1/f-Noise BJT Measurements using a Low Noise Current Amplifier

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1 Introduction

This report deals with methods for bjt low frequency noise measurement and 1/f-parameter extraction .

2 Noise Term Definitions

It seems to be useful to explain and define in a first step some terms of noise quantities, e.g. “noise spectra”, because they are often not wellknown, sometimes unequal used and therefore misunderstood. As an example we will use the equation for the thermal noise resistance voltage:

$$\overline{v_{NR}^{\ 2}} = 4kT\Delta f * R \tag{2-1}$$

with

$\overline{v_{NR}^{\ 2}}$ = Noise voltage mean square value
k = Boltzmann constant (k=1.38 *10^{-23} Ws/K)
T = Absolute temperature
Δf = Bandwidth
R = Resistance value

The product (4kTΔf) in Eq. (2-1) is a power, its dimension is V*A. Normalising this power to the bandwidth Δf would obviously give a power density, i.e. 4kT. Normalising Eq.(2-1) to the bandwidth Δf (usually Δf=1Hz), however, gives:

$$\frac{\overline{v_{NR}^{\ 2}}}{\Delta f} = 4kT * R \tag{2-2}$$

Plotting this quantity vs. frequency gives a spectra. This spectra is often called the “power noise spectral density”. However, the word “power” in this term is mathematically not exact, because normalising the power (4kTΔf) to Δf gives(4kT), not (4kT)*R . So, the more appropriate term is “voltage noise spectral density”. Its most often used symbol is S_{NV} or S_V and its dimension is [V^2/Hz].

$$S_V = \frac{\overline{v_{NR}^{\ 2}}}{\Delta f} \tag{2-3}$$

Sometimes the square root of S_V is used as the noise quantity characterising a device. It is called the equivalent noise voltage, using the symbol E_N , and its dimension is [$V/\sqrt{Hz}$] or [V/rtHz]:

$$E_N = \sqrt{\frac{\overline{v_{NR}^{\ 2}}}{\Delta f}} \tag{2-4}$$

The same principles are valid for the thermal noise current of the resistor, considered in this example:

$$\overline{i_{NR}}^{2} = \frac{4kT\Delta f}{R} \qquad (2\text{-}5)$$

with

$\overline{i_{NR}}^{2}$ = effective noise current value (mean square value)

The " current noise spectral density " S_{NI} or S_I [in terms of A^2/ Hz] is given by:

$$S_I = \frac{\overline{i_{NR}}^{2}}{\Delta f} \qquad (2\text{-}6)$$

The equivalent noise current E_I is given by [$A/\sqrt{Hz}$] or [A/rtHz]:

$$E_I = \sqrt{\frac{\overline{i_{NR}}^{2}}{\Delta f}} \qquad (2\text{-}7)$$

3 1/f-Measurement Methods

3.1 1/f- Noise Voltage Measurement

1/f-noise measurements on bipolar transistors are usually realised as a measurement of the noise voltage appearing at the collector of the transistor [1][2] [4]. A very descriptive explanation of this method including practical hints is given by Sinnesbichler [3], whereon this section is based on. The used circuit for the measurements is shown in Fig 2 .

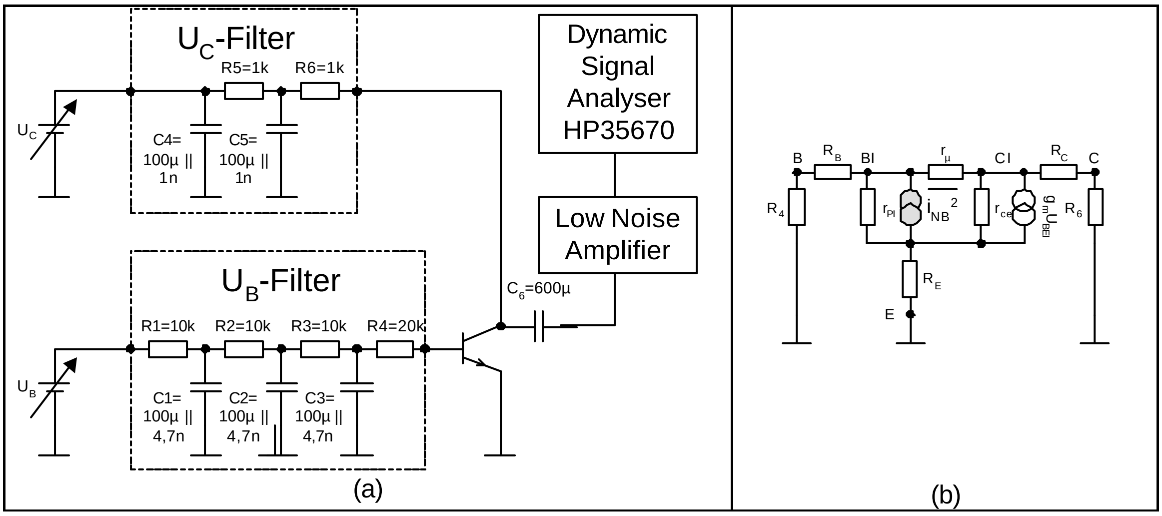

Fig 1: 1/f-noise voltage measurement circuit (a) and simplified bjt noise equivalent circuit, illustrating the effect of R4 and R6 (b)

The noise voltage at the collector is measured using an LNA and an Dynamic Signal Analyser, realising the Fast Fourier Transformation (FFT). The following principles are realised for that circuit:

- Both the bias voltages for base and collector are filtered by a low pass to suppress the noise of the voltage sources
- Resistance R4 is used to avoid a short for the noise voltage created by the noise current generator $\overline{i_{NB}}^{2}$ parallel to the input resistance r_π of the bjt (Fig 1(b)). A reasonable value for R4

is in the range of 20k to 100k. R4 should be a metal film resistor, because this resistor type does not exhibit 1/f-noise.

- The voltage drop vs. R1 ... R4 has to be taken into account to adjust the desired base current; that is why a DC-measurement of a gummel plot is necessary before the noise measurement, to get the V_{BE} - I_B relation of the DUT.
- The same principle is used to avoid a short of the noise voltage at the collector using R6. R6 should be substantially higher than the input resistance of the LNA (R_{ILNA} = 50 Ohms).
- The couple capacitor C6 creates a high pass in conjunction with R_{ILNA} . Its corner frequency should be low enough to avoid an attenuation of the low frequency 1/f-noise signal (f_C < 10 Hz)

To extract the low noise bjt parameters KF and AF, a relation between the measured collector noise voltage and the base noise current is necessary. This equation is given by [3]:

$$\overline{i_{NB}^{\,2}} = \frac{1}{\left[b_{DC}(I_B)\right]^2} \cdot \frac{\overline{v_{NC}^{\,2}}}{R_L^{\,2}} \tag{3-1}$$

with
R_L = load resistance, given by the input resistance of the LNA
$\beta_{DC}(I_B)$= DC gain

This equation is based on the following assumptions:

- $r_o >> R_L$ (r_o = transistor output resistance, $R_L = R_{ILNA}$ = 50 Ohms)
- $\beta_{AC} \approx \beta_{DC}$ (given for low frequencies)
- $R_4 >> r_\pi$ (note: may be critical for low bias, because $r_\pi = V_T / I_B$)

3.2 1/f – Noise Current Measurement

Fig 2 shows the measurement circuit we used for our 1/f-measurements[1].

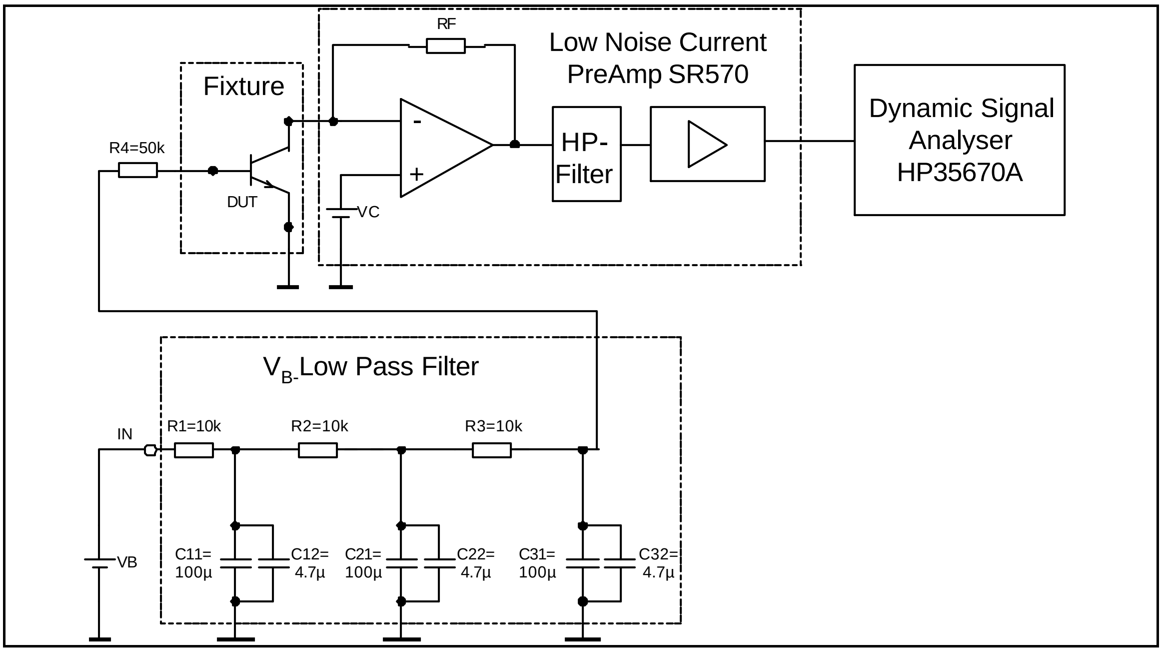

Fig 2: 1/f-noise current measurement circuit

The main topics describing the circuit are:

- A low noise current amplifier (LNCA) is used for detecting the collector noise current instead of a voltage LNA.

[1] The measurements are made using a mounted test transistor, investigations of on wafer measurements using RF-probes ar ongoing.

- The LNCA is an transimpedance amplifier; the noise current at the input is amplified and converted to an output noise voltage. Note, that the gain of the LNCA SR570 is (unusual) defined by the ratio of input current to output voltage in terms of a conductance: $g_{LNCA} = I_{IN} / V_{OUT}$.
- The gain of the LNCA has to be set on a value nearly to the output resistance of the DUT to get the best sensitivity , that is why a DC-measurement of an output characteristic $I_C(V_B)$ is necessary to get the g_o vs. I_C relation of the DUT
- The main advantage of such an arrangement over the usual circuit in Fig 1(a) is the necessity of only one low pass filter for V_B , because the V_C–bias is supplied by the LNCA
- Again, the voltage drop vs. R1 ... R4 has to be taken into account to adjust the desired base current; a measurement the gummel plot gives the required V_{BE} - I_B relation of the DUT

The Dynamic Signal Analyser HP35670 may deliver as output quantity an equivalent output noise voltage E_{VO} [2]

$$E_{VO} = \sqrt{\frac{\overline{v_{NO}^{\ 2}}}{\Delta f}} \tag{3-2}$$

as well as an output voltage noise spectral density S_{VO}:

$$S_{VO} = \frac{\overline{v_{NO}^{\ 2}}}{\Delta f} \tag{3-3}$$

Using the known amplifier gain g_{LNCA} used for the measurement, the collector current noise spectral density S_{IC} is given by:

$$S_{IC} = g_{LNCA}^{\ 2} \cdot S_{VO} \tag{3-4}$$

For $r_o >> R_{ILNCA}$ we have the relation between the collector and the base noise current spectral density as:

$$S_{IB} = \frac{S_{IC}}{g_m^{\ 2}\left(r_\Pi \parallel \left(R_4 + R_B\right)\right)^2} \tag{3-5}$$

with
R_B =base resistance
g_m = bjt transconductance

This equation may be simplified further if $R_4 >> R_B$ and $R_4 >> r_\pi$:

$$S_{IB} = \frac{S_{IC}}{g_m^{\ 2} r_\Pi^{\ 2}} \tag{3-6}$$

[2] Note: Use the HP35670 ICCAP-instrument option table for set the unit (e.g. CH1 Units = V/RTHz)

4 KF and AF Parameter Extraction

The following method is based on [5][2]. Using the definition of the 1/f base noise current

$$\overline{i_{NB}^{\ 2}} = KF \cdot \frac{I_B^{\ AF}}{f} \Delta f \qquad (4\text{-}1)$$

we have the base current noise spectral density as

$$S_{IB} = KF \cdot \frac{I_B^{\ AF}}{f} \qquad (4\text{-}2)$$

On the other hand S_{IB} is calculated according to equ.**(3-6)** based on the measurements. S_{IB} shows a 1/f-dependence vs. frequency. For the extraction of the model parameters KF and AF, describing the dependence of the 1/f-noise on the base current, however, we need a frequency independent noise quantity vs. base current. Such a quantity is the S_{IB}*f product. Because the measured S_{IB} –values are noisy, we use in practice the mean of S_{IB}*f :

$$\overline{S_{IB} \cdot f} = KF \cdot I_B^{\ AF} \qquad (4\text{-}3)$$

This quantity is furthermore called S_{IB1Hz} , because calculating the product means normalizing S_{IB} to 1Hz. Logarithm gives now:

$$\log_{10} S_{IB1Hz} = AF \log(I_B) + \log(KF) \qquad (4\text{-}4)$$

This is a linear equation y = f(log I_B). So, using S_{IB1Hz} for different I_B –values gives a linear characteristic, which is usable for KF and AF extraction: the x_o–value n gives KF and the increase m gives AF:

$$KF = 10^n \qquad (4\text{-}5)$$

$$AF = m \qquad (4\text{-}6)$$

5 Simulations

The simulations are made using SPICE3 in the ICCAP-environment. Fig 3 shows the simulation circuit. The source VAC is a dummy, only necessary for noise simulations using SPICE. Different to the measurement setup, the base bias VB is connected using L1 to avoid the voltage drop on R1 to R4. A current controlled voltage source H1 is used to create the output noise voltage on Rout.

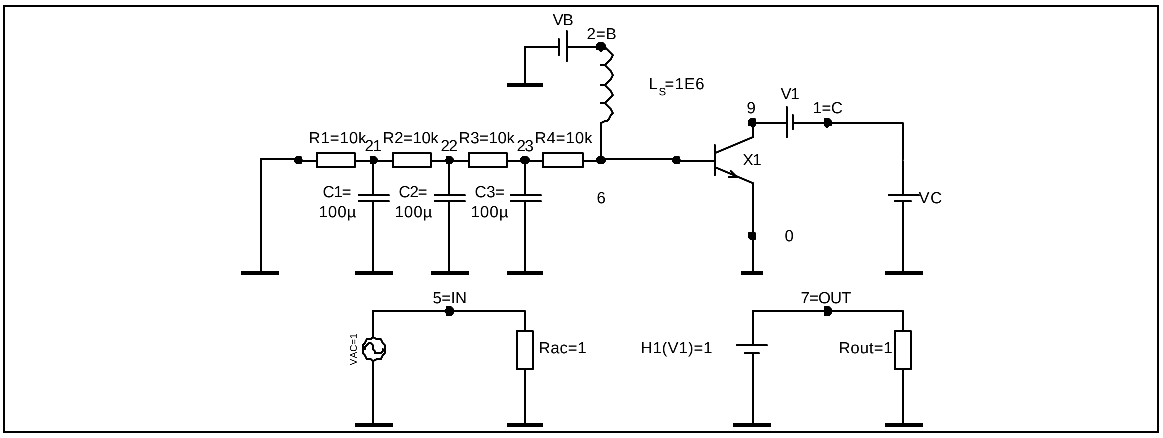

Fig 3: 1/f-SPICE-simulation circuit

6 Results

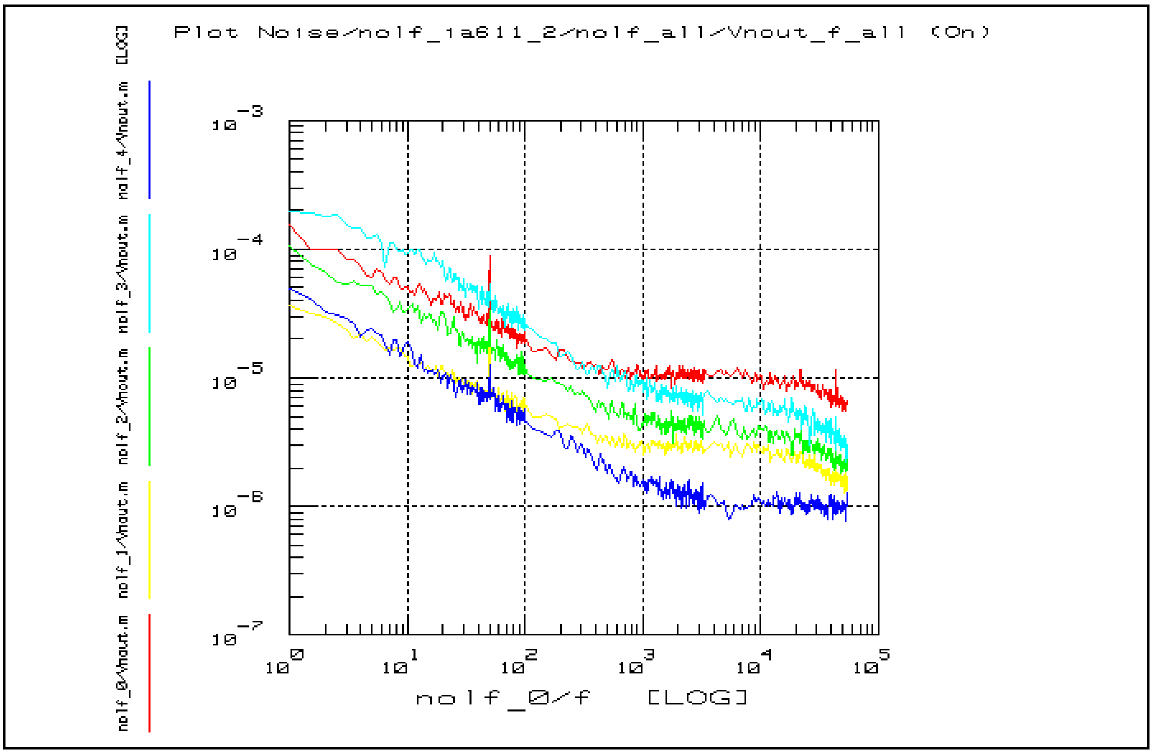

Fig 4: Equivalent output noise voltage E_{VO} [of A/ rtHz], V_B = 0.65 ... 0.75 V, V_C = 2.5V

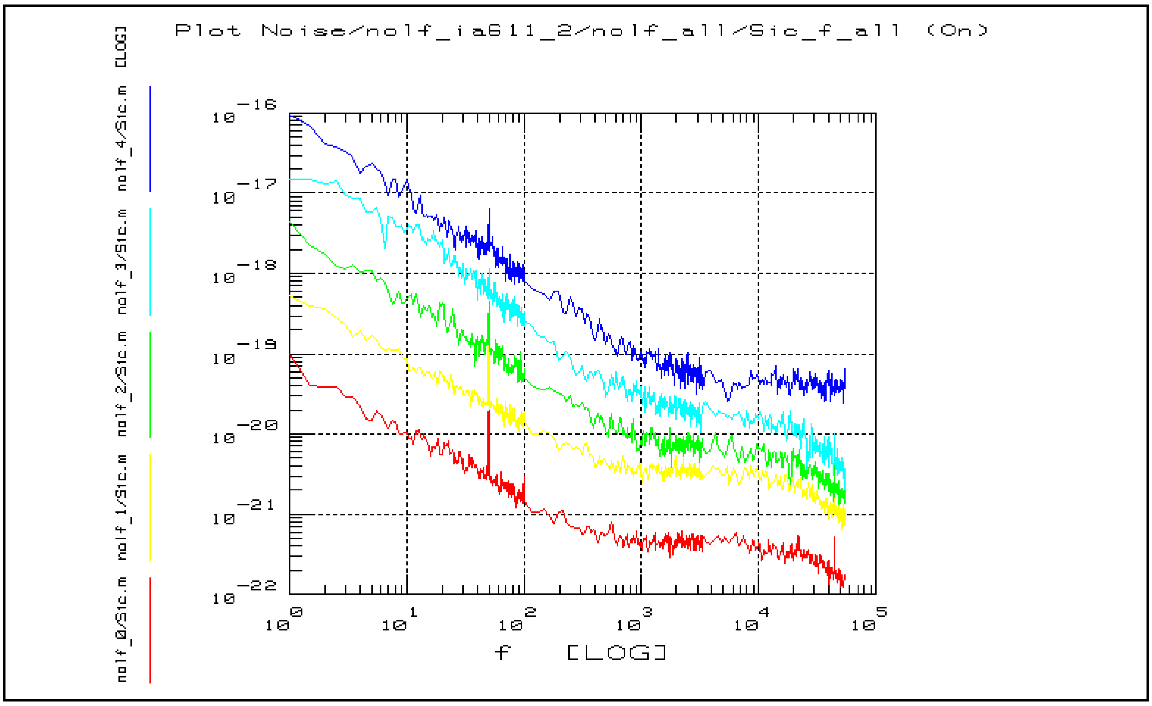

Fig 5: Collector current noise spectral density S_{IC}, V_B = 0.65 ... 0.75 V, V_C = 2.5V

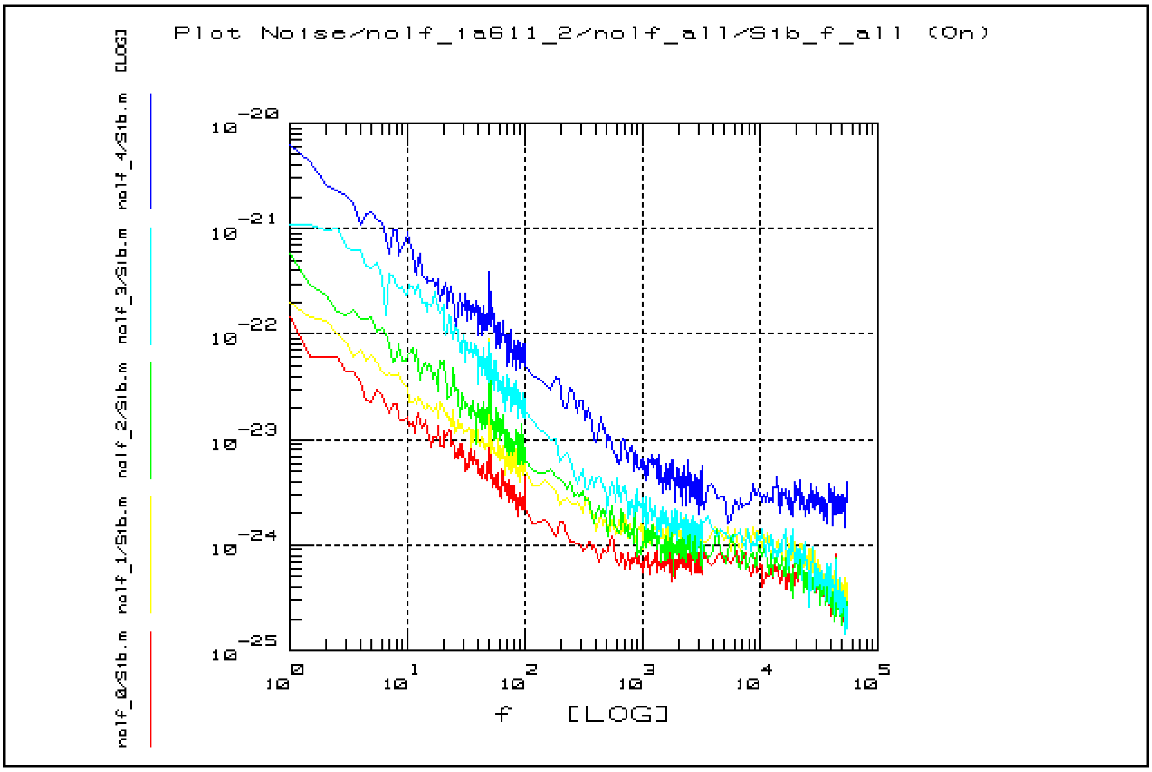

Fig 6: Base current noise spectral density S_{IB}, V_B = 0.65 ... 0.75 V, V_C = 2.5V

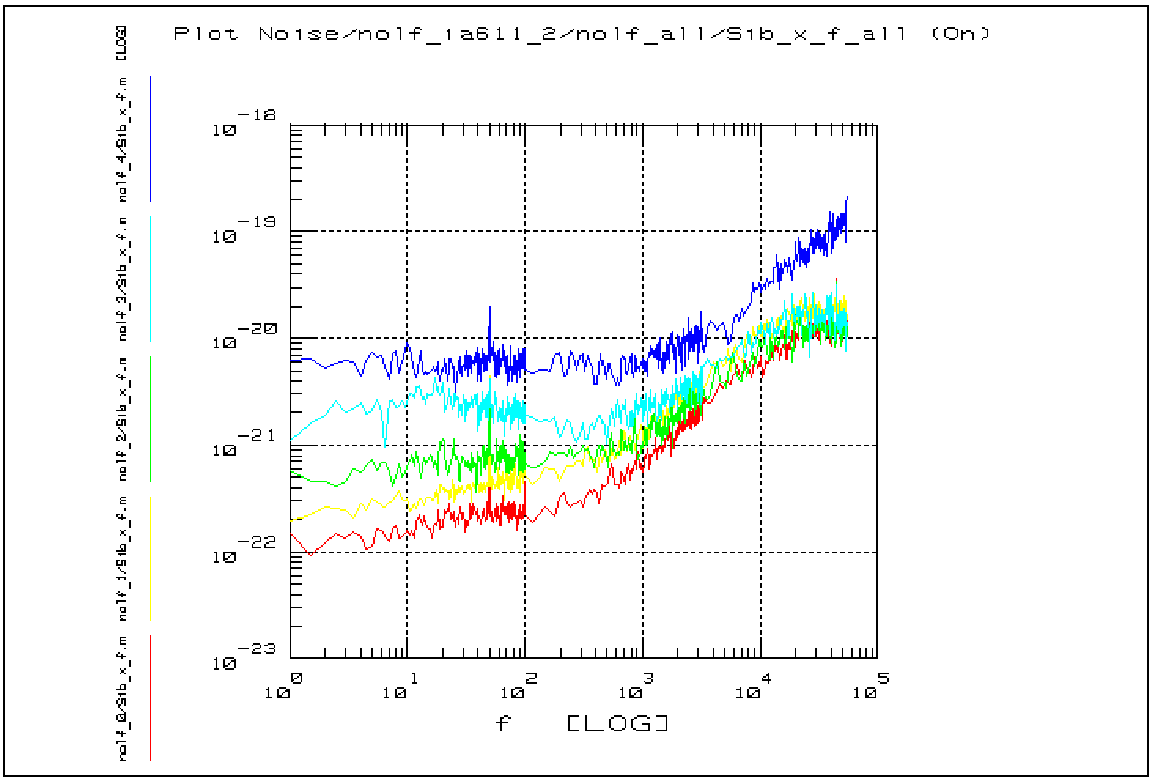

Fig 7: $S_{IB\ 1Hz} = S_{IB}*f$, $V_B = 0.65 \ldots 0.75$ V, $V_C = 2.5V$

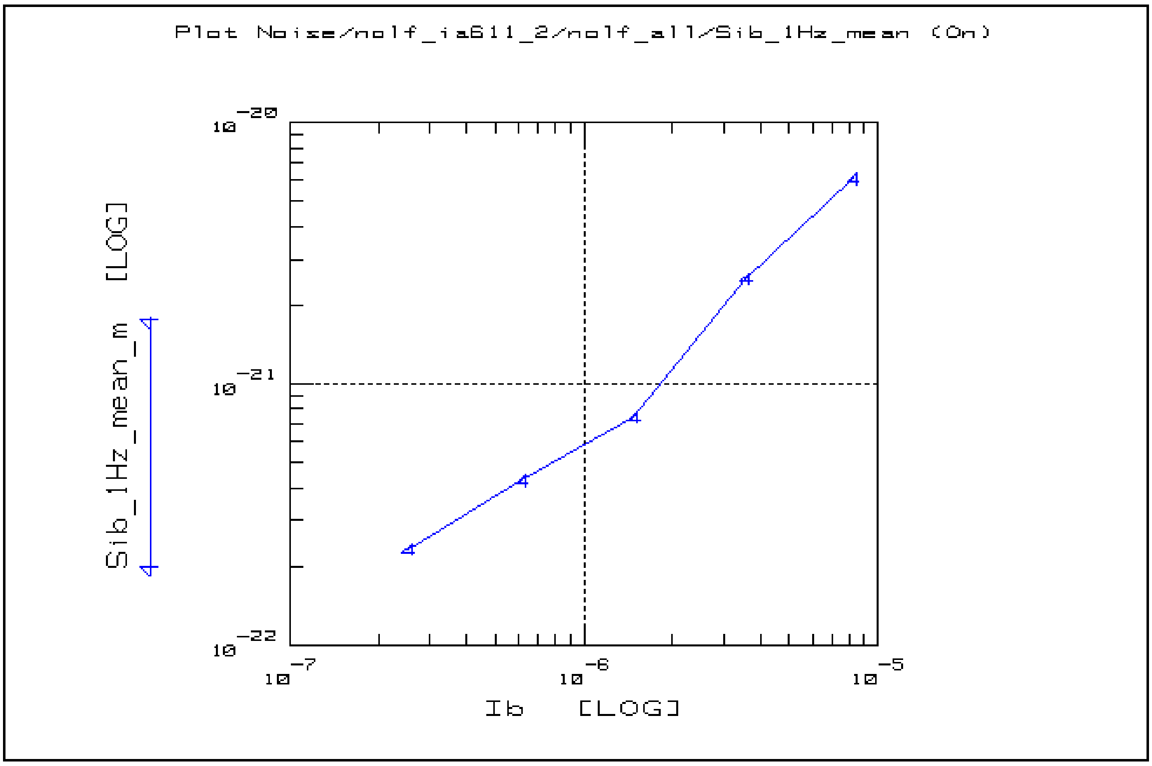

Fig 8: $S_{IB\ 1Hz}$ **mean value,** $V_B = 0.65 \ldots 0.75$ V, $V_C = 2.5V$

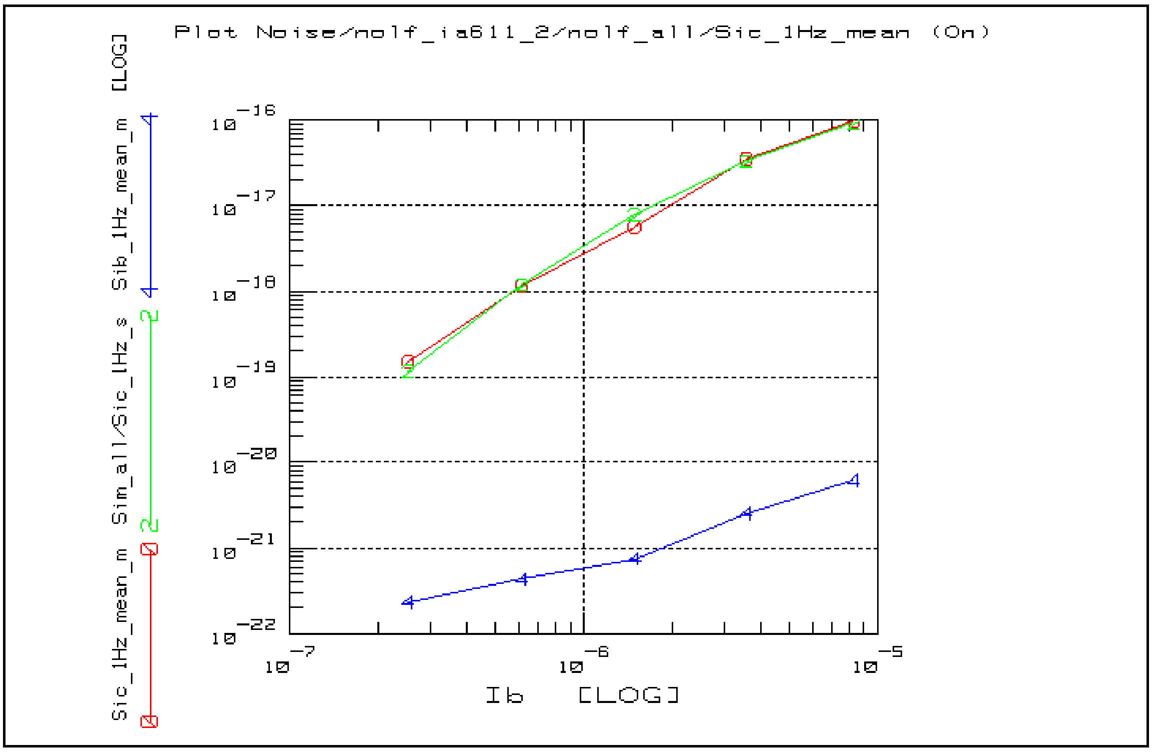

Fig 9: Comparison of simulation and measurement: $S_{IC\ 1Hz\ SIM}$ = green, $S_{IC\ 1Hz\ MEAS}$ = red, $S_{IB\ 1Hz\ MEAS}$ = blue, Simulation using KF=1.5E-15, AF=1

7 Summary

A measurement technique for 1/f-noise measurements using a low noise current amplifier (LNCA) was presented. The measurement circuit was compared to the usual noise voltage measurement circuit. The extraction of the noise parameters KF and AF was demonstrated.

8 Acknowledgements

The authors would like to thank Mr. F.Sischka, Agilent Technologies, for useful discussions regarding bjt noise measurement principles and the support during ICCAP model file development.

9 Literature

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