Measuring noise parameters of twoports with Spectrum Analyzer FSM

Determining the noise parameters of twoports requires measurement of spectral noise-power density. Normally such measurements are carried out with highly sensitive receivers by the radiometer principle or with commercial, automatic noise-factor meters. Lately spectrum analyzers too come equipped for this application, although they are mainly intended for observing spectra with discrete frequencies rather than precise measurement of extremely low noise levels. Stability of receiver parameters with time is an important criterion for these measurements so that calibration should not be necessary more than once a day.

Spectrum Analyzers FSM from Rohde & Schwarz [1] are not just analyzers but also highly stable test receivers suitable for noise measurements up to 26.5 GHz, and in fact they offer clear advantages over commonly used noise-factor meters. The advantages are very evident when it comes to determining transistor noise parameters. This is far more complex than measurements on complete amplifiers or mixers in a 50-Ω system for example. Various impedances, which can show a lot of dependence on frequency, have to be applied to a transistor input, so the variable receiver bandwidth of the spectrum analyzer is a great advantage. MESFETs and HEMTs exhibit extreme mismatch in the lower GHz region and have high gain, so they are prone to oscillations. For this reason a spectrum analyzer would be required in the setup anyway to detect the absence of oscillations during noise measurements.

The above formula shows that four parameters are needed to determine the complete noise characteristic of a network at a particular frequency: minimum noise figure $F_{\text{min}}$, noise resistance $R_n$, optimum source reflection coefficient $\Gamma_{\text{opt}}$ and the phase angle of $\Gamma_{\text{opt}}$. These four parameters are normally deduced by connecting a circuit to the input that has been determined beforehand in a reflection coefficient measurement and by measuring the noise power at the output. The best known method is that of Lane [2]. It is based on noise-figure measurement for different source reflection coefficients and subsequent matching to the straight part of the characteristic as defined by the formula above. Since four unknown quantities are to be determined, at least four measurements are required. But a greater number of measurements (25 in this case) is normally performed to increase accuracy. The various source reflection coefficients are in most cases obtained with low-loss impedance tuners, preferably under computer control, connected between the noise source and the DUT. In the Y method the noise figure is determined by alternate measurements with the noise source switched on and off. But there are two shortcomings that cause problems particularly in measurement of low-noise transistors (MESFETs, HEMTs) in the lower GHz region. Firstly, the source admittance is different in the on and off state and, secondly, tuner loss (1 to 2 dB) is usually higher than the noise figure of the DUT (0.1 to 0.5 dB), besides being different from setting to setting.

For these reasons other types of test setup are increasingly being used. The cold-source method [3] means measuring for at least five different source reflection coefficients, just one of them with increased noise temperature. The others are formed by the inherent noise of tuner losses at ambient temperature. The cold connections are implemented by mechanical or PIN-diode switches for instance, the hot connection by a noise generator. This method eliminates the two error sources mentioned above. However, it does involve permanent use of a vector network analyzer, because the s-parameters of the DUT, tuner system and receiver have to be known. A simpler way is the standard 8-term model [4]. In addition to the four noise parameters, the input admittance of the DUT is also determined. So once a
A practical noise measurement system

FIG 1 shows the test setup with a controller. Spectrum Analyzer FSM is used as a power meter with frequency conversion. The measured level can be read in the display with a marker or indicated on a highly sensitive power meter connected to the IF output (21.4 MHz). The latter solution was used at the Ferdinand Braun Institute because the linearity of the marker display is not sufficient for all purposes and measured values would have to be linearized with the aid of a correction function. However, very good results were obtained with the power meter. The broadband amplifier (0.1 to 4 GHz) connected ahead reduces the noise.

FIG 2 On-wafer test setup for noise measurements with Spectrum Analyzer FSM at Ferdinand Braun Institut für Höchstfrequenztechnik, Berlin
Photo: Blask

### Special features of transistor noise measurements

While only one measurement is required for routine measurements on amplifiers or mixers in a 50-Ω system, ie \( G_{\text{opt}} \) and \( R_{n} \) are not determined at all, transistors make much higher demands for the following reasons:

1. The minimum noise figure of MESFETs and HEMTs in the lower GHz region is very small (\( F_{\text{min}} \approx 0.5 \) dB).

2. The input impedance is almost purely capacitive, so noise matching for the source reflection coefficient \( |\Gamma_{\text{opt}}| \) occurs at approx. 1. This is difficult to achieve with an impedance tuner.

3. The very high gain resulting from strong transformation at the input may cause a transistor to oscillate (> 20 dB).

4. Strong transformation is of narrow bandwidth, meaning that double-sideband measurements are not possible because \( \Gamma_{S} \) is different in the two sidebands, even if they are only a few MHz apart. In the lower GHz region the bandwidth has to be limited for single-sideband measurement too. This is not possible with noise-factor meters, which usually have a bandwidth of 4 MHz.

Here, by contrast, the decisive advantages of FSM as a noise-factor meter:

- High sensitivity in conjunction with a low-noise preamplifier ensures low noise figure in the receiving system. The wide FSM frequency range (100 Hz to 26.5 GHz) is only limited by this preamplifier.

- Single-sideband reception means that no tunable microwave filters are required.
figure of the receiver system to $F < 2$ dB. The DUT is connected between an impedance transformer and the broadband amplifier. This DUT may be either a single transistor in a test fixture with coaxial connectors or an on-wafer transistor contacted by microwave test probes (FIG 2). The impedance transformer consists of a step attenuator (switchable between 0 and 11 dB) and an electromechanical SP12T switch, the outputs of which are alternately open or shorted. Because the line length varies with the switch position, the phase angle of the reflection coefficient is different at each frequency. The magnitude can be varied in addition using the attenuator, and a 50-Ω system can be implemented in the 11-dB setting. Thus a great variety of source reflection coefficients is obtained. Although these are arbitrary values, they may be employed for evaluation by the Lane method.

The following system parameters must be known for fully determining the noise parameters of a transistor at different frequencies:

- The four noise parameters of the receiver referred to the input. In this case the microwave probe at the transistor output is used as the reference plane. The test receiver therefore comprises the microwave probe, DC feed, switch, preamplifier and FSM as well as the connecting cables, which should be as short as possible and of low loss. For measuring these parameters the impedance tuner is connected to the input via a thru, all tuner settings are selected and the receiver is measured in the same way as the DUT subsequently. Using these data the contribution of the receiver can be corrected when noise measurements on the transistor are performed.

- The reflection coefficients of the following components:
  a) receiver with respect to the input reference plane,
  b) noise generator at the same reference plane,
  c) impedance tuner at the reference plane of the input microwave probe. The impedance tuner therefore includes a DC feed and the required connecting cables in addition to the SP12T switch and the attenuator. Particular care should again be taken that low-loss components are used so that areas around the outer edges of the Smith chart can be reached for approaching the $\Gamma_{\text{opt}}$ of the field-effect transistors.

- The bandwidth-gain product of the receiving system is measured with the calibrated noise generator connected to the input. For this, the attenuation between the coaxial noise generator and the reference plane at the receiver input has to be known accurately and is determined in a twoport measurement.

For interpretation of noise measurements, the twoport s-parameters of the DUT also have to be known to calculate mismatch at the receiver input and the noise power delivered from the tuner to the DUT [5]. Noise parameters are determined mostly at discrete frequencies in a specific frequency band. The required s-parameters are previously measured and stored. When measurements are repeated at the same frequencies and the test setup is not changed, calibration of the bandwidth-gain product is seldom required.

**Measurement examples**

In a trial of the test setup, measurements were carried out on enclosed MESFETs, HEMTs in a coaxial test fixture [6] and on-wafer MESFETs produced at the Ferdinand Braun institute. The following settings were made on FSM for the on-wafer meas-

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**Application notes**

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**FIG 3** Noise test structure in MMIC technology. Bright meander lines are ohmic resistors. MIM capacitance to ground can be seen in upper left third. Four noise parameters can be calculated accurately from equivalent T circuit.

**FIG 4** Distribution of reflection coefficients of impedance network at various attenuations ($f = 700$ MHz). Noise figures measured with test structure in FIG 3 are marked. Distribution of reflection coefficients is different for each frequency and therefore random but exactly reproducible.
A "noise standard" with parameters reproducible by the test setup would be desirable for assessing system accuracy. Ideally a standard of this kind would be a transistor with accurately known s- and noise parameters. This cannot be obtained with an on-wafer device and with conventional test equipment because of the problems described with noise measurements in the frequency range 0.2 to 2.7 GHz. Furthermore, the accuracy of factory calibration of the noise generator (max. inaccuracy 0.3 dB) is not sufficient to measure transistors with F_{min} from 0.1 to 0.5 dB. For this reason a purely passive test structure was produced on the wafer together with the transistors (FIG 3), the four noise parameters of which are similar to those of the MESFET – without gain of course – and which can be extracted from the s-parameters, which can be measured with high accuracy. The measurement should not only confirm these four parameters but also yield the corresponding noise figure for each of the source reflection coefficients. The deviation of each testpoint from the theoretical value according to the equation is an indicator of measurement quality and thus of the performance of the test setup. Calibration of the noise generator can also be checked. The Smith chart in FIG 4 shows the source reflection coefficients obtained at different switch settings of the impedance tuner together with the measured noise figure of the test structure. The theoretical characteristic and measurement results are compared in FIG 5: even at a great distance from the noise minimum, no deviation can be found between the two sets of values. This is a measure of the high accuracy of the test setup based on Spectrum Analyzer FSM.

This high accuracy is also confirmed in transistor measurements. But the evaluation method has to be modified this time because of the extremely low noise figures and high gain. According to the equation the minimum noise figure is obtained by intercepting the ordinate from the theoretical value according to \( R_n \). \( R_n \) is determined by the slope of the equation and can therefore be read more exactly than the intercept on the axis. The method uses a theoretical noise model for field-effect transistors and yields simple formulae in the lower GHz region, thus permitting this kind of evaluation. Above about 5 GHz these conditions are not fulfilled, but since the noise figure of transistors is higher and \( \Gamma_{opt} < 1 \), this method is no longer required. FIG 6 shows a MESFET measurement in the frequency range 0.2 to 2.7 GHz.

**FIG 5** Lane diagram of noise figure versus deviation from noise minimum \( x = (1 - |S|^2) / (1 + |S|^2) \). Intercept on ordinate is given by \( F_{min} \), slope of noise resistance by \( R_n \). Examples for measurement at 700 MHz. Blue straight line represents calculated values of test structure.

**FIG 6** Minimum noise figure versus frequency. Two MESFETs with gate widths of 80 and 160 µm. Operating point: \( V = 3 \) V, \( I = 10 \) mA. Determination according to [7].

for \( \Gamma_5 = \Gamma_{opt} \). However, with noise figures around 0.1 dB this value cannot be determined accurately as \( \Gamma_{opt} \) can very seldom be directly set. For this reason the method used in this case is based on evaluation of noise resistance \( R_n \) [7]. \( R_n \) is determined by the slope of the equation and can therefore be read more exactly than the intercept on the axis. The method uses a theoretical noise model for field-effect transistors and yields simple formulae in the lower GHz region, thus permitting this kind of evaluation. Above about 5 GHz these conditions are not fulfilled, but since the noise figure of transistors is higher and \( \Gamma_{opt} < 1 \), this method is no longer required. FIG 6 shows a MESFET measurement in the frequency range 0.2 to 2.7 GHz.

**REFERENCES**


