ISSN 1392-9631 ELEKTRONIKA IR ELEKTROTECHNIKA. 2005. Nr. 4(60)

T 171 MIKROELEKTRONIKA

Bipolar Junction Transistor 1/*f* Noise Simulation and Parameter Extraction Technique

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Introduction

Even in advanced semiconductor technology 1/f noise level still is a problem in several applications as direct conversion receivers and other. Parameters of 1/f noise could not be theoretically predicted and must be obtained from the measurement.

Different configurations of noise measurement circuits (MC) are used in practice and all of them have their advantages and weak points in application. Common for all MC is that they contribute with their own noise sources making it difficult to distinguish wanted noise source from the device under test (DUT). Measured total noise contains not only pure noise from the device under the test but also contribution from other noise sources in the measurement circuit such as bias circuits, load resistance and other.

There are several noise sources in the DUT itself and it is desirable to discriminate them from each other during measurement and/or data processing. One we would like to determine we will call “target noise source”.

In this paper error sources in determination of noise parameters from measurement data are discussed. Different bipolar junction transistor noise measurement circuits are analysed using simulation technique to determine the most favourable circuit configuration and bias conditions. Some specific cases and problems related to noise parameter extraction are discussed.

Error sources in noise measurement and processing

There are several sources of error in noise measurement and they could be classified in following groups:

- Processing errors of FFT - caused by relatively shorter averaging time interval at lower frequencies.
- Errors in determination of power spectral density (PSD) of each particular noise source - caused by approximate or even unknown gain factors of target and known noise sources and by contribution of unknown noise sources in measurement circuit [1].
- Errors in estimating of flicker noise parameters from calculated S(*f*,*I*).

To estimate the second of mentioned errors following equation is used [1]:

$$\frac{S_{TI}-S_T}{S_T}=\frac{K_{TR}^2-K_{TI}^2}{K_{TI}^2}+ +\sum\frac{S_K}{S_T}\cdot\frac{K_{KR}^2-K_{KI}^2}{K_{TI}^2}+\sum\frac{S_U\,K_{UR}^2}{S_T\,K_{TI}^2}, \quad (1)$$

where S_T - PSD of target noise source, f.e. base current noise of BJT; S_K - PSD of known noise source. This source we are able to measure separately or calculate with satisfactory accuracy; S_U - PSD of unknown noise source, which we are not able to determine; K_{TR}, K_{KR}, K_{UR} - true values of corresponding gain factors; K_{TI}, K_{KI}, K_{UI} - approximate values of corresponding gain factors.

The only way to estimate this error is by modeling in following steps.

1. Use possibly complete model and some set of parameters to simulate real DUT and measurement circuit, including all noise sources.
2. Choose some simplified model of DUT and MC to obtain gain factors for target and known noise sources.
3. Use calculation results from step 2 and simulated ″measurement results″ from step 1 to estimate discrimination opportunity for target noise source from other known noise sources.
4. Compare values of target noise source PSD obtained using model from step 1 with those calculated in step 3.

In case of BJT as a full model for step 1 we can use SPICE model (Fig.1). Simplified models contain current gain factor, bulk base resistance and output conductance. Even more simplified model may contain only current gain factor.

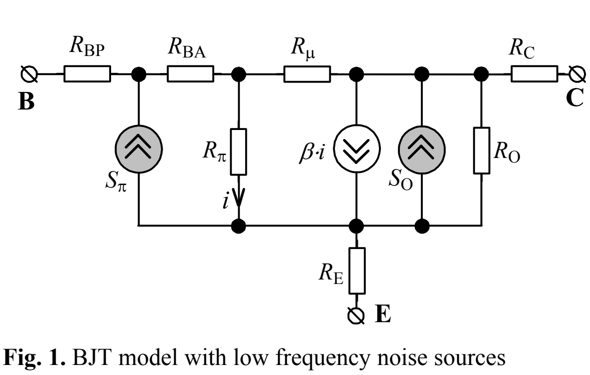

Fig. 1. BJT model with low frequency noise sources

We are using this technique for several purposes:

1. to compare various MC and to choose the most appropriate,
2. to choose the most appropriate measurement conditions to enhance target noise source contribution,
3. to evaluate methodical measurement data processing errors while extracting noise parameters of target source.

Measurement circuits and measurement conditions

Different low frequency noise measurement circuit configurations are used in practice, but some common features can be found in all cases. Measurement circuit consists of elements maintaining:

- appropriate bias conditions for DUT,
- low-noise current or voltage amplifier with feedback circuit and/or calibration opportunity,
- careful shielding and filtering ensured to avoid influence of external interference.

Noise measurement set-up's are ranging from simple ones used for obtaining experimental evidence in noise modeling [2] up to very sophisticated complex measurement systems from Agilent Technologies for industry applications containing $1/f$ noise measurement opportunity [3, 4].

In this paper we are concentrating on optimization of noise measurement circuit to minimize errors and improve measurement efficiency for Bipolar Junction Transistors (BJT). Special elements, bias conditions and circuit configuration could be chosen to ensure dominance of target noise source at the output of MC.

Let us review several measurement circuit configurations used in BJT noise measurement and their specific features. In more detail these measurement circuits are analysed elsewhere [1].

Measurement circuit without common feedback (Fig.2) is one of the simplest from widely used ones. Main advantage of this MC configuration is that there are no limitations in choice of signal source resistance R_G and load resistance R_L. Output noise level in this MC is dependant on parameters of DUT, on R_G and R_L values. Therefore, DC bias adjustment and calibration of the circuit must be provided for each measurement as any of mentioned factors is changing. The analysis leads to conclusion that this MC is not good for noise measurement of large number of transistors in variety of bias conditions.

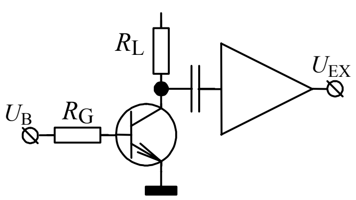

Fig. 2. Noise measurement circuit without common feedback

Measurement circuit with current to voltage converter-amplifier (Fig.3) is used for example in [6]. This MC configuration is good for current noise source measurement because the output noise signal directly represents current noise. Other transistor parameters have a negligible impact on the value of output signal.

At large collector current value of R_L may not be very large and output signal level in this MC will be comparably low. It is also quite difficult to maintain stability of DC bias in this MC.

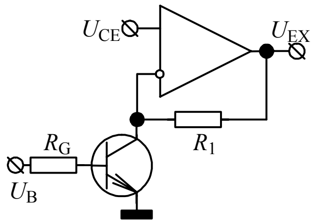

Fig. 3. Noise measurement circuit with current to voltage converter-amplifier

Measurement circuit with common feedback is presented in Fig.4. Output signal of this MC is proportional to input voltage or current (at large R_G values) noise source. Common feedback for DC provides stabilization of DC bias conditions even if parameters of DUT are changing. This circuit is the best choice for noise tests in fixed bias conditions in industrial applications.

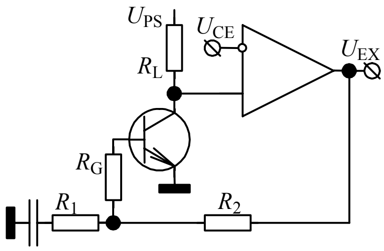

Fig. 4. Noise measurement circuit with common feedback

Simulation method can provide an interesting result for some particular cases. For example, in MC with current to voltage amplifier connected to the emitter (Fig.5) at certain I_C we can observe drastic decrease in contribution of base current noise source in output noise signal. This particular current value depends only on the value of base resistance R_B

$$I_C \approx \frac{\varphi_T}{R_B}. \tag{2}$$

Unfortunately there are serious limitations for the application of this MC in practice. For such MC we need very stable and low noise reference voltage source for U_{BE} as well as the ultra low noise amplifier.

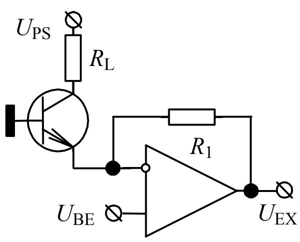

Fig. 5. Noise measurement circuit with common feedback

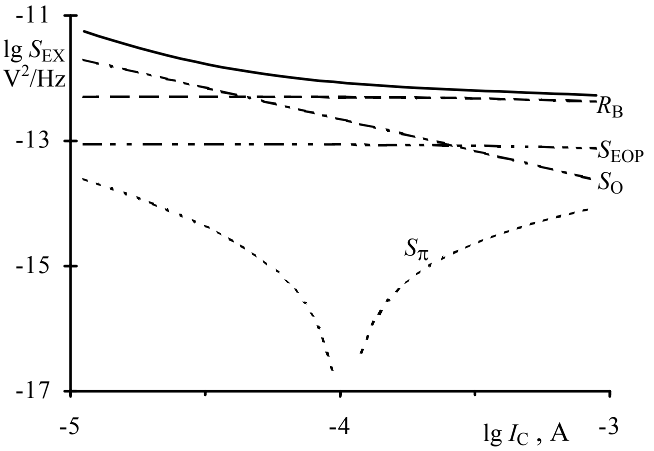

Fig. 6. Simulation result for output noise content as a function of collector current I_C at f=1 kHz for the circuit in Fig.5

Measurement data processing

In practice the processing of measurement data is an important stage in determining noise parameters. Simulation technique provides us not only with opportunity to choose the best measurement conditions but also allows extraction of particular noise parameters from the measurement data.

Besides the application of Fast Furrier Transformation with averaging and windowing some other procedures must be introduced as well. The aim of these procedures is canceling interfering signal components and extraction of measurement target noise source (for example, $1/f$ noise) parameters from the measured signal. Data processing must include:

• the filtering of measured noise power spectral density to avoid such interfering components as 50 Hz with harmonics and other,

• subtraction of unwanted noise spectra components (for example, thermal and shot noise, G-R noise, RTS noise),

• determination of the specific parameters in the noise model, such as KF, AF and γ for $1/f$ noise.

Careful design of data processing procedures is important to reduce eventual errors and misleading interpretations of measurement results. Accuracy of results while averaging could be determined analysis of measurement errors related to the estimation of low frequency noise parameters as the parameters of the stochastic process [8]. For the spectral components calculated by FFT at the low frequency end accuracy will be much lower than at the high frequencies. This must be taken into account in the approximation of the power spectral density function.

Typical 'raw' spectral density for equivalent input noise voltage source of low noise OP-AMP AD797 is presented in Fig.7. There is a clearly observable spectral component (0,05 Hz) from known local interference source that must be filtered out.

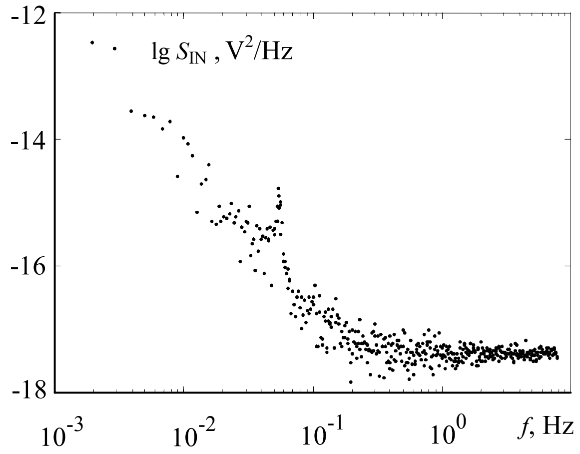

Fig. 7. Example of 'raw' power spectral density for data of measured OP-AMP noise before processing

Discussion on important measurement conditions

Application of simulation technique and analysis of real noise measurement conditions revealed some other problems which are worth to discuss.

SPICE model contains noise sources with even PSD (thermal noise, shot noise) and flicker noise sources both in base and collector circuits. Some authors [5,7] base their $1/f$ noise analysis (and measurement) only on one - base current noise source - motivating that with strong correlation between base and collector noises at low frequencies. As simulation shows (Fig.5) at low I_C current and low source resistance R_G values this assumption is no more valid.

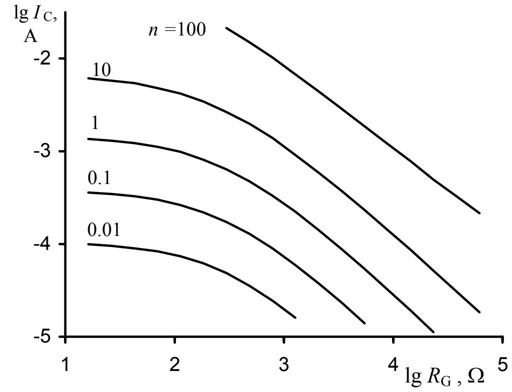

Fig. 8. Ratio (n) of base noise S_π to collector noise S_o in total output current noise as a function of collector current I_C and source resistance R_G

These simulation results show that $1/f$ noise of BJT could be represented by one base noise source just when providing measurement at large collector current and large value of R_G. This result should be tested experimentally.

In some cases it is assumed and some experimental data conform this that base resistance R_B is split in two and base noise source is connected to the middle of two. It makes experimental determination of R_B consisting of two components much more complicated.

As follows from our simulation results influence of R_B on accuracy of determination of base noise source is significant only for small values of source resistances R_G. It is one more argument considering measurement of BJT base noise at large value of R_G.

In the MC with common feedback, maximum value of R_G is limited by DC bias conditions and R_B influence on the accuracy of determination of base noise source could be significant. Still in this case important is total value of R_B but not the split ratio.

Conclusion

In many cases it is important for practical applications to determine 1/*f* noise parameters of BJT for SPICE model but their exact values could not be theoretically predicted and must be obtained from the measurements.

Error sources in determination of noise parameters from measurement data could be determined and evaluated using simulation technique. This approach made possible to evaluate different BJT noise measurement circuits to determine the most favourable circuit configuration and bias conditions. The most appropriate for BJT noise measurement is the measurement circuit configuration with common feedback and large value of R_G.

Noise simulation and extraction technique allows identify some specific cases and problems related to noise parameter extraction as, for example, the influence of base resistance R_B on the accuracy of determination of noise parameters.

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Pateikta spaudai 2005 04 20

M. Zeltins, I. Slaidins. Bipoliarinių tranzistorių 1/f triukšmo modeliavimas ir parametrų skaičiavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2005. – Nr. 4(60). – P. 77–80.

Daugeliu atvejų reikiamus bipoliarinių tranzistorių 1/f triukšmo parametrus galima gauti tik remiantis triukšmo matavimo rezultatais. Išnagrinėti paklaidų šaltiniai bei surastos jų reikšmės. Modeliavimo būdu sulygintos įvairios matavimo schemos. Apskaičiuotos bipoliarinių tranzistorių optimalios darbo sąlygos. Aptartos problemos, kurios atsiranda 1/f parametrų skaičiavime. Il 8, bibl. 8 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

M. Zeltins, I. Slaidins. Bipolar Junction Transistor 1/f Noise Simulation and Parameter Extraction Technique // Electronics and Electrical Engineering. – Kaunas: Technologija, 2005. – No. 4(60). – P. 77–80.

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М. Зелтиньш, И. Слайдиньш. Моделирование и расчет параметров 1/f шума биполярных транзисторов // Электроника и электротехника. – Каунас: Технология, 2005. – № 4(60). – С. 77–80.

Часто в практике необходимые параметры 1/f шума биполярных транзисторов можно получить только из результатов измерений шума. В статъе рассмотрены источники погрешностей в процессе определения параметров 1/f шума БТ. Путём моделирования сравнены несколько схем измерения и оптимальные условия работы БТ. Обсуждены проблемы расчета параметров 1/f шума БТ. Ил. 8, библ. 8 (на английском языке; рефераты на литовском, английском и русском яз.).