Correlation technique to reach ultimate resolution in noise measurements

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ABSTRACT

The Correlation Spectrum Analyzer, thanks to the presence of two independent acquisition channels, has demonstrated to reach very high performance in measuring noise spectra and to be extremely flexible in adapting to different devices under test (DUT) in term of impedance values, of flowing standing current, of DC applied voltage and of the physical quantity to be measured, either current or voltage. In addition, it can selectively extract the noise contribution of a specific current flow in multi-electrodes devices. The paper will briefly highlights these features together with the influence of the DUT characteristics, such as its impedance to ground and the cross-impedance between the two electrodes connected to the instrument input ports, in determining the ultimate limits in the performance of the instrument in terms of its sensitivity, its precision and its spectral extension. A practical realisation for measurements made with an AFM especially modified for correlation investigations is also commented.

Keywords: Correlation Spectrum Analyzer, noise measurements, current spectra, AFM, electron devices

1. INTRODUCTION

The correlation technique applied to noise measurements demonstrated to be essential to reach the extraordinarily high resolution needed nowadays in the most demanding experiments. The experimental evidence of the suppression of shot noise in tunneling junctions [1,2] and the presence of shot noise in macroscopic resistors [3,4] are two examples of how fruitful such a powerful technique can be in validating innovative theories [5,6,7,8].

The Correlation Spectrum Analyzer (CSA) scheme is used to overcome the limit of instrumental spurious noise and thus probe very low noise of the sample. Indeed, the sample noise is fed to two distinct input amplifiers operated in parallel, followed by a frequency selector circuit and a correlation stage. This multiplies each component of the two channels and then averages out the result in time. The sample noise is therefore processed in phase by the two channels and multiplied frequency by frequency, thus obtaining at the output the noise power spectral density of the sample. Conversely, since the instrumental noise of the two channels is uncorrelated one to each other, it gives at the output of the multiplier an additional contribution with average value equal to zero and with standard deviation $\sigma_{S_{DUT}}$ of the fluctuations around the DUT power density that can be strongly reduced by increasing the averaging time:

$$\sigma_{S_{DUT}} = \overline{s_n^2} \cdot \frac{1}{\sqrt{2 \cdot RBW \cdot T_m}} \qquad (1)$$

where RBW is the resolution bandwidth of the spectrum. Thus, the measurement sensitivity can be improved to extremely low noise level, at the expense of required measurement time Tm. Few minutes measuring time are in general sufficient to improve sensitivity by an order of magnitude, and few days give another factor of ten [9,10].

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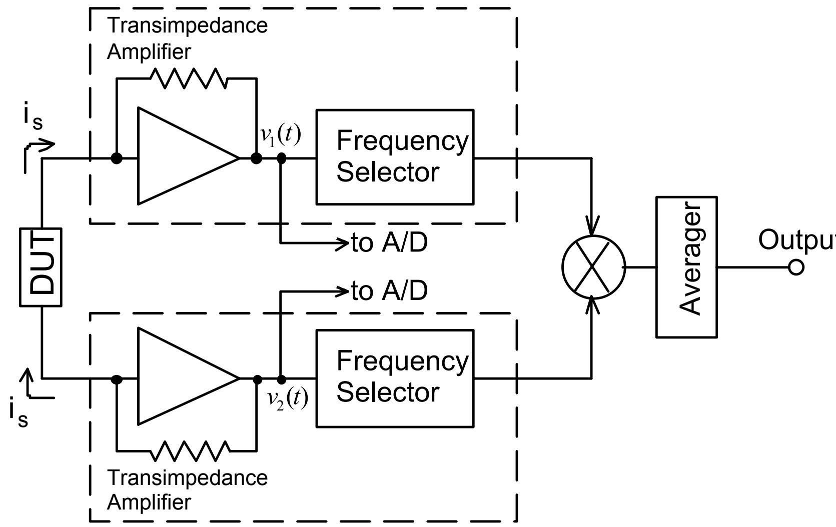

Fig. 1. Scheme of a Correlation Spectrum Analyzer.

The time needed to obtain a given sensitivity can be traded with the resolution bandwidth RBW, as indicated by Eq.(1): a frequency resolution relaxed by a factor of 10 would produce 10 times faster measurement for the same noise sensitivity. This, of course, implies that the low frequency section of a DUT spectrum would require a proportionally long measurement time.

As most of the primary physical noise sources in electronic devices are in the form of current, the current-sensitive scheme is often preferred as closer to physical intuition [11,12,13]. It has practical advantages in term of simplicity of connection and biasing of the device directly through the instrument and, by avoiding voltage conversion, often simplifies the measuring set-up leading to an improvement of the overall performance. Nevertheless, the clue to make the choice between current-sensitive or voltage-sensitive set-up stands on the DUT impedance.

1.1 Limitations due to strays

The level of fluctuation given by Eq.(1) defines the minimum DUT signal that can be ideally measured. In practice, the ultimate performance of the instrument in term of sensitivity is set by the amount of correlated spurious signals generated by those sources of noise in the input preamplifiers that produce a signal exactly in parallel to the one produced directly by the DUT. Figure 2 shows the noise sources and the electrical connections that are responsible for these correlated spurious signals in the case of a current sensitive set-up. These correlated components are read by the two channels of the instrument the same way as the DUT component and can therefore not be removed.

For what concerns current noise measurements with the set-up of Fig.2, the correlated component is produced by the noise voltage sources $\overline{e_n^2}$ and sets the minimum DUT signal that can be measured by the instrument as:

$$\overline{i_{corr}^2} = 2 \cdot \overline{e_n^2} \left[\frac{1}{R_D} \left(\frac{1}{R_F} + \frac{1}{R_D} \right) + \omega^2 C_D \left(C_D + C_{stray} \right) \right] \qquad (2)$$

where R_D and C_D are the equivalent resistance and capacitance of the DUT and C_{stray} is the stray capacitance of the connection. We have assumed that both amplifiers and connections are exactly equal.

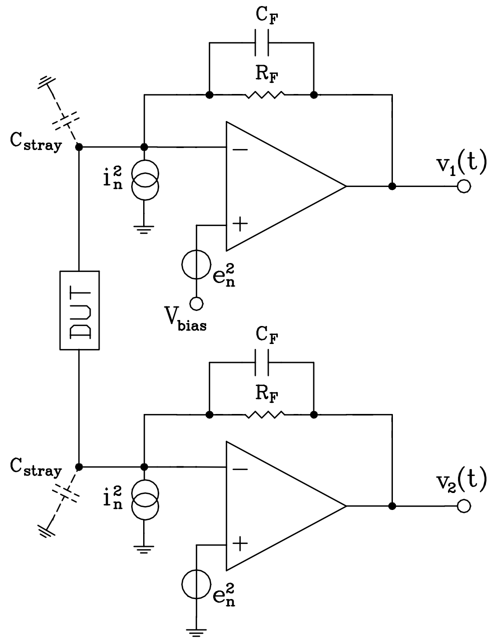

Figure 2. Schematics of instrument input stage for the case of a current sensitive set-up. Main noise sources, parasitic capacitances and DUT impedance are indicated to help in the evaluation of the spurious correlated signal that set a lower limit in the instrument sensitivity.

The limits predicted by Eq.(2) are function of the frequency and of the impedance of the DUT. Note that at low frequencies the 1/f noise component of $\overline{e_n^2}$ may be the limiting factor. Special care should therefore be taken when designing the transimpedance amplifier by choosing low 1/f noise components for the input stage. At high frequencies, the second term in Eq.(2) increases and becomes the limiting factor when the impedance of the DUT is particularly large. This is unavoidable and practically sets the effective bandwidth of the instrument, when measuring very low noise levels, to less than 1MHz. It is evident from Eq.(2) that a DUT with a large resistance R_D and a small capacitance C_D would fully exploit the capability of the instrument reaching noise levels well below the femtoAmperes/√Hz.

1.2 Advantages with respect to standard analyzers

In a comparison with a standard spectrum analyzer, a correlation-based instrument shows not only a significant advantage in term of sensitivity, but also advantages in term of dynamic range, bandwidth and immunity to stray capacitance. To understand this point consider for example the current sensitive set-up of Fig.2 in which the feedback resistance R_F of the transimpedance amplifier may be chosen low enough to manage the standing current from the DUT and/or to extend the bandwidth of the instrument (inversely proportional to R_F) as required (or imposed) by the application. The sensitivity of the measurement would not be affected by this reduction of R_F as long as a correspondingly longer measuring time is used. Conversely, if only one transimpedance amplifier is used, as it is the case in a standard analyzer, the reduction of R_F to satisfy dynamic range or bandwidth would reduce sensitivity correspondingly.

By considering the effect of a stray capacitance, in a standard analyzer the signal produced by the input voltage noise through the stray input capacitance sums directly to the DUT signal and reduces the instrument sensitivity. In a correlated instrument, the signal generated on the stray capacitance tends to flow on a single channel (depending on the DUT impedance) and therefore may be reduced by proper averaging time. Only the fraction that flows trough the DUT is correlated on the two channels and sets the sensitivity limit of the instrument.

2. MULTIELECTRODES SELECTION CAPABILITY

The CSA is also able to distinguish one source of noise among others in a complex multielectrode device [14]. Typical examples are the increasing complexity of the gate leakage current in nanoscaled MOSFET due to vanishing thin oxides and its correlation with the drain current [15,16] or the interchange of gates fluctuation in double-gate silicon-on-insulator (SOI) devices [17]. The CSA distinguishes and sort-out only the noise contribution due to the physical source placed between two defined terminals of the instrument, irrespectively of the overall amount of noise at both terminals due to other independent physical sources of noise. In a MOSFET, for instance, the technique would allow to detect and measure the noise due to the gate leakage current at the drain side irrespectively of the uncorrelated amount of current flowing in the channel or coming from the substrate.

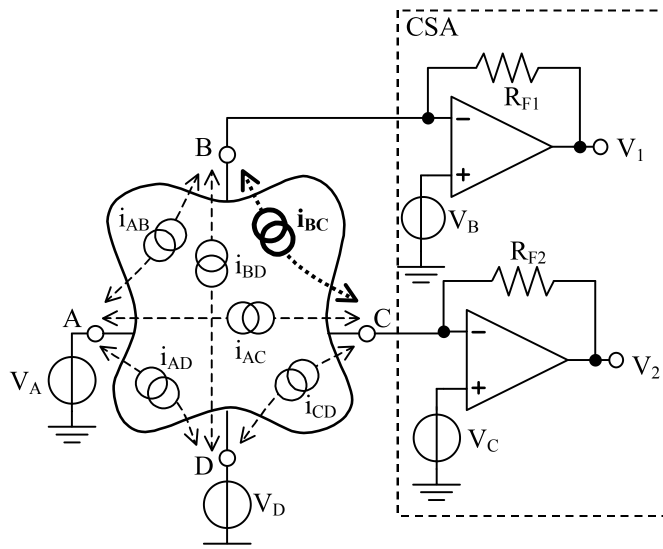

Figure 3 Schematics of the connection of the Correlation Spectrum Analyzer to a generic four-electrodes device to extract only the noise source i_{BC}.

Considering the case in Fig.3, among the many uncorrelated currents flowing through the electrodes of the device, the instrument selectively extracts only one single component, namely the one flowing through the two terminals directly connected to the input nodes of the instrument. This current component, indicated with i_{BC} in Fig.3, is indeed the only one flowing in phase in both channels and therefore processed as correlated by the instrument. Other current components present at the same terminals, that is i_{AB} and i_{BD} at the electrode B (channel 1), and i_{AC} and i_{CD} at the electrode C (channel 2), are uncorrelated between the two channels and can be reduced by the instrument after a properly long measuring time. Also, as already mentioned, the noise produce by the two amplifiers and by the feedback resistances R_{F1} and R_{F2} is uncorrelated and therefore is reduced in the same way.

The total power spectral densities of the signals in the two channels can be written as:

$$S_{W1} = S_{BC} + S_{AB} + S_{BD} + S_{n1}$$
$$S_{W2} = S_{BC} + S_{AC} + S_{CD} + S_{n2}$$

where S_{AB}, S_{AC} are the power spectral densities of the current components i_{AB},i_{AC},…, S_{n1} and S_{n2} are the instrumental noises (amplifier and feedback resistance) of the channel 1 and of the channel 2 respectively. To extract a single component (i.e. S_{BC}) from the overall noise a measuring time T_m is needed and it can be estimated as [5]

$$T_m \approx \frac{1}{2\,RBW}\frac{S_{W1}\cdot S_{W2}}{S_{BC}^2} \qquad (3)$$

where RBW is the frequency resolution of the measured spectrum . Thus, with a few minutes long measurement, the proposed technique can extract signals hundreds times smaller that the other components with a frequency resolution of RBW=100Hz.

In order to avoid DC saturation of the amplifiers, the values of feedback resistances are chosen according the amount of standing current from the DUT. In case the currents from the DUT are different, different feedback resistances can be chosen. As their value set the amount of uncorrelated instrumental noise (S_{n1} and S_{n2}), their choice would not affect the minimum detectable signal, provided that a corresponding different measuring time is used, in agreement with eq. 3.

To show how this technique can be effective in sorting a vanishing small noise contribution out from a large noise ground level, let us consider the reference case where different resistances have been connected to form a three-electrode network. Resistances R_1 and R_2 are of 1MΩ and are chosen smaller than R_3=100MΩ. The network is biased with 0.5V in such a way to produce a current flow into R_1 and R_2, but not in R_3. Thanks to the virtual ground offered by the two transimpedance amplifiers and the free access to the other electrodes, the working point of the multipole device can be set very easily directly by the instrument without additional biasing networks, thus reducing external noise contamination.

The instrument is expected to sort-out only the small thermal noise produced by R_3, whose value is given by $\overline{i_n^2}=4kT/R_3=1.6\ 10^{-28}\ A^2/Hz$, irrespectively of the presence, at the same two input nodes of the instrument, of higher current flux produced by R_1 and R_2. The results of the measurement are reported in Figure 4.

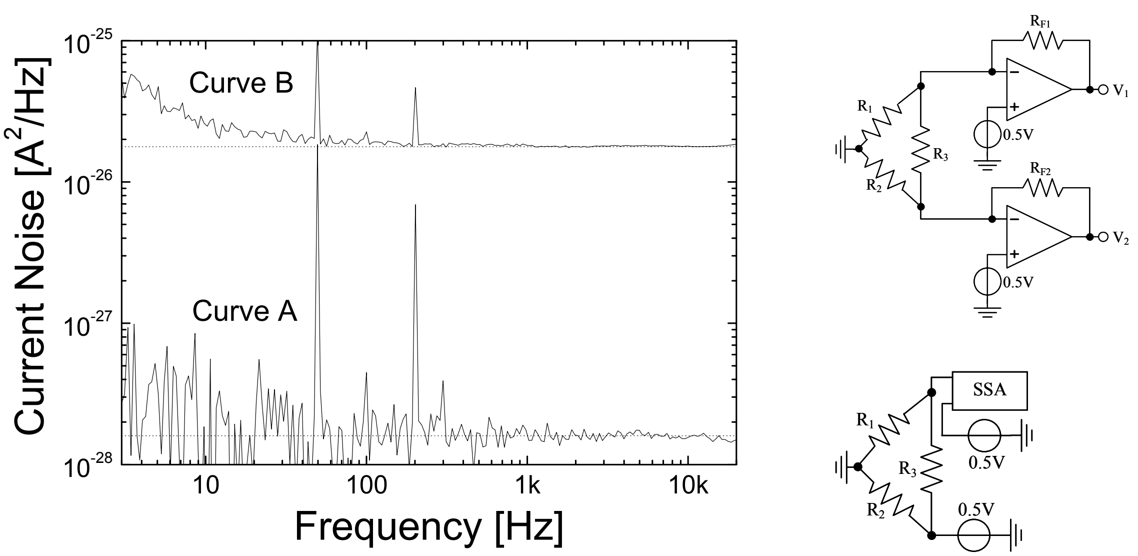

Figure 4 Current noise spectra obtained from the resistive network connected as in the configuration at the right top or connected to a single channel spectrum analyzer (SSA) as in the configuration at the right bottom . The noise produced by R_3 can only be sorted out by using CSA after a measuring time of $T_m \approx 4$ hours.

Curve A is the result of the measurement: as expected, the obtained spectrum represents the thermal noise white spectrum produced only by R_3. Similar spectrum could have not been done by a traditional spectrum analyzer, which would have processed the total noise current available at the instrument input node, as shown in curve B of Fig.3. The curve shows a white noise component given by $4kT/(R_1||R_3||R_{F1})$ and a 1/f noise component due to the current flowing through R_1 and R_{F1}. Note that 1/f noise component is not present in curve A because the resistance R_3 has zero Volt across it.

3. AFM MOUNTING FOR NANOSCALE MEASUREMENT

Electrical noise is expected to gain importance in nanometer scale electronic devices, where atomic and defects fluctuations can dominate the average current flow [18-20]. Performing noise spectroscopy with nanoscale spatial resolution is therefore of fundamental importance. A powerful technique to do it consists in adapting an atomic force microscope (AFM) [21] to probe the electrical noise of the sample. AFM is well-established technique for nanoscale surface imaging, based on the force interaction between the sample and a flexible cantilever with a nanometric tip. Modified AFMs that are capable to obtain simultaneous images of surface topography and nanoscale electrical properties are commercially available. Despite of that, nanoscale electrical noise measurements by means of AFM have been largely neglected up to now, mainly due to the requirement of highly sensitive instrumentation.

By connecting two current amplifiers to a commercial AFM in a CSA configuration, noise measurement using AFM can be address. While maintaining in contact the AFM with the sample surface, the current fluctuations of the sample can be probed, thus performing extremely sensitive noise measurement with nanometer spatial resolution.

To demonstrate the viability of this method, noise measurements were performed with a commercial AFM (Nanotec Electrónica S.L.) operated in contact mode with a conductive probe acting like an electrode scanning over the surface (Figure 5). The sample under test has been mounted on conductive substrate, which works as the second electrode. A complete custom-made electronics has been employed and connected in a correlation spectrum analyser (CSA), as already described above. This setup requires two identical channels of measurement, one connected to the AFM probe and the other to the sample substrate. The outputs of the two amplifiers are sampled by the high-speedacquisition board (National Instrument 10MS/s 12bit ADC) and processed by a fully custom-developed software.
Since in this configuration an external voltage source cannot be directly connected to the sample to apply a DC bias across the sample, the wide-bandwidth current amplifier has been designed with an internal circuitry able to change a DC voltage of the input node (normally at ground level). Indeed, the voltage level of the amplifier power supplies is opportunely partitioned by an internal trimmer network. Therefore, DC bias can be monitored by an external voltmeter (connected to the V_{bias} output) and manually set at the desired level by simply changing the trimmer value of the two amplifiers.

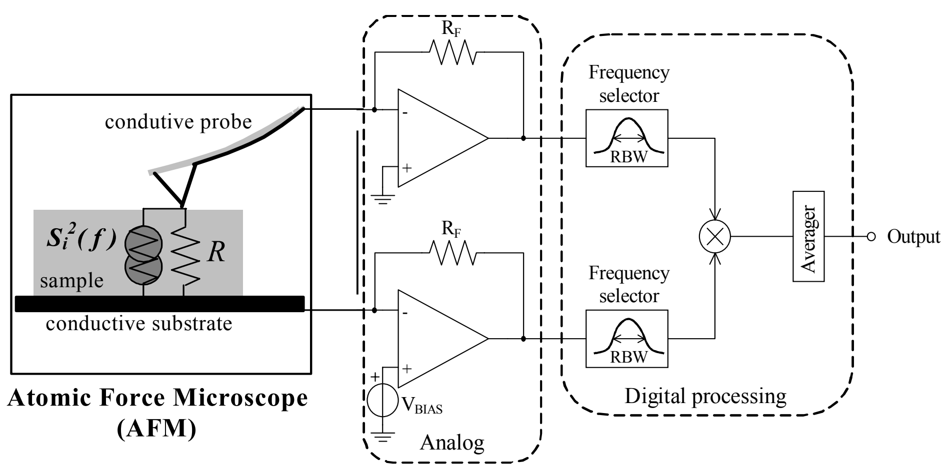

Figure 5 Diagram of the experimental set-up for nanoscale noise spectroscopy. The atomic force microscope (AFM) is connected to two wide-bandwidth current-to-voltage amplifiers in a correlation spectrum analyzer scheme to perform high sensitivity noise spectroscopy measurement.

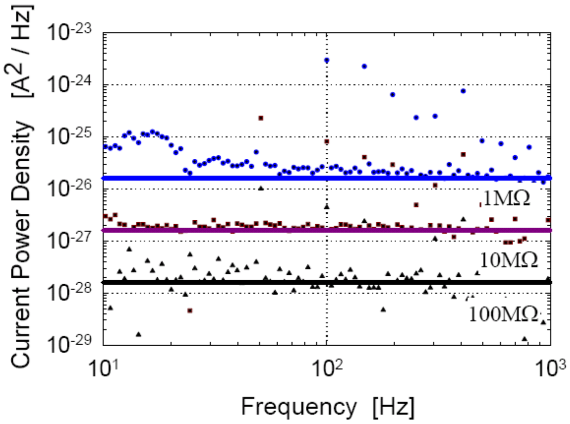

Fig. 6. Noise spectroscopy using AFM of discrete resistor of well-known value (1MΩ, 10MΩ, 100MΩ) connected in series of a gold substrate. Solid lines indicate the corresponding theoretical level of Nyquist noise, showing excellent agreement with measured data.

Proof-of-principle measurements were performed using the developed set-up. Discrete resistors of well-known value, namely 1MΩ, 10MΩ and 100MΩ, were connected in series of a gold substrate. The obtained noise spectra are given in figure 6. The figure shows that the current power density level measured by the instrument and the corresponding theoretical level (solid lines) of Nyquist noise using the expression 4kT/R, as explained above. Measurements and theoretical data are in good agreement in the spectral range from around 10Hz up to 1kHz. At higher frequency range, the increase of correlated instrumental noise prevents the measurement of thermal noise.

We remark that the major difficulty of performing noise measurement using current-sensing AFM resides in the high-level electromagnetic pick-ups. In conventional noise measurement, external interference can be properly screened by shielding the whole setup, composed by the device under test and the cables. In the case of AFM, the major source of external interference is the AFM controller itself. AFM control signals are directly picked up at the electrical connection between the nanoscale system of the microscope and spectrum analyzer instrumentation. Therefore, although the AFM and the cables are carefully shielded, some pick-ups cannot be suppressed.

Furthermore, we notice that noise measurements are extremely sensitive to the tip/surface contact. A discontinuous electrical contact determines current fluctuations which completely change the noise spectrum. A stable electrical contact has to be maintained during the whole time required by noise spectroscopy (that can be a few minutes long in the case of low-frequency measurements).To this aim, the use of diamond-coated tips is fundamental (2.8N/m, CDT-FMR Nanosensors™).

4. CONCLUSIONS

The Correlation Spectrum Analyzer scheme has proved to be effective in measuring noise spectra with very high sensitivity and in a various DUT conditions. Its application to an AFM instrument opens the field of electronic fluctuation measurements at the nanoscale of large interest in the scientific community.

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