Thermal noise and spectral measurements

Propiedades electrónicas, magnéticas y de transporte en sistemas de baja dimensionalidad y nanoestructuras *Máster de física de la materia condensada y nanotecnología, UAM*

"The noise is the signal" (*Rolf Landauer*). In this experiment, we are going to measure the thermal noise of a resistance, using the setup that will be described in the next section.

In general, noise can be described as spontaneous fluctuations in a physical system. When noise is measured (tipically as voltage fluctuations), there are two possible options: first, removing it to obtain a cleaner signal of what we want to measure or, second, trying to get some useful information out of it.

Noise can be due to many different factors, even when measured on the same sample, and it is best best studied in the frequency domain. If we take a discrete sample of points of a time series, its Fourier transform divided by the step in frequency Δf is called the power spectral density or PSD, and it has units of V^2/Hz. Depending on the cause of the noise, the dependence of the PSD with frequency varies. Thermal noise (caused by the thermal agitation of the carriers) or shot noise (due to the discreteness of electric charge in electric current carriers) present a frequency indepedent or *white* spectrum. Other types of noise, such as 1/f noise or random telegraph noise present frequency dependent spectra.

A nice chapter describing different types of noise can be found in our former group member's thesis.

We are going to use a system that allows us to extract information about the thermal noise present in every electrical device due to fluctuations induced by the thermal motion of electrons inside the devices.

1 Experimental set-up

To carry out the experimental measurements of thermal noise we will use a Stanford Research spectrum analyzer (you can find the manual here). This device gives us the Fourier Transforms of the input signals. These input signals are voltage signals that fluctuate in time. Therefore, the spectrum analyzer will give us the distribution of the signal power as a function of the thermal fluctuations frequency.

Figure 1 shows a sketch of the experimental set-up, where G_{HM} and G_C is the gain in voltage of the home made and commercial amplifier respectively. Noise fluctuations are small, so it is necessary to amplify the measured signals. The system uses two stages of amplification: (1) a home-made pre-amplifier and (2) a SR560 commercial amplifier (manual) that allows us to set a very correct value of voltage gain. The home made amplifiers consists of an operational amplifier and a potentiometer that controls the gain, by switching among four values of resistance. The home made amplifier gives us four different gains: 1, 5, 20 and 51.

The system should carry the signal from the resistance, through the pre-amplifier, to the commercial

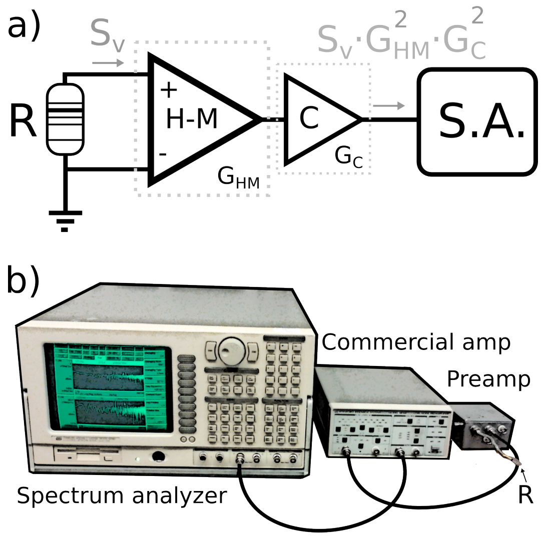

Figure 1: *(a) Wiring diagram (b) Photo of setup*

amplifier and into the spectrum analyzer.

1.1 Activity 1

Set up the system. Follow the wiring diagram and connect everything in its place.

2 Thermal noise

Thermal noise was discovered in 1928 by J.B. Johnson in the Bell Labs, and it is a kind of stationary noise that exists even in systems at equilibrium. Its physical explanation is the random movement of electrical charge carriers (in this case, electrons) due to thermal agitation. Using classical physics arguments and statistics, Nyquist showed that the RMS noise voltage across any resistance R is:

$$S_v = 4k_B TR \tag{1}$$

Here, k_B is Boltzmann's constant, T is the temperature (in K) and R the value of the electrical resistance (in Ω) of the device under study.

The thermal noise of each resistor will be obtained by calculating the mean value of the flat spectra, an example of which is shown in Figure 2.

Since we have amplified the signal twice, and the power spectral density presents power, the real value of the noise is:

$$S_V = S_V^{measured}/(G_{HM} \cdot G_C)^2 \tag{2}$$

Very narrow peaks at 50 Hz and its harmonics will be seen in the spectra, due to the alternating current from the mains, and they can be deleted from the curves. Also, the resistors will present some

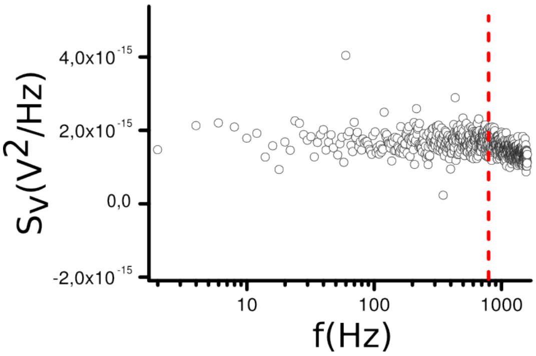

Figure 2: *Typical thermal noise spectrum of a resistor*

filtering of the signal, which will appear as a dip of the spectrum at high frequencies. Only the flat part of the spectrum should be taken into account.

2.1 Activity 2

Obtain an estimation of k_B by measuring the thermal noise of several resistors. By defining $x = T \cdot R$, k_B will be obtained (with its tolerance) by the linear fit $S_V = A \cdot x$. A thermometer will give us the value of the temperature when each resistor is measured. Each resistor will be characterized with a multi-meter.

2.2 Activity 3

Determine the different gain values of an uncalibrated amplifier. These home made amplifiers consist of operational amplifiers, and a four-way switch that controls the gain by choosing among four values of resistance. One of the positions of the switch corresponds to zero resistance, so then $G = 1$. To calibrate the amplifier, we are going to measure the thermal noise of a known resistor for all the positions of the switch and use the $G = 1$ spectrum as a reference. The measured PSD after the amplification stages will be:

$$S_v = 4k_B TR(G_{HM}^2)(G_C^2) \tag{3}$$

from where G_{HM} can be estimated.

References

[1] D. Herranz. *Electron transport and noise in magnetic tunnel junctions with MgO barriers.* PhD thesis, Universidad Autónoma de Madrid, March 2012.