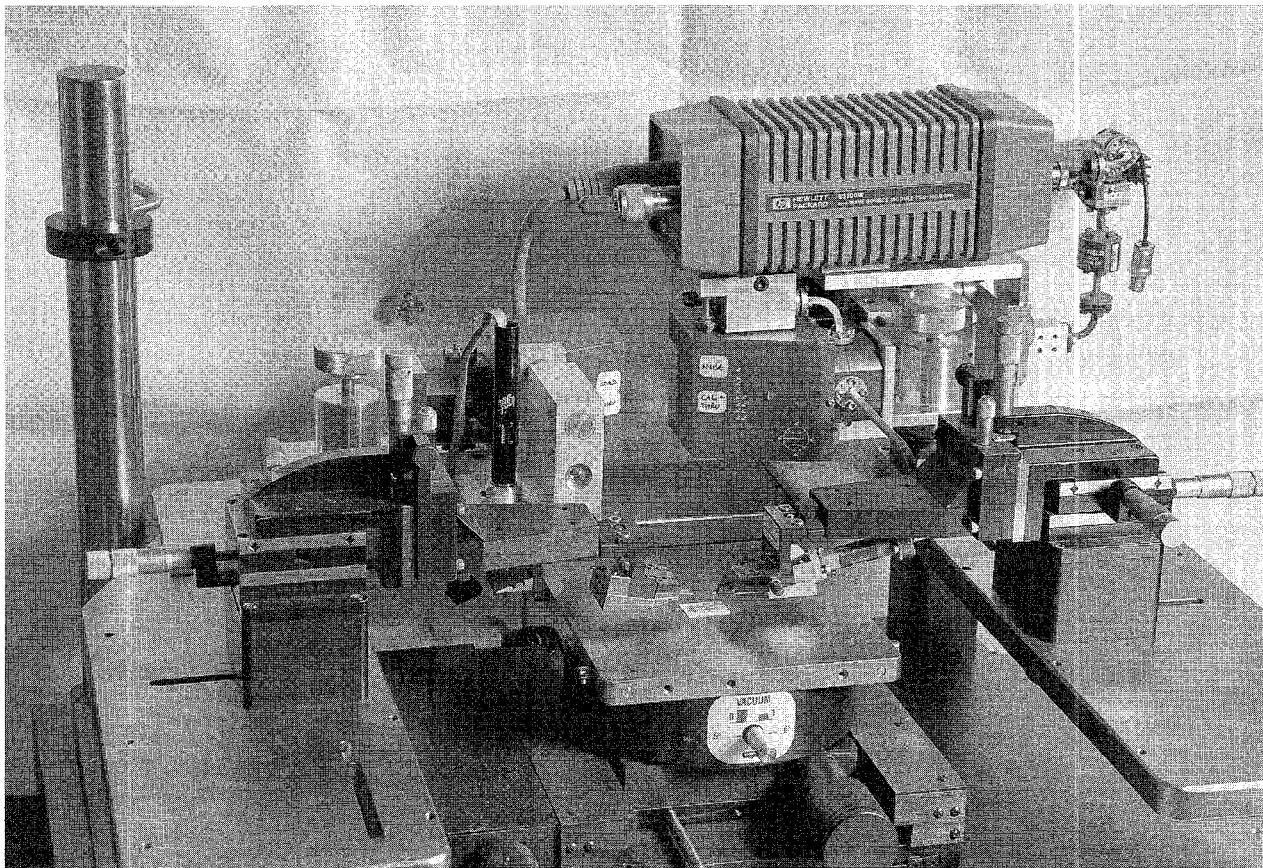


Figure 2 Photograph of the combined on-wafer S-parameter & noise figure measurement bench. A waveguide switch & tuner precede the left-hand probe and the receiver module is shown coupled to the right-hand probe.

The noise powers delivered to the receiver in the 'hot' and 'cold' states are calculated from:

$$P_h = kB \cdot [T_h G_{a_h} + (1 - G_{a_h}) T_a] \cdot M_h$$

$$P_c = kB \cdot [T_c G_{a_c} + (1 - G_{a_c}) T_a] \cdot M_c$$

where kB is the Boltzmann constant-bandwidth product, T_h and T_c are the hot and cold noise source temperatures, G_a is the available gain of the interconnecting two-port (including the waveguide switch), T_a is the ambient temperature and M_h and M_c are the mismatch factors in the hot and cold states respectively.

2. PASSIVE TWO-PORT EXTRACTION PROCEDURE

The parameter extraction procedures for determining the full two-port S-parameters of the components between the DUT and the receiver are based upon the solution of the standard equation governing a reflection coefficient as 'seen' through a passive two-port.

$$\Gamma_o = S_{11} + \frac{S_{12}S_{21}\Gamma_i}{1 - S_{22}\Gamma_i}$$

where Γ_i and Γ_o are the input and output reflection coefficients and S_{11} , S_{12} , S_{21} and S_{22} are the two-port S-parameters.

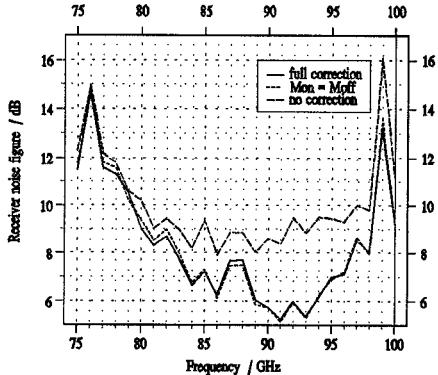


Figure 3 Receiver noise-figure with no mismatch correction, hot source correction and both hot and cold source correction

A minimum of three coupled reflection coefficient measurements are required to de-embed the two-port. However, the solution of this scheme is non-trivial since the denominator in the above equation and measurement uncertainties conspire to produce large variations in the derived two-port parameters, leading to potentially inaccurate results. Consequently an optimisation procedure has been written, based upon the Down-Hill Simplex method [2], which extracts the least-square fit for an over-determined set of measurements. Alternative schemes were implemented, including Powell's and the Conjugate Gradient methods, both of which added noticeable complexity to the model, required good first approximations and did not produce a significant increase in speed to warrant the use of these more demanding algorithms. In all the schemes the real and imaginary pairs in the three variables, S_{11} , S_{22} and the $S_{12} \cdot S_{21}$ product were split into six real variables and optimised individually. To check the solution scheme random sets of S-parameters and input reflection coefficients were generated. The output reflection coefficients were then calculated for each case and a random, gaussian error, with a standard deviation of 0.1% was

introduced to simulate the uncertainty accompanying real measurements. The two-port S-parameters were then extracted using the optimisation scheme and the differences between the new and original S-parameters presented as a function of the number of samples. The results of this procedure are shown in Figure 4. This analysis shows the total error of the S-parameters of the interconnecting waveguide only reduces below the simulated error level of 0.1% after at least 15 samples.

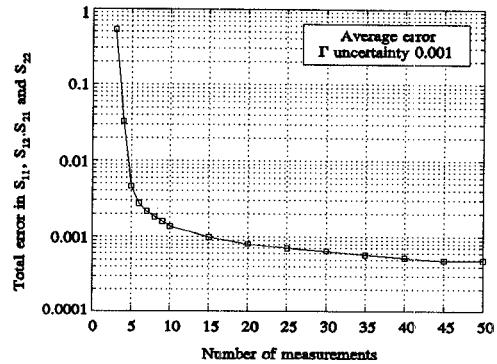


Figure 4 Two-port S-parameter extraction errors as a function of the number of coupled one-port measurements (0.1% random errors added to the data)

3. ON-WAFER S-PARAMETER & NOISE-FIGURE TEST BENCH

The source tuner and combined receiver, including a waveguide switch, calibrated noise source, tuner, isolator, mixer and IF amplifier together with the LO source are all mounted on the probe station in order to reduce losses. The source tuner and receiver elements are mounted on linear bearings, together with the S-parameter test set modules. Rigid stays are used to link the probe mounts to the source and receiver arrays, permitting the probes to be moved freely via the manipulators without transferring any stress to the components.

4. W-BAND SLIDE SCREW TUNERS

The W-band tuners are of novel design and exhibit excellent range, with reflection coefficient magnitude, $|\Gamma|$, continuously variable from 0.0 to 0.9 over all phase values and repeatability currently limited only by S-parameter measurement repeatability. A typical selection of maximum loads is shown in Figure 5, with all loads lying within the illustrated region obtainable. The tuners are automated, driven using encoded linear actuators which have a positional accuracy of $0.1\mu\text{m}$, corresponding to 20 and 40 seconds of arc of phase at 75 and 110 GHz respectively. Further, they are designed to mount directly to the probe waveguide port with only a short section of waveguide to minimise losses between the tuner and DUT.

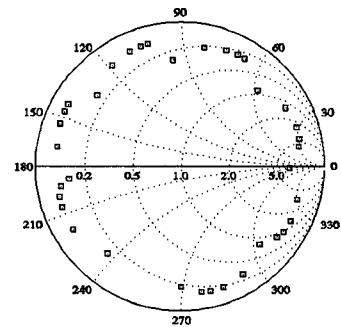


Figure 5 Typical selection of loads with maximum reflection coefficient measured @ 94 GHz

5. CONCLUSIONS

The first reported W-band on-wafer combined small-signal and noise parameter measurement system has been described. An improved de-embedding procedure is described for calculating the scattering parameters of the section of the system connecting the DUT to receiver. It is shown that a minimum of 15 one-port

measurements are required in conjunction with the simplex optimisation procedure to extract passive two-port S-parameters to within the system measurement uncertainties.

A pair of automated W-band slide-screw tuners have been constructed displaying excellent range and repeatability, designed to fit directly onto the probe waveguide ports. This, together with the receiver reference plane adjustment, allows the noise parameters of the DUT to be measured directly as a function of the source impedance.

6. REFERENCES

- [1] Roman Meierer and Christos Tsironis, "An On-Wafer Noise Parameter Measurement Technique with Automatic Receiver Calibration", *Microwave Journal*, Vol. 38, No. 3, pp. 22-37, March 1995
- [2] William H. Press, Saul A. Teukolsky, William T. Vetterling and Brian P. Flannery, "Numerical Recipes in C, second edition", *Cambridge University Press*, ISBN 0 521 43108 5

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