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On-Wafer Noise-Parameter Measurements at *W*-band

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On-Wafer Noise-Parameter Measurements at W-Band

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***Abstract*—A wide-band on-wafer noise-parameter measurement setup has been developed for W-band. The system is based on a cold-source method and uses a simple manual impedance tuner. In addition to noise parameters, S-parameters can be measured with the same setup. Using the developed system, noise parameters of an InP high electron-mobility transistor have been measured and results are shown in the 79–94-GHz frequency band. This is the first comprehensive report of noise-parameter measurements made on active devices at W-band.**

***Index Terms*—High electron-mobility transistor (HEMT), noise measurement, noise parameter, on-wafer characterization.**

I. Introduction

SEVERAL current and planned space missions for earth observation and astronomy applications require very low-noise receivers at W-band (75–110 GHz). A key component in this kind of low-noise receiver is a low-noise amplifier (LNA). The design of LNAs is greatly dependent on the availability of good noise models for devices used in the LNAs. Therefore, to design an optimum amplifier both noise and scattering (S)-parameters are needed. The noise parameters cannot be measured directly. The determination of the noise parameters involves scattering parameter and noise-figure measurements and data processing. The S-parameters of a two-port can be measured using a standard commercial vector network analyzer (VNA). However, the noise-parameter measurements are very challenging. Commercial measurement systems are available only up to 40 GHz. A good description of measurements below 40 GHz is given in [1]. Measured W-band noise parameters have been presented earlier only for passive devices and at a single frequency [5], [6]. We have recently been working with noise-parameter measurements at V- and W-bands. Our V-band (50–75 GHz) noise-parameter measurement setup and results were reported in [2]–[4] and the first results with an active device at W-band were published in [7]. This paper presents a full report on the measurement system that allows simultaneous on-wafer noise and scattering parameter measurements at W-band.

To determine the noise parameters, the noise figure of a device-under-test (DUT) is measured with different values of the input reflection coefficients. The noise figure of a two-port as a function of source reflection coefficient Γ_i is given by [8]

$$F = F_{\min} + \frac{4r_n}{1-|\Gamma_i|^2}\left|\frac{\Gamma_i - \Gamma_{\rm opt}}{1+\Gamma_{\rm opt}}\right|^2 \qquad (1)$$

where $F_{\min}$ is the minimum noise figure of the two-port, r_n is the normalized noise resistance, and $\Gamma_{\rm opt}$ is the optimum reflection coefficient. Variables $F_{\min}$, r_n, and $\Gamma_{\rm opt}$ are called noise parameters. The noise parameters are obtained by fitting the above equation with the measured data.

II. Measurement Setup

The measurement system is shown schematically in Fig. 1, and the photograph of the measurement setup is shown in Fig. 2, respectively. The measurement setup is based on the cold-source method [9], [10]. The improved technique, described in [2], is used. This technique corrects the effects of reflection-coefficient changes between the cold and hot states of the noise source and takes into account the losses of the passive network between the DUT and noise receiver.

The DUT is connected to the measurement system using waveguide probes. By including two waveguide switches, both noise and S-parameter measurements can be done without breaking any connections. These are commercial switches with less than 1-dB loss, more than 60-dB isolation between ports, and repeatability better than 0.05 at W-band. Only a simple uncalibrated one-port impedance tuner is needed in the input side of the DUT. This is possible due to switch 1. The one-port tuner consists of an adjustable waveguide short and attenuator. System characterization and the S-parameter measurements of the DUT are done using the HP8510C VNA. The VNA is also needed during noise measurements of the DUT to measure the reflection coefficient of the impedance tuner. The noise source is used here only during the calibration of the noise receiver. The noise-receiver calibration can also be done during long measurement sessions without breaking any connections due to switch 2. An LNA is used to increase the sensitivity of the noise receiver. The LNA was obtained through the Planck surveyor collaboration [11]. The mixer is used to downconvert the noise power from W-band to the measurement region of the HP8970A noise-figure meter. The local oscillator (LO) chain consists of the HP83650A synthesized sweeper, HP 8349B microwave amplifier, and HP83558A millimeter-wave source module. All measurement instruments are controlled using a personal computer (PC) via general-purpose interface

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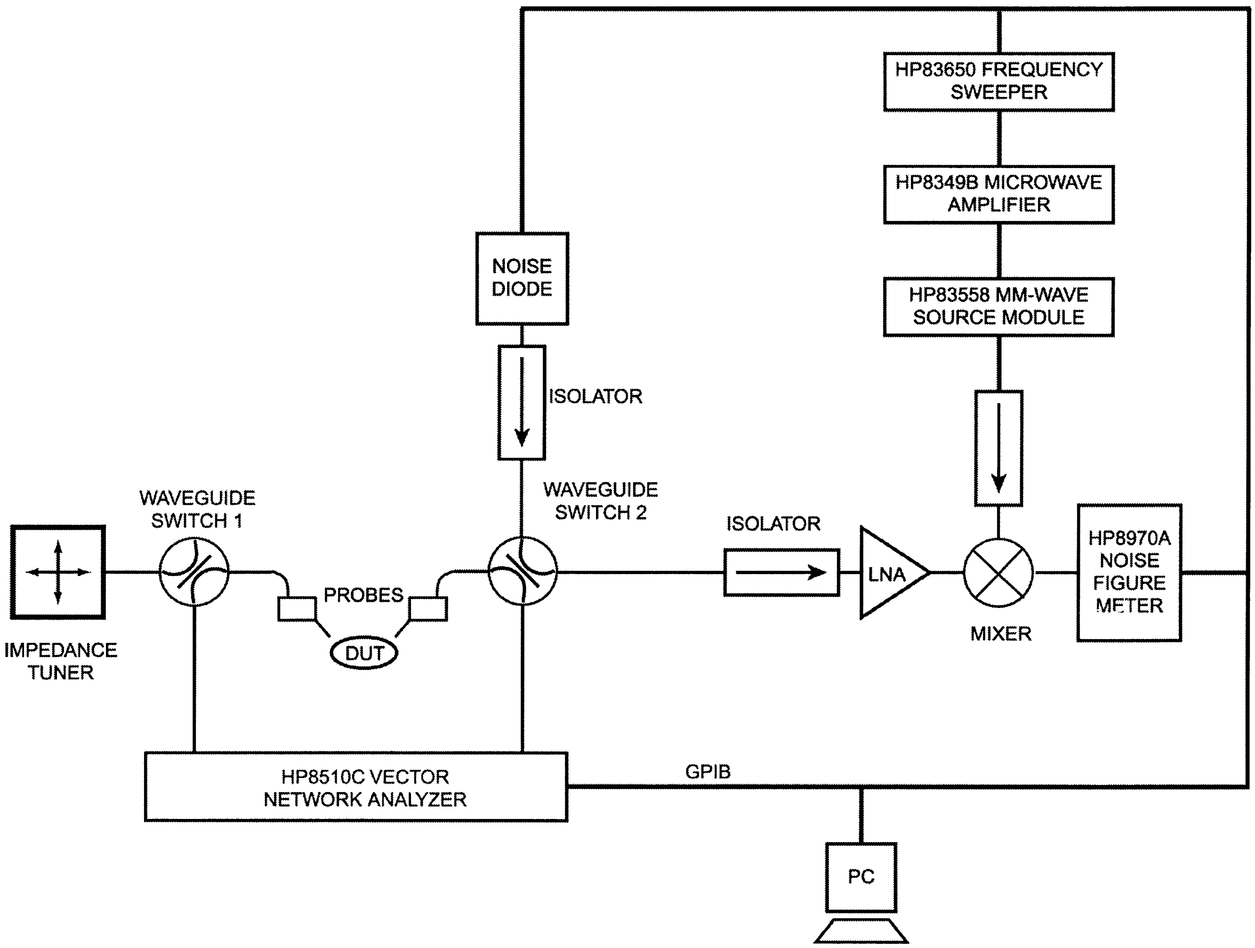

Fig. 1. Setup for noise-parameter measurements at 79–94 GHz.

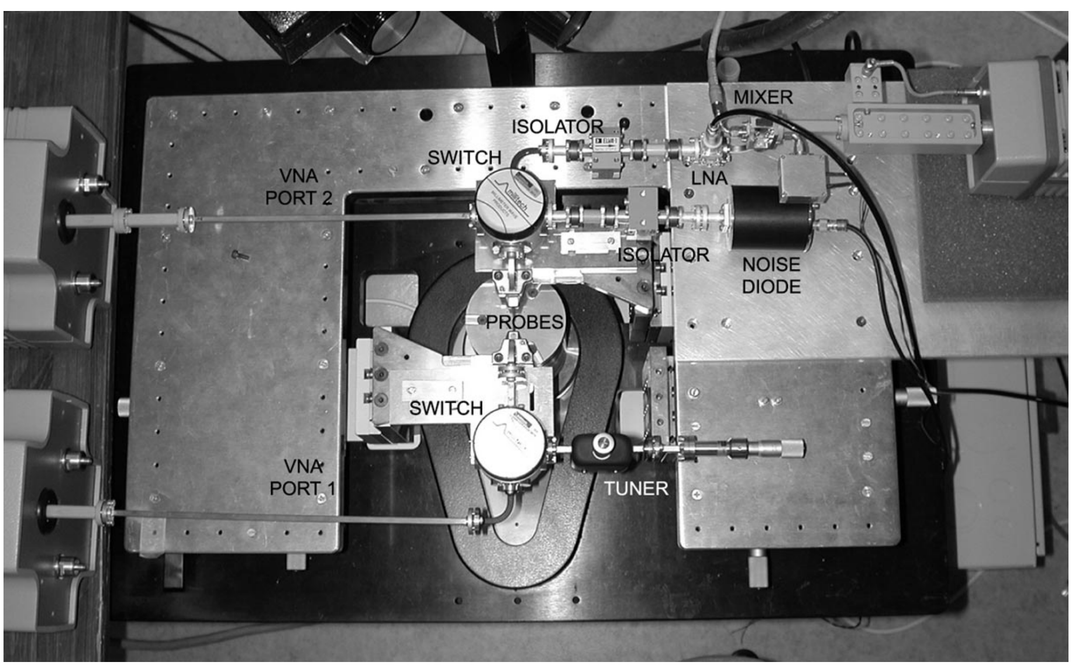

Fig. 2. Photograph of the measurement setup. All waveguide components are on top of a probe station.

bus (GPIB) line. The PC and in-house-made software make automatic data acquisition and complex calculations possible.

III. Measurements

Measurements can be divided into the following three parts:

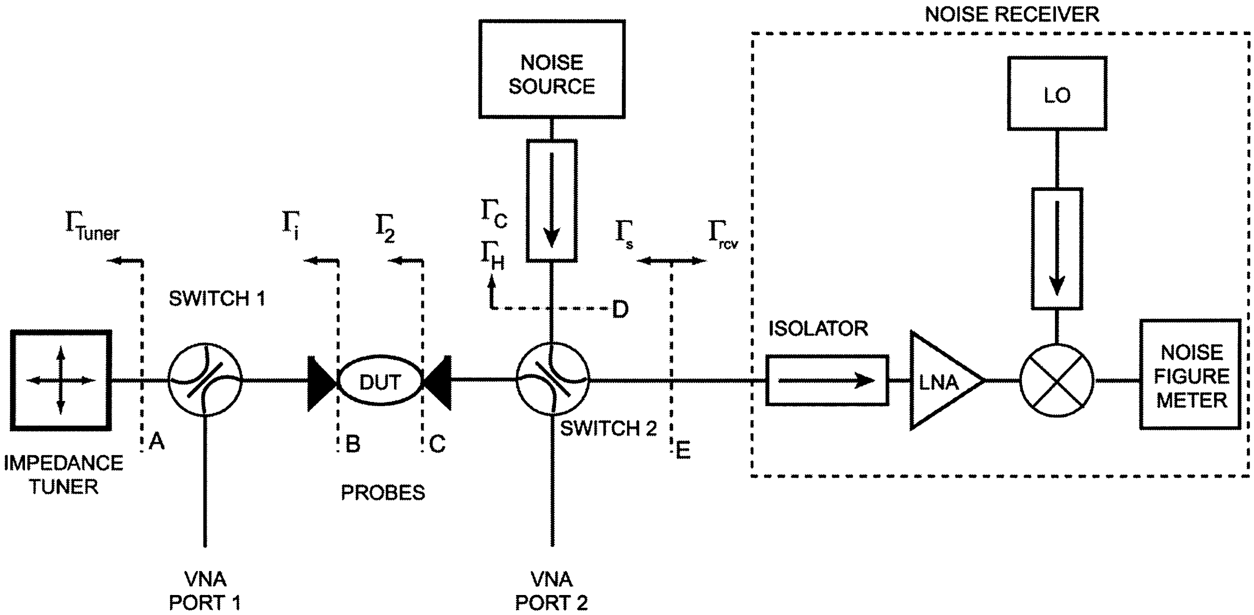

Fig. 3. Measurement system with reference planes and reflection coefficients.

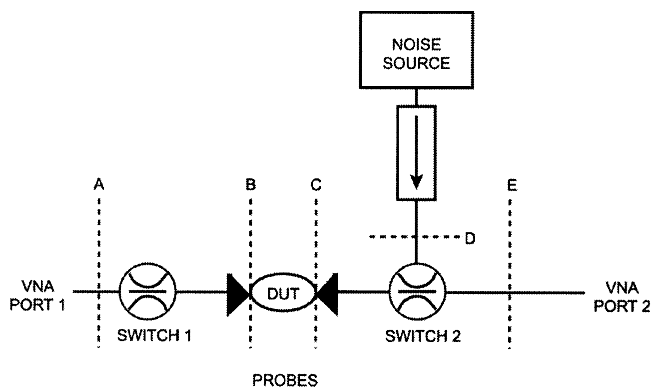

Fig. 4. Measurement setup for the characterization of the passive networks A–B and C–E.

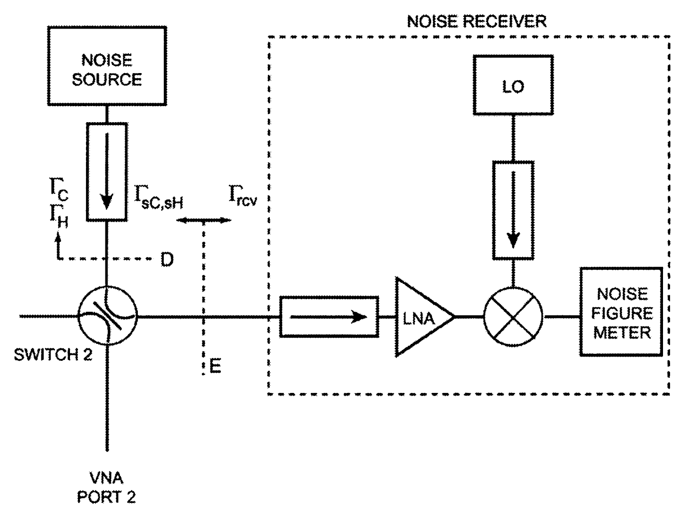

Fig. 5. Measurement setup for the noise-receiver calibration.

1) system characterization;
2) noise-receiver calibration;
3) noise measurements of the DUT.

A. System Characterization

The system characterization is done using the VNA. It consists of the S-parameter measurements of the passive networks A–B, C–E, and D–E and the reflection-coefficient measurements of the noise receiver $\Gamma_{\rm rcv}$ and the noise source $\Gamma_{\rm C}$, $\Gamma_{\rm H}$ (both cold and hot states). The meanings of these reference planes and reflection coefficients are shown in Fig. 3.

The passive networks A–B and C–E cannot be measured directly with the VNA because they are noninsertable. To characterize these networks, the VNA is first calibrated to the reference planes A and E using a one-port waveguide calibration. The configuration is shown in Fig. 4. An on-wafer two-port LRRM calibration [12] is then done to reference planes B and C. The S-parameters of these networks are calculated from the two sets of error coefficients. The passive network D–E and reflection coefficients are also measured with the VNA. Measured attenuation of the passive network A–B was from 1.6 to 1.8 dB and attenuation of the passive network C–E was between 0.8–1.4 dB. Attenuation of passive network A–B limits impedance range of the impedance tuner. The maximum amplitude of achievable source reflection coefficient Γ_i is approximately 0.72 at 90 GHz at reference plane B.

B. Noise-Receiver Calibration

The noise-receiver calibration includes a determination of the kBG factor and the noise figure of the noise receiver. The noise source is connected to the noise receiver by switch 2. The noise power of the noise source is measured in the cold and hot states. This is done at all frequencies with the setup shown in Fig. 5. This figure also shows the notations of the reference planes D and E and reflection coefficients.

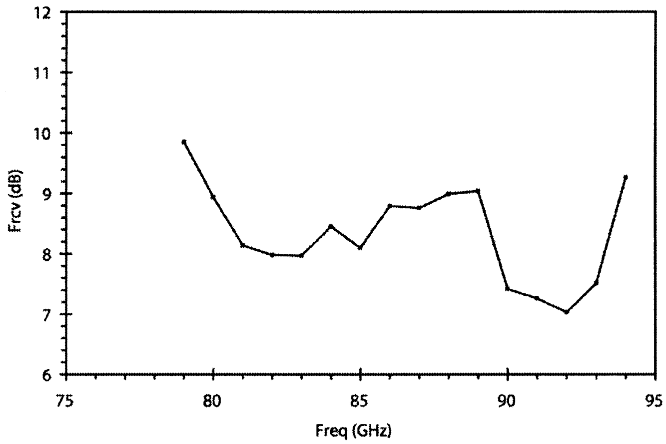

Fig. 6. Measured noise figure of the noise receiver.

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

$$P_{\rm C} = kBGT_{\rm Ceff} \quad (2)$$
$$P_{\rm H} = kBGT_{\rm Heff} \quad (3)$$

where $T_{\rm Ceff}$ and $T_{\rm Heff}$ are the effective noise temperatures of the cold and hot states. Effective noise temperatures can be expressed in the form

$$T_{\rm Ceff} = [T_{\rm C}G_{\rm aC} + (1 - G_{\rm aC})\,T_{\rm a}] \cdot M_{\rm C} \quad (4)$$
$$T_{\rm Heff} = [T_{\rm H}G_{\rm aH} + (1 - G_{\rm aH})\,T_{\rm a}] \cdot M_{\rm H} \quad (5)$$

where $T_{\rm a}$ is the ambient temperature, $T_{\rm C}$ and $T_{\rm H}$ are the cold and hot noise temperatures of the noise source, $G_{\rm aC}$ and $G_{\rm aH}$ are the available gains of the passive network between the reference planes D and E in the cold and hot states, and $M_{\rm C}$ and $M_{\rm H}$ are the mismatch factors of the cold and hot states [13]

$$M_{\rm C,H}\,(\Gamma_{\rm sC,sH}) = \frac{\left(1 - |\Gamma_{\rm sC,sH}|^2\right)\left(1 - |\Gamma_{\rm rcv}|^2\right)}{|1 - \Gamma_{\rm sC,sH}\Gamma_{\rm rcv}|^2}. \quad (6)$$

The kBG factor is

$$kBG = \frac{P_{\rm Hm} - P_{\rm Cm}}{T_{\rm Heff} - T_{\rm Ceff}} \quad (7)$$

where $P_{\rm Hm}$ and $P_{\rm Cm}$ are the measured noise powers in the hot and cold states.

When a noise diode is used as a noise source, then $T_{\rm C} = T_{\rm a}$ and (4) reduces to

$$T_{\rm Ceff} = T_{\rm a}M_{\rm C}. \quad (8)$$

The noise factor of the noise receiver $F_{\rm rcv}$, which is independent of the source reflection coefficient Γ_i, can be expressed in the form

$$F_{\rm rcv} = \frac{T_{\rm Heff} - Y \cdot T_{\rm Ceff}}{T_0\,(Y - 1)} + 1 \quad (9)$$

where T_0 is the standard temperature, and the Y coefficient is

$$Y = \frac{P_{\rm Hm}}{P_{\rm Cm}}. \quad (10)$$

The measured noise figure of the noise receiver is presented as a function of frequency in Fig. 6.

C. Noise Measurements of the DUT

After system characterization and noise-receiver calibration, the noise measurements of the DUT are carried out. The VNA is calibrated to the reference planes B and C using the line–reflect–reflect–match (LRRM) on-wafer calibration. The DUT is then placed between the probes and set to the operating point of interest. The S-parameters of the DUT are measured. Noise-figure measurements are done in two steps. The first step is to measure the reflection coefficient of the impedance tuner $\Gamma_{\rm tuner}$ using the VNA, and the second step is to measure the corresponding noise power of the entire system. The VNA port 1 is switched to the tuner. The tuner is set and its reflection coefficient $\Gamma_{\rm tuner}$ is measured. The tuner is then switched to the DUT and the corresponding noise power P_i is measured with the noise receiver. These steps are done for every selected value of the tuner and as a function of the frequency. Since the S-parameters of the passive network A–B are known, the source reflection coefficient Γ_i can be calculated. It is then possible to calculate the noise figure of the entire system as a function of the source reflection coefficient Γ_i [2]

$$F_{{\rm tot},i} = \frac{P_i\,|1 - S_{\rm 11DUT}\Gamma_i|^2\,|1 - \Gamma_s\Gamma_{\rm rcv}|^2\,|1 - S_{\rm 11CE}\Gamma_2|^2}{T_0kBG\,|S_{\rm 21DUT}|^2\left(1 - |\Gamma_i|^2\right)|S_{\rm 21CE}|^2} - \frac{T_{\rm a}}{T_0} + 1 \quad (11)$$

where $S_{\rm 11DUT}$ and $S_{\rm 21DUT}$ are the S-parameters of the DUT and $S_{\rm 11CE}$ and $S_{\rm 21CE}$ are the S-parameters of the passive network between reference planes C and E, respectively.

The noise figure of the DUT as a function of the source reflection coefficient $F_{\rm DUT}(\Gamma_i)$ is calculated using the Friis formula [14]

$$F_{\rm DUT}\,(\Gamma_i) = F_{\rm tot} - \frac{F_{\rm rcv}\,(\Gamma_i) - G_{\rm aCE}}{G_{\rm aDUT}G_{\rm aCE}} \quad (12)$$

where $G_{\rm aDUT}$ and $G_{\rm aCE}$ are the available gain of the DUT and network between reference planes C and E, $F_{\rm rcv}(\Gamma_i)$ is the noise figure of the noise receiver that is dependent of source reflection coefficient Γ_i

$$F_{\rm rcv}(\Gamma_i) = F_{\rm rcv} \cdot \frac{|1 - \Gamma_{\rm rcv}\Gamma_s|^2}{1 - |\Gamma_s|^2} \quad (13)$$

where Γ_s is the reflection coefficient seen by the noise receiver. After solving $F_{\rm DUT}$ and Γ_i data pairs, noise parameters can be extracted with mathematical fitting methods.

IV. Results

As an example of W-band noise-parameter measurements, a DaimlerChrysler InP high electron-mobility transistor (HEMT) was measured. It has 0.18-μm gate length and 2×40 μm gatewidth. During the measurements, the HEMT was set to the operating point with a drain voltage $V_{\rm ds} = 1.0$ V and a drain current $I_{\rm ds} = 10$ mA. The noise parameters of the HEMT are shown in Figs. 7–10. To show repeatability, three different measurements are presented ($M1$–$M3$ in Figs. 7–10). The noise parameters are extracted from measurement data using Lane's method [15]. Five different source impedances were used. One

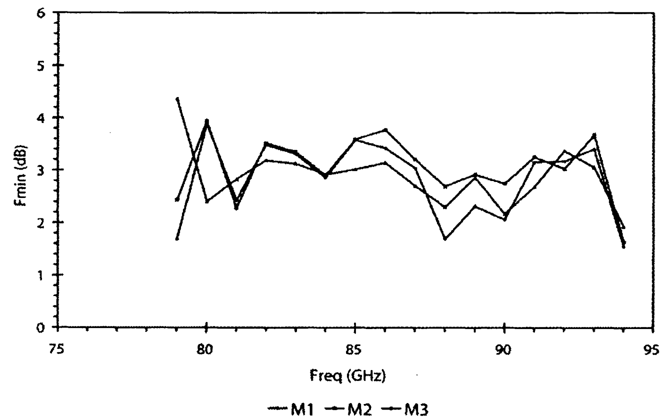

Fig. 7. Measured minimum noise figure as a function of frequency. Measurements were carried out three times.

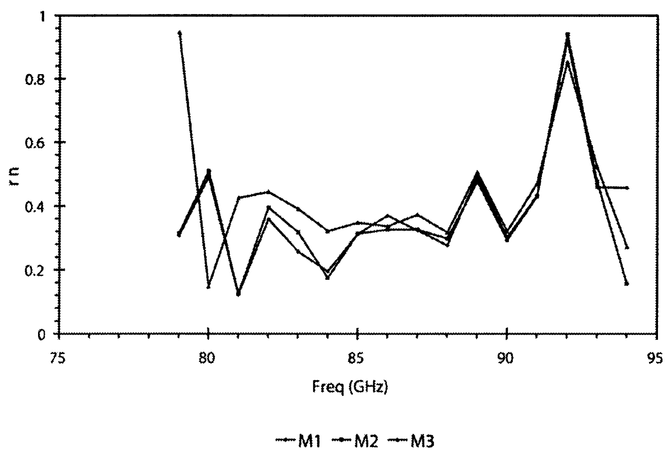

Fig. 8. Normalized noise resistance as a function of frequency. Measurements were carried out three times.

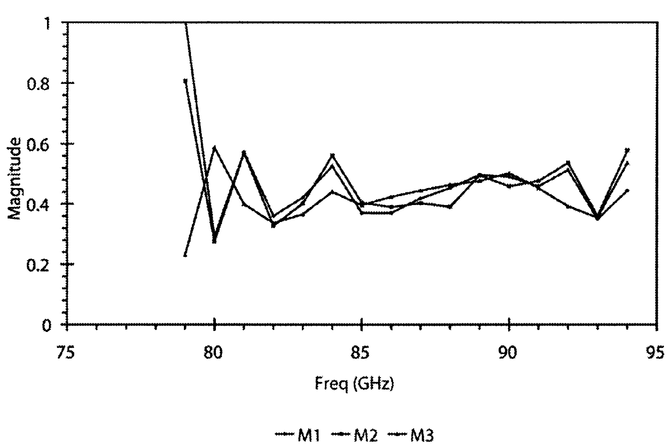

Fig. 9. Magnitude of the optimum reflection coefficients. Measurements were carried out three times.

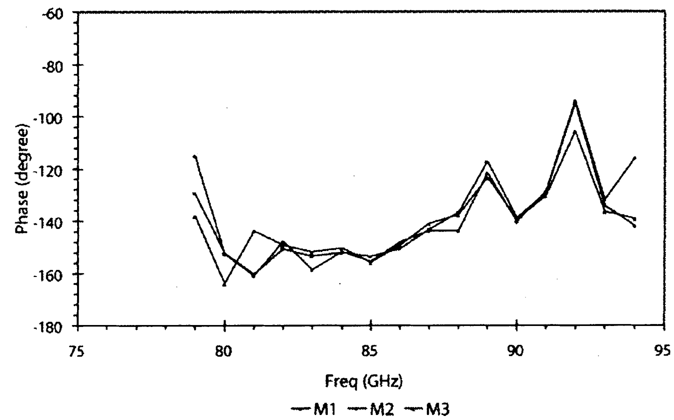

Fig. 10. Phase of the optimum reflection coefficients. Measurements were carried out three times.

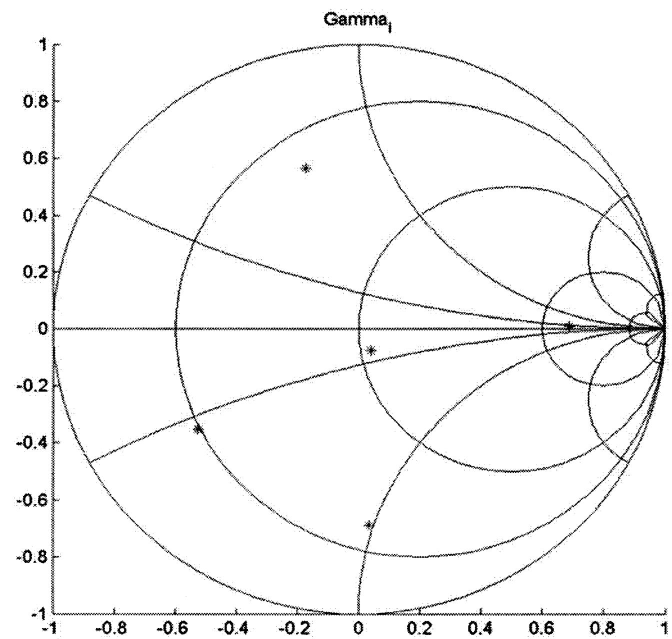

Fig. 11. Source reflection coefficients Γ_i at 90 GHz in measurement 2.

was set close to the center of the Smith chart and the others were set symmetrically around the center of the Smith chart. These are presented in Fig. 11 at 90 GHz. Noise parameters of similar HEMTs were presented in [4] at the V-band. V-band measurements were made on a different device from the same wafer. Peaks are seen in the normalized noise resistance and the phase of $\Gamma_{\rm opt}$ around 89–92 GHz. These are likely due to the difficulties in the on-wafer calibrations and the sensitivity of the noise receiver at these frequencies.

V. Discussion and Error Analysis

Sensitivity and linearity of the noise receiver are important in noise-parameter measurements. The noise power P_i as a function of frequency is shown in Fig. 12. The source reflection coefficient Γ_i is the nearest value of the center of the Smith chart (see Fig. 11). The noise power is under 400 K below 88 GHz and increases rapidly toward higher frequencies reaching 13 600 K at 93 GHz. This is one possible explanation for the peaks in the normalized noise resistance and the phase of $\Gamma_{\rm opt}$. The measurement system will be improved by obtaining a W-band LNA for the noise receiver with lower noise figure, higher gain, and wider bandwidth.

As can be seen from the measurement results, single-frequency measurements are not reliable at the W-band. Wide-band measurements are important for obtaining reliable

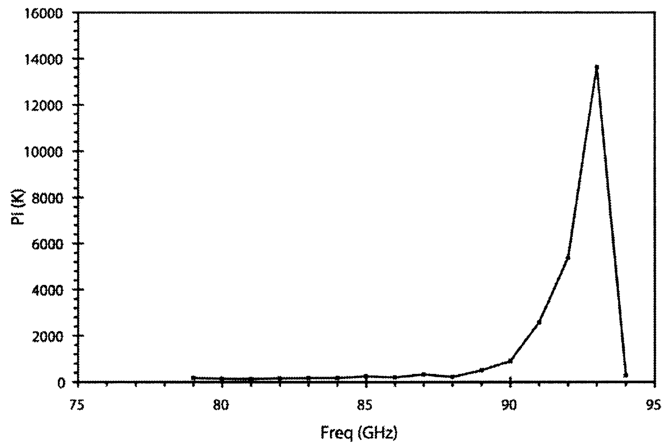

Fig. 12. Noise power P_i as a function of frequency. The corresponding source reflection coefficient Γ_i is the point closest to the center of the Smith chart.

results. All steps are critical in the noise-parameter measurements with characterization of the passive networks A–B and C–E needing careful attention. These include both waveguide and on-wafer calibrations. If system characterization is not done carefully, large systematic errors may remain undiscovered. These errors are usually caused by reflections in the setup, which are difficult to calibrate out.

Since there are no active on-wafer noise-parameter standards, which could be used directly to determine the uncertainty of the measurement system, the uncertainties have to be determined indirectly. The task is quite complex since the noise-parameter measurements involve a large number of variables and numerous different measurement steps and calibrations. Approximately 40 measured variables are used to calculate the noise parameters. Measurements consist of S-parameters and reflection coefficients (both magnitudes and phases), noise power measurements, and the excess noise ratio (ENR) calibration of the noise source.

A partial derivative method is usually used in uncertainty analysis, but when the number of variables is large or variables have complicated functional relations, it becomes impractical [16]. Instead, a statistical Monte Carlo method is applied in the analysis of the uncertainties of noise parameters [17]. In the Monte Carlo method, a large set of noise parameters are created by adding random fluctuations to the measured data. When the number of conducted runs is large (thousands), results can be studied statistically. Graphical presentation of the Monte Carlo method is shown in Fig. 13. Uncertainties with random distribution are added to measured values, and noise parameters are calculated. This is repeated many times and the new calculated noise parameters are stored after every run. Having many sets of noise parameters, results can be analyzed statistically.

Monte Carlo simulations were done at a single frequency. Uncertainties, presented in Table I, were used for each measured variable, and noise parameters were calculated. Uncertainties are divided in classes A and B [18]. The evaluation of type-A uncertainty was done by statistical method and type B was evaluated by other means, e.g., using approximation or manufacturer's specifications. Evaluation of uncertainty values of measured values is based mostly on [17], where similar work was carried out for V-band cold-source noise-parameter setup. For the uncertainties of S-parameters, the magnitude is determined using a rectangular distribution and corresponding angle using a uniform distribution from -180° to 180°. Calculated Monte Carlo simulation results for measurement 2 at 90 GHz are presented in Table II. The mean of each noise parameter and 2σ (95.5% confidence level) of 10 000 simulation runs are shown in this table.

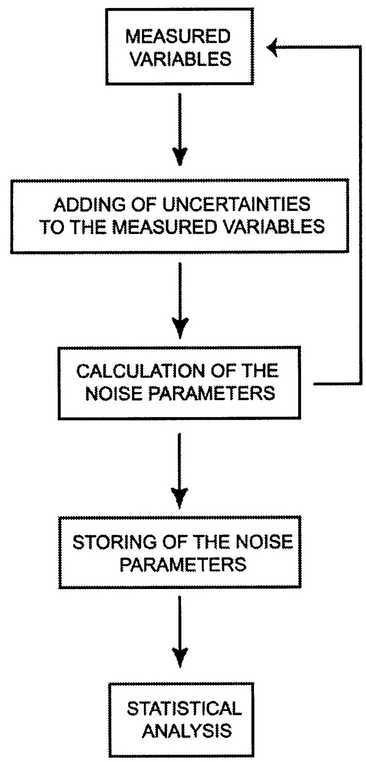

Fig. 13. Graphical presentation of Monte Carlo analysis used to analyze uncertainties of the noise parameters.

TABLE I
UNCERTAINTIES FOR MEASURED PARAMETERS

Measured parameter	Uncertainty	Type
Γ_{tuner}, Γ_{rcv}, Γ_H, Γ_C	0.005	B
S_{11_AB}, S_{11_CE}	0.036	A, B
S_{22_AB}, S_{22_CE}	0.036	A, B
S_{12_AB}, S_{21_AB}, $S_{12\_CE} \times S_{21\_CE}$	0.0013	A, B
S_{11_DE}, S_{22_DE}	0.005	B
S_{12_DE}, S_{21_DE}	0.006	B
S_{11_DUT}	0.036	A
S_{12_DUT}, S_{21_DUT}	0.05	A
S_{22_DUT}	0.024	A
ENR [dB]	0.1	B
P_H, P_C, P_i [K]	1.01	A
T_a [K]	1	A

TABLE II
RESULTS OF MONTE CARLO SIMULATIONS AT 90 GHz

Parameter	Mean	2σ
F_{min} [dB]	2.8	±0.7
r_n	0.3	±0.09
$\|\Gamma_{opt}\|$	0.46	±0.09
ϕ_{opt}	-139	±10

VI. Conclusion

A W-band on-wafer noise-parameter measurement system has been designed and built. For the first time, to the author's knowledge, wide-band results for the W-band on-wafer noise parameters of an active device have been reported. The noise parameters of an InP HEMT (DaimlerChrysler 2×40 μm) were measured using the cold-source method. Measurement results were presented between the 79–94-GHz frequency band.

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