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MEASUREMENT OF COHERENCE FUNCTION BETWEEN NOISE CURRENTS OF TRANSISTORS

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Abstract – Relationships between input and output noise parameters of a twoport expressed by correlation and coherence functions has been described. Low noise transimpedance amplifiers (current-to-voltage converters I/V) are used to measure base (gate) and collector (drain) noise currents of transistors in the low frequency range.

To reduce an influence of inherent noise of these amplifiers an additional buffer amplifier with special noise properties can be introduce to the input channel of measurement system. A supplementary measurement of the input noise voltage (besides input noise current) can also be used to improve the accuracy of coherence function measurement. To estimate the coherence function with a suitable accuracy adequate digital signal processing procedures should be used.

Keywords: transistor noise measurement, low noise preamplifiers, coherence function.

1. INTRODUCTION

Noise characterization of transistors can be accomplished by calculation of four noise parameters fully describing noise properties of a transistor treated as a twoport. Two basic noise representations are commonly used: in terms of equivalent input voltage $S_{\mathcal{E}}(f)$ and current $S_{\mathcal{J}}(f)$ noise sources (Fig. 1a) or in terms of input $S_{\mathcal{J}_i}(f)$ and output $S_{\mathcal{J}_o}(f)$ short-circuit current noise sources (Fig. 1b).

A calculation of noise quantities from Fig. 1a requires a usage of multi-impedance measurement technique, it means the noise measurement at the output of Transistor Under Test (TUT) at several input terminal loads and then the data processing to get the noise parameters including the correlation factor defined as

$$c(f)=\frac{S_{\mathcal{E}\mathcal{J}^*}(f)}{\sqrt{S_{\mathcal{E}}(f)S_{\mathcal{J}}(f)}}\ . \tag{1}$$

Using the direct technique one can measure the short-circuit input and output current noise spectra and their correlation (Fig. 1b) directly at the TUT input and output. An input port load does not change during noise wave forms acquisition, therefore the measurement process is much faster and can be easier controlled by the computer.

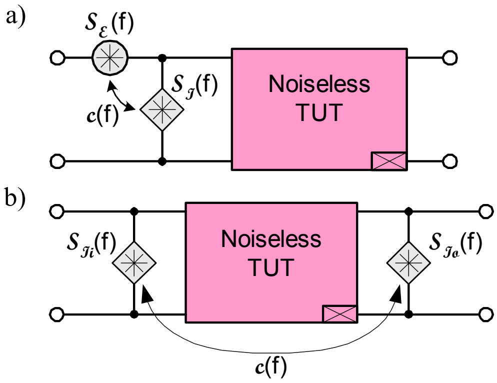

Fig. 1. Noise equivalent circuit of TUT with voltage and current noise sources at the input (a) or current noise sources at the input and output (b) expressed as spectral densities of noise quantities

However, the influence of inherent noise of a measurement system is much more critical for the direct method, especially for the measurement of the magnitude-squared coherence

$$\gamma^2(f)=\frac{\left|S_{\mathcal{J}_i\mathcal{J}_o^*}(f)\right|^2}{S_{\mathcal{J}_i}(f)\cdot S_{\mathcal{J}_o}(f)}\ . \tag{2}$$

The correlated spectrum in the nominator is calculated through a multiplication in the frequency domain between the complex Fourier transforms of two measured independently noise signals. The coherence $\gamma^2(f)$ supply in a very efficient and accurate way a good estimation of the output noise signal energy entity exclusively due to the input noise.

2. GENERAL MEASUREMENT SETUP

Current noise of a TUT $S_{\mathcal{J}_i}(f)$ and $S_{\mathcal{J}_o}(f)$ can be directly measured for a wide range of source resistance R_S using transimpedance amplifiers T_i and T_o (with current gain A_{Ii} and A_{Io}) in a measurement setup shown in Fig. 2 as the impedance of the measured TUT is larger than input impedance of the current amplifier T_i. This enables measurements of both current noise simultaneously and direct calculation of the coherence between noise currents.

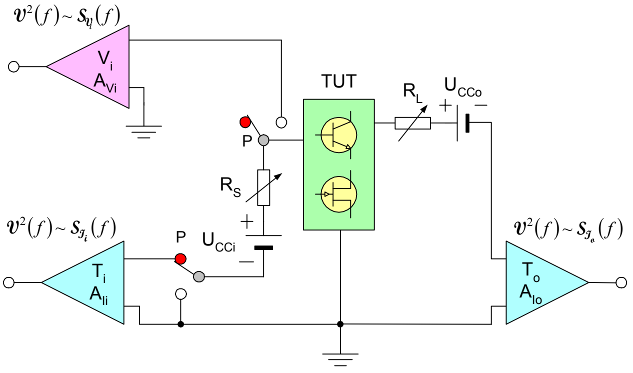

Fig. 2. Simplified setup for short-circuit input (base, gate) and output (collector, drain) noise currents measurement

An extra voltage amplifier V_i in the input measurement channel serves to measure the coherence between noise currents with better accuracy in the additional measurement step (the switches P in Fig. 2 are then shorten to the white terminal).

Depending on TUT the different types of low-noise preamplifiers and transimpedance amplifiers V_i, T_i and T_o, respectively, can be included in the front-end part of the system. For FETs noise measurements in the gate channel an ultra low-noise I/V converter with the appropriate conversion factor is required (for example, the gate current noise level for MESFETs equals often only a few nA). The equivalent input noise current of the converter circuit (OP 128 as the transimpedance amplifier) was estimated as $I_{ni} \approx 41\ fA/\sqrt{Hz}$ for the feedback resistor of the converter having the resistance $10\ M\Omega$. The results of the noise analysis were confirmed experimentally.

Other type of transimpedance amplifiers facilitates internal voltage bias of TUT with a high resolution and can be easily controlled by a computer. However these internal noise sources induce much higher noise level into the measurement setup.

switch measurement of	P_1	P_2	P_3	P_4	P_5	P_6
inherent noise	○	○	○	○	○	not connected
T_i gain	●	○	●	●	●	●
T_o gain	○	●	●	○	not connected	○
DUT noise	●	●	○	○	○	not connected

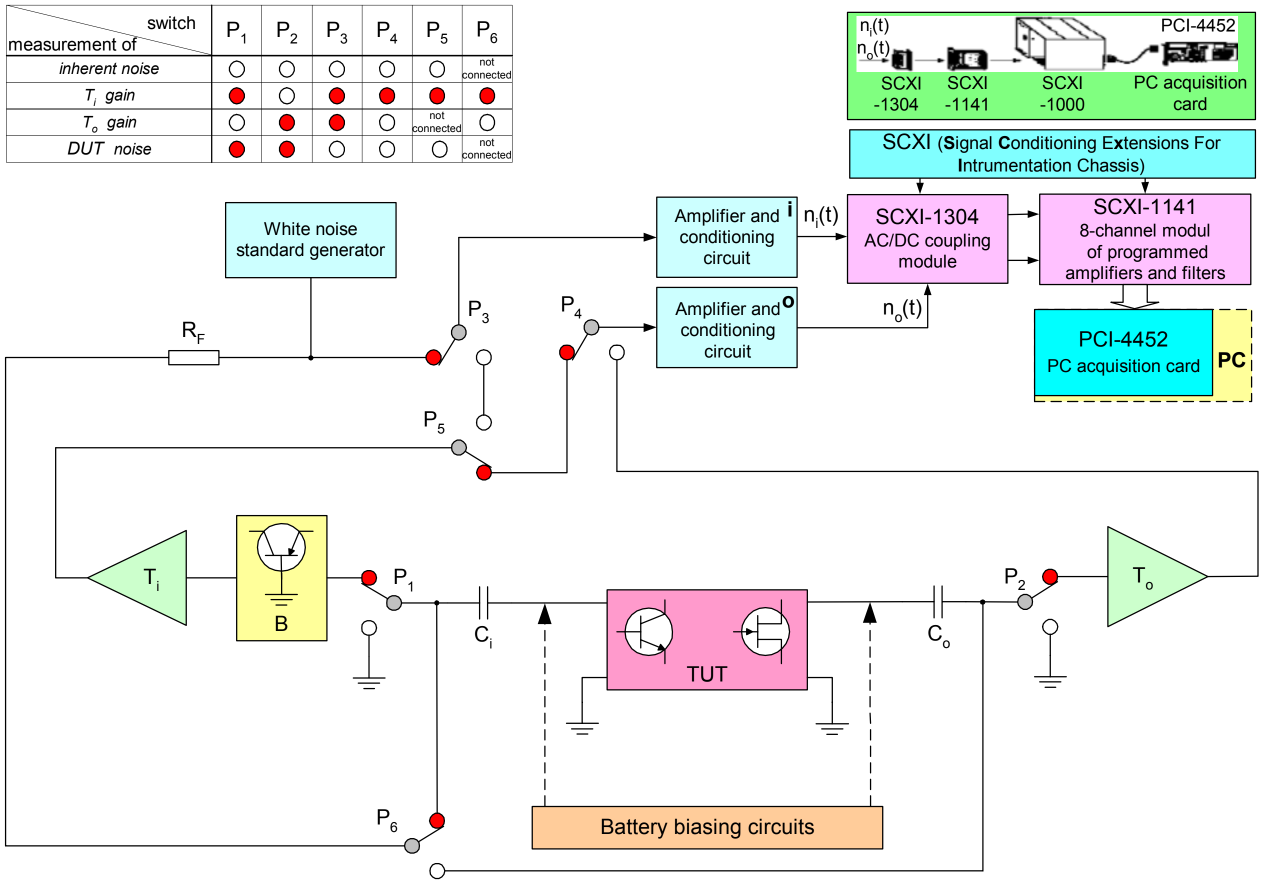

Fig. 3. General block diagram of two-channel measurement system

General block diagram of the whole measurement system with two data acquisition channels built with National Instruments 4452 dynamic signal acquisition board controlled by LabVIEW software is shown in Fig.3.

External voltage sources (in biasing circuits) with variable alternate current impedances realized on batteries enables a higher amplification factor of transimpedance ampliers (they do not neet to sink the direct current).

The antialiasing filter SCXI-1141 (having eight software-controlled input channels with the software -selectable cut-off frequency $f_a = 100/m\ kHz$, where m is an integer - $m \geq 4$) gives an output signal range ±5 V. The low noise and low distortion Dynamic Signal Acquisition Board PCI-4452 (used optionally for noise characteristics estimation in the wider frequency range) simultaneously digitise input signals (within the range from ±10 mV to ±42.4 V) by means of a 16-bit resolution, 64-times oversampling, delta-sigma modulating Analog Digital Converter (ADC) over a bandwidth from DC to 95 kHz. The data can be next processed on-line or stored on a disk as time series with a required number of samples according to the accuracy of noise parameters and characteristics estimation. The final amplification factor is settled by means of the output amplifiers. The switches P_i (i = 1÷6) are used in the calibration phase to measure inherent noise and the main electrical parameters of the particular sub-assemblies of the system.. The inherent noise of the measuring system can be subtracted from the results of the noise measurements.

3. COHERENCE MEASUREMENT

The measurement of the coherence between the input and output noise currents of a transistor TUT operating as an amplifier is a critical task [1,2]. All noise sources associated with the input transimpedance amplifier T_i can therefore give a significant contribution to the output noise current and hence to the coherence. To improve accuracy for low values of source resistance R_S (when the measured coherence between $S_{\mathcal{J}_i}(f)$ and $S_{\mathcal{J}_i}(f)$ is systematically too low) the voltage preamplifier V_i (Fig. 2) with passive input can be used in the second step of the measurement mainly to find the coherence. It is especially recommended for the bipolar transistors. In this step the value of R_S should be sufficiently high.

4. SEPARATION WITH BUFFER AMPLIFIER

To measure properly all noise parameters directly with transimpedance amplifiers the input voltage noise source of the T_i should be separated from the input of TUT without degradation of T_i noise properties and not introducing an attenuation into the ultra low level stage of the measurement system. These requirements can be fulfilled by insertion a special low noise buffer amplifier B (Fig. 3) between T_i and input terminals of TUT having dc gain equal unity and very small reverse gain. It was designed with a common base bipolar junction transistor with carefully selected bias conditions (a compromise between the lowest output noise of the buffer amplifier B and the as low small-signal input impedance as possible). Its noise properties with strongly correlated input and output noise sources have no major effects on the system noise background but it effectively isolates the T_i input voltage noise source from the TUT input.

5. NOISE PARAMETERS ESTIMATION PROCEDURES

A special attention should be paid for the appropriate averaging procedures during coherence estimation to achieve a low value of the random component of mean square error.

A LabVIEW virtual instrument provides the computation and display of coherence function in conjunction with the output noise power spectrum to allow an efficient comparison between the coherence function variations and the related base (gate) and collector (drain) noise spectra components. The estimator of magnitude-squared coherence (2) uses the cross spectrum function with an adequate level of linear averaging. In the average, the ratio of periodic to random components is proportional to $\sqrt{k}$, where *k* is the number of records used (a signal to noise ratio improvement of $10 \cdot \lg(k)[dB]$ - often $k = 124 \div 516$). A hypothetical 90% confidence limits for $\gamma^2(f)$ are specified in Table I.

Values of $\gamma^2(f)$ are less than 1 if both noise signal are uncorrelated, exists additional noise source in the input noise signal (e.g. not negligible inherent noise of T_i), TUT should be treated as non-linear or error leakage is not reduced with windowing during data processing (resolution bias errors are present in the spectral estimates).

Table I. 90% confidence limits on coherence function measurement

$\gamma^2(f)$	k = 16	k = 32	k = 64	k = 128	k = 256
0.40	0.15÷0.59	0.23÷0.54	0.28÷0.50	0.32÷0.47	0.34÷0.45
0.50	0.25÷0.67	0.33÷0.63	0.39÷0.59	0.42÷0.57	0.45÷0.55
0.60	0.36÷0.74	0.45÷0.71	0.50÷0.68	0.53÷0.66	0.55÷0.64
0.70	0.50÷0.81	0.57÷0.78	0.61÷0.76	0.64÷0.76	0.66÷0.73
0.80	0.65÷0.88	0.70÷0.86	0.74÷0.84	0.76÷0.83	0.77÷0.82
0.90	0.81÷0.94	0.85÷0.93	0.87÷0.92	0.88÷0.92	0.88÷0.91

The variance of the coherence function can be used as a measure of the accuracy of the spectral analysis. For different amounts of window overlap (referring to segmented spectral analysis) the variance of the coherence function is reduced as more averages are taken. A suitable value for overlap can be around 60%. The precision and resolution of the spectral estimate depends on the choice of the number of data samples and the window size, respectively.

6. EXPERIMENTAL RESULTS

Two channel noise measurements enables to localize noise sources in measured devices and to verify to mechanisms of noise generation. Very often a common noise source causes e.g. for polysilicon emitter bipolar transistors both 1/f noise in the base current and in the emitter series resistance [3]. However as experiments showed these two noise sources are not fully correlated as a result of local inhomogeneities in the oxide layer.

In Fig. 4 the coherence for GaAs MESFET is shown. The maximum of coherence function γ^2 occurs at the frequency $f \approx 700$ Hz and is associated with the presence of a generation-recombination trap (g-r noise component appearing in the spectrum $S_{\mathcal{J}_i}(f)$). The traps were identified by the presence of Lorentzians in the measured noise spectra and also by the higher value of the coherence function at some frequency ranges.

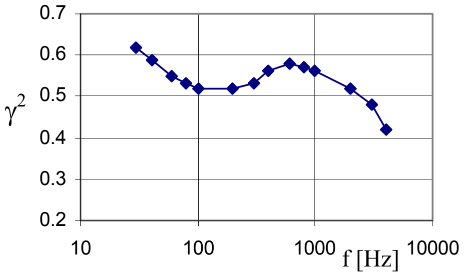

Fig. 4. Coherence function for measured GaAs MESFET

The obtained results suggest that for the measured transistor the most influential noise source at the output is related to the surface leakage between gate and source [4]. This fact can be associated with the existence of g-r centre and very noisy processes in this region [5]. Therefore a coherence measurement can be used as an additional diagnostic tool for MESFET and MODFET reliability studies.

7. CONCLUSIONS

The measurement system with transimpedance amplifiers can be used to measure directly noise parameters of transistors including the coherence function. To improve the accuracy of coherence measurement an additional voltage preamplifier should be used at the input terminal of the measured transistor. The influence of its inherent voltage noise source thermal noise of the resistor R_S has been analysed.

Another way to achieve a reduction of inherent noise influence is to separate the input transimpedance amplifier from the measured TUT by means of the special buffer amplifier reducing the T_i noise influence on the output of measured transistor.

From the coherence measurement for different source resistance a dominant noise source in a transistor can be established.

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