Introduction

On-wafer S-parameter measurements through 50 GHz are now commonplace, with expectations of higher frequency performance in the near future. Many engineers are accustomed to the speed and ease of on-wafer probing techniques and have been requesting that these probing techniques be applied to other on-wafer measurements. The payoff is in time, money and accuracy because dicing, bonding, fixtures and fixture de-embedding are eliminated, and measurements can be performed in minutes instead of days. The next measurement to automate is that of characterizing the high frequency noise performance of devices and amplifiers. The measurement of noise parameters, including minimum noise figure \( F_{\text{min}} \), optimum source admittance \( Y_{\text{min}} \), and noise resistance \( R_{\text{n}} \), has been tedious and fraught with errors and lack of repeatability. However, with the new on-wafer noise parameter testers like Cascade Microtech’s NPT18 system entering the market, noise parameters can be obtained in seconds rather than days, and repeatability has been improved by nearly an order of magnitude.

Several parameters have to be considered when evaluating a noise parameter tester: accuracy, verification and repeatability. Accuracy is the degree to which measurements conform to national or international standards. Noise reference standards exist only for coaxial or waveguide media for matched impedance measurements. Test system manufacturers and users rely on “verification” (i.e. comparison to other known measurements of active and passive devices) to derive confidence in the measurements. Repeatability is the degree to which measurements of a given device conform to previous measurements of that same device.

Old and New Noise Measurement Methods

Noise parameters used to be measured using setups like the one shown in Figure 1: To find \( F_{\text{min}} \) and \( Y_{\text{min}} \), one had to search for \( F_{\text{min}} \) varying the input matching network until \( F_{\text{min}} \) was found:

- Measure noise figure, varying source impedance until \( F_{\text{min}} \) is found:
  - measure loss of adapters and transitions
  - measure loss of tuners
  - repeat for each bias condition and frequency
- De-embed each DUT fixture and associated bond wires with calibration standards.

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Accurate measurements were difficult to obtain, often requiring days or weeks of effort. Small losses in the components between the noise generator and the DUT contribute directly to the indicated total noise figure. This means that the losses of the tuner, isolator, switch, bias network, adapters, fixtures and cables must be accurately known. In addition to these considerations, noise source calibration and mismatch and second-stage noise contribution are also important to the final noise measurement. For best accuracy, many measurements are made and averaged to minimize repeatability uncertainties.

The newest noise parameter system (Figures 2 and 3) uses an automatic network analyzer (ANA) together with a calibration substrate to calibrate the adapters and wafer probes up to the probe tips. Fixture de-embedding is not required because wafer probes are calibrated at DUT connection. Figure 3 shows a block diagram of the system, and the sidebar describes the theory of operation. The impedance standard substrate (ISS) is important to both the calibration of the ANA and the verification of system operation (discussed later). The ISS contains very small geometry calibration standards, including trimmed resistors, shorts, opens and throughs. Because these standards are physically small, the capacitive and inductive parasitics are negligible, allowing accurate ANA calibration. A perspective view of a wafer probe touching down on the ISS is shown in Figure 4.

Once the ANA is calibrated to the probe tips, the source impedance network is calibrated at each frequency of interest using the ANA. Finally, the noise parameters of the receiver is measured using the noise meter and the calibrated noise diode and the programmable source. These calibration parameters are stored and used by the controller to correct noise figure measurements at each frequency.

The NPT18's MicroCAT Test Executive software guides the operator through the calibration steps, controls the function of all the equipment, corrects all the measurements using calibration data, and performs post-measurement data crunching. MicroCAT will also control autoprobers, power supplies and meters. Both S-parameters and noise parameters can be obtained at the same time. Therefore, in one system one can measure DC parameters, S-parameters and noise parameters, as well as extract models, all under program control.

Measurement Uncertainties

A measurement uncertainty limit is the range of values within which the true value of the quantity being measured is estimated to lie. The overall measurement uncertainty is composed of several parts:

- Systematic uncertainties associated with the measurement system; these are dependent on the system design, calibration standards and the DUT
- Repeatability uncertainties associated with both the equipment and operator technique and
- Drift associated with temperature variations.

Repeatability refers to how well a given measurement compares to a previous measurement of the same device. Repeatability uncertainties originate from random system variations, probe placement variations, and test set switch variations, and they are random in nature (having a zero mean value over time).

As is true for all noise measurement systems, the absolute accuracy of the $F_{\text{in}}$ value is dependent on the calibration of the excess noise ratio (ENR) of the noise diode with respect to a standard, and is further degraded by the uncertainties contributed by the noise figure meter’s response to the DUT’s gain and noise characteristics.

The NPT18 has smaller uncertainties than the traditional methods because of its improved repeatability. The largest contributor to repeat-
Fig. 5 Smoothed data of $F_{\text{in}}$ of a 0.5 x 300 µm device, taken one day apart. (Test conditions: $V_{\text{DS}} = 2.5$ V, $I_{\text{DS}} = \text{loss}$.)

Fig. 6 Smoothed rapt data of device mentioned in Figure 5 taken one day apart. Frequency range is from 2.2 to 17.8 GHz. Repeatability vector error is less than 0.02 dB.

Fig. 7 (a) Circuit schematic diagram and (b) photograph of ISS passive circuit used in system verification.

Verification

One verification method developed by Cascade Microtech involves measuring and comparing the S-parameters and noise parameters of a simple lossy passive network (Figure 7) on the ISS. This is a simple yet powerful procedure that checks all phases of the system including the ANA calibration, noise calibration and system operation. One measures the S-parameters and the noise parameters of this passive circuit and compares the results. This procedure depends on the relationship that the noise factor of a lossy circuit equals the inverse of the available gain of the network. Therefore, the maximum available gain is calculated from the S-parameters and compared with the measured $F_{\text{min}}$. $F_{\text{min}}$ will equal the reciprocal of the maximum available gain, indicating that all parts of the NPT18 are working correctly. The ISS, with its small geometries and resultant small parasitics, is ideal as a verification standard.

The verification procedure is described as follows:

1) Calibrate the system for S-parameters using the ANA and the impedance standard substrate.
2) Calibrate the system for noise parameters by using probes on an ISS through connection.
3) Measure S-parameters and noise parameters of the passive verification element and plot the results:

   a. View $\Gamma_{\text{opt}}$ on a Smith chart (Figure 8). The $\Gamma_{\text{opt}}$ values should form a small clump on or near the real axis at about 32 ohms because the network measured is almost entirely resistive.

   b. View noise figure and available gain circles on a Smith chart at a particular frequency. In a perfect system the available gain and noise circles will be coincident. The source impedance resulting in the maximum available gain (simultaneous conjugate match) should coincide with $Z_{\text{opt}}$ as shown in the
zoomed plot (Figure 9), the reflection coefficients resulting in maximum gain and minimum noise are generally coincident within 0.05 magnitude vector error.

c. View $F_{\text{min}}$ and associated gain over the entire frequency range from 2 to 18 GHz (Figure 10). $F_{\text{min}}$ and the maximum available gain should coincide within 0.1 dB. This indicates that the ANA and the noise measurement parts of the NPT18 are consistent within 0.1 dB over the entire frequency range.

Conclusion
Noise figure measurements that previously required weeks of effort now can be done in minutes with the NPT18, with improved accuracy.

References