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:

\[ v_{NR}^2 = 4kT\Delta f \times R \]  \hspace{1cm} (2-1)

with

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

The product \((4kT\Delta f)\) in Eq. (2-1) is a power, its dimension is \(V^2\text{A}\). Normalising this power to the bandwidth \(\Delta f\) would obviously give a power density, i.e. \(4kT\). Normalising Eq. (2-1) to the bandwidth \(\Delta f\) (usually \(\Delta f=1\text{Hz}\)), however, gives:

\[ \frac{v_{NR}^2}{\Delta f} = 4kT \times R \]  \hspace{1cm} (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 \((4kT\Delta f)\) to \(\Delta f\) gives\((4kT)\), not \((4kT)\times R\). So, the more appropriate term is “voltage noise spectral density”. Its most often used symbol is \(S_V\) or \(S_V\) and its dimension is \([V^2/\text{Hz}]\).

\[ S_V = \frac{v_{NR}^2}{\Delta f} \]  \hspace{1cm} (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 \([V/\sqrt{\text{Hz}}]\) or \([V/\text{rtHz}]\):

\[ E_N = \sqrt{\frac{v_{NR}^2}{\Delta f}} \]  \hspace{1cm} (2-4)

The same principles are valid for the thermal noise current of the resistor, considered in this example:
\[ i_{NR}^2 = \frac{4kT\Delta f}{R} \]  
\[ (2-5) \]

with

\[ i_{NR}^2 \] = 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:

\[ S_I = \frac{i_{NR}^2}{\Delta f} \]  
\[ (2-6) \]

The equivalent noise current \( E_i \) is given by \( [A/\sqrt{Hz}] \) or \( [A/rtHz] \):

\[ E_I = \sqrt{\frac{i_{NR}^2}{\Delta f}} \]  
\[ (2-7) \]

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.

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 \( i_{NB}^2 \) parallel to the input resistance \( r_i \) of the bjt (Fig 1(b)). A reasonable value for R4

Fig 1: 1/f-noise voltage measurement circuit (a) and simplified bjt noise equivalent circuit, illustrating the effect of R4 and R6 (b)
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 $K_0$ and $A_0$, a relation between the measured collector
noise voltage and the base noise current is necessary. This equation is given by [3]:

$$\bar{i}_{NB}^2 = \frac{1}{[\beta_{DC}(I_B)]^2} \cdot \frac{V_{NC}^2}{R_L^2}$$

(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)
- $R_i > r_e$ (note: may be critical for low bias, because $r_e = V_T / I_B$)

### 3.2 1/f – Noise Current Measurement

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

![Measurement Circuit Diagram](image)

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 are ongoing.
The LNCA is a 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: $g_{\text{LNCA}} = \frac{i_{\text{IN}}}{V_{\text{OUT}}}$. 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 input quantity an equivalent output noise voltage $E_{VO}$

$$E_{VO} = \sqrt{\frac{v_{NO}^2}{\Delta f}}$$

(3-2)

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

$$S_{VO} = \frac{v_{NO}^2}{\Delta f}$$

(3-3)

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

$$S_{IC} = g_{\text{ LNCA}}^2 \cdot S_{VO}$$

(3-4)

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

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

(3-5)

with

$R_b =$ base resistance

$g_m =$ bjt transconductance

This equation may be simplified further if $R_i \gg R_b$ and $R_i \gg r_\pi$:

$$S_{IB} = \frac{S_{IC}}{g_m^2 r_{\Pi}^2}$$

(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

\[
\frac{i_{NB}}{\Delta f} = KF \cdot \frac{I_B^{AF}}{f} \tag{4-1}
\]

we have the base current noise spectral density as

\[
S_{IB} = KF \cdot \frac{I_B^{AF}}{f} \tag{4-2}
\]

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 \(S_{IB}^\ast f\) product. Because the measured \(S_{IB}\)–values are noisy, we use in practice the mean of \(S_{IB}^\ast f\):

\[
\frac{S_{IB}^\ast f}{f} = KF \cdot \frac{I_B^{AF}}{f} \tag{4-3}
\]

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

\[
\log_{10} S_{IB1Hz} = AF \log(I_B) + \log(KF) \tag{4-4}
\]

This is a linear equation \(y = f(x)\). 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:

\[
KF = 10^n \tag{4-5}
\]

\[
AF = m \tag{4-6}
\]
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.

![Simulation Circuit](image)

Fig 3: 1/f-SPICE-simulation circuit

6 Results

![Result Graph](image)

Fig 4: Equivalent output noise voltage $E_{\text{vo}}$ [of $A/\text{rHz}$], $V_B = 0.65 \ldots 0.75 \text{ V}$, $V_C = 2.5\text{V}$
Fig 5: Collector current noise spectral density $S_{IC}$, $V_B = 0.65 \ldots 0.75 \text{ V}, V_C = 2.5\text{ V}$

Fig 6: Base current noise spectral density $S_{IB}$, $V_B = 0.65 \ldots 0.75 \text{ V}, V_C = 2.5\text{ V}$
Fig 7: $S_{in, \text{III}} = S_{in} \cdot f$, $V_B = 0.65 \ldots 0.75$ V, $V_C = 2.5$V

Fig 8: $S_{in, \text{III}}$, mean value, $V_B = 0.65 \ldots 0.75$ V, $V_C = 2.5$V
Fig 9: Comparison of simulation and measurement: $S_{IC\text{ 1Hz \text{SIM}}}$ = green, $S_{IC\text{ 1Hz \text{MEAS}}}$ = red, $S_{IB\text{ 1Hz \text{MEAS}}}$ = 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

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9 Literature


