FET Noise Model Extraction Methods

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Abstract

This paper presents an overview of the noise modeling extraction methods developed at the Microwave Electronics Laboratory at Chalmers University of Technology. The presented methods are suitable for different kinds of noise models, the one and two parameter Pospieszalski model, and the three parameter PRC model. We also present a low power low noise amplifier.

Introduction

To facilitate the development of high performance amplifiers, e.g. amplifiers for cryogenic temperatures with extremely low noise specifications it is important to have reliable and accurate models. There are two models commonly used for RF FETs (Field Effect Transistor); the Pospieszalski model [1] and the PRC model [2]. The Pospieszalski model use the temperature T_d of the intrinsic drain-source resistance R_{ds}, and also sometimes the temperature T_g of gate-source resistance R_i, Fig. 1a. The PRC model uses correlated noise current sources across the intrinsic gate-source port (i_g with T_g=0), and intrinsic drain-source port (i_d with T_d=0), Fig. 1b. The next step is to extract values for the model parameters. There are several approaches available to do this extraction. The first approach is to use a physical model to calculate the model parameters. The second approach is to measure the noise figure, or noise parameters and use a circuit optimizer to get the model parameters. The third method is to measure the noise figure, or noise parameters and use some extraction algorithm to get the model parameters. The extraction algorithm approach is especially useful when implementing an automated extraction procedure. A bias dependent [3-5] model can be obtained by applying the extracted values from a range of biases and either generate a table-based model or a large-signal model with noise sources. This paper will focus on the extraction procedure but also mention our recent efforts in bias dependent modeling.

Noise model extraction

A general overview of the extraction process is shown in Fig. 2. As a first step cold FET S-parameter measurements are performed. These measurements are fed into the parasitics extraction algorithm [6]. This is done once for each device and the resulting circuit parameters are fed into an intrinsic circuit extraction routine for deembedding. The third step is to measure the device noise and S-parameters at all bias points of interest. The fourth step does the intrinsic extraction and the resulting equivalent circuit is fed into the noise extraction algorithm together with the noise measurements [4].

There are several choices of extraction algorithms depending on what kind of measurements are available [7-16]. This paper discusses three different methods useful for different kinds of measured data, summarized in Table 1.

The direct methods presented here [13, 14, 16] use an admittance matrix description of the transistor. This approach makes it possible to use the same algorithms on other types of transistors than FETs. For the one and two parameter model, methods A and B of Table 1, we use (1) where $F(Y_{s,j})$ is the measured noise figure at source admittance $Y_{s,j}$, j is the jth source impedance state, a_i is calculated from the admittance matrix, and T_i is the temperature of each resistance in the equivalent circuit. The T_i can be either the model parameters or the other resistor temperatures held at ambient. For the one parameter model this gives us one equation, j=1, to solve for one measurement. For the two parameter model we need two measured noise figures, j=1,2, and we get a system of equations from (1).

$$F(Y_{s,j}) = 1 + \sum_i a_i(Y_{s,j})T_i \qquad (1)$$

If we instead have measured noise parameters we could calculate the noise figure for some source admittance and use that with (1). There are however sensitivity problems with the choice of admittance for the two-parameter model [14]. It is possible to calculate the Y_s values that give a zero a_i coefficient for any i this means we can choose the $Y_{s,j}$ that separates our system of equations to a system of two independent equations.

Table 1 Direct extraction methods

	Measurement	Extracted model
A	One noise figure (arbitrary Z_s)	One parameter model (Pospieszalski T_d)
B	Two noise figures (two arbitrary Z_s)	Two parameter model (Pospieszalski T_d, T_g)
C	Noise parameters	Two source model including correlation. (PRC, Pospieszalski)

If noise parameters were measured they can be used directly in the extraction procedure [16]. This approach is suited for the extraction of models with two correlated sources, e.g. PRC. It is enough to use method B for models with no correlation, e.g. Pospieszalski, because it gives the exact same result as method C for the magnitude of the noise sources, this has not been proven mathematically but has been seen for all tried cases.

Discussion of extraction methods

Several methods have been presented here. They are useful in different cases. For cryogenic applications where it is difficult to measure noise parameters some method that use few impedance states is preferable. Usually high performance transistors can be modeled by the Pospieszalski model. For this reason we prefer the first method above, Table 1, or using a circuit simulator to fit the one model parameter. We believe the first method is the most convenient one for a bias dependent model, it is however more complicated to implement especially if the device is measured in a fixture and not on wafer. The circuit simulator approach is more convenient for the model at a few bias points. It is possible to model the fixture and transistor and adjust the model parameter, T_d, until simulation and measurement agrees.

Another commonly used method is to measure the noise temperature of a complete amplifier. The advantage of this method is that the output of the amplifier can be matched, reducing errors due to source pulling of the receiver. The measured noise temperature is used with a circuit model of the complete amplifier to optimize measured noise vs. model.

Bias dependent modeling

A simple approach to bias dependent modeling is to extract the model for a number of bias points. The extracted parameters are put into a data file that can be interpolated by the circuit simulator. A drawback with this method is that it requires a lot of measured noise data. The other way is to add a noise model to some large-signal model, in some circuit simulators there are suitable noise sources associated with the built-in large-signal models. The noise model parameters are functions of for instance the drain current, the parameters of this relationship are calculated from a few noise measurements. The advantage of this method is that it can cover a wider bias range with less measured noise data [4].

To extract the model parameters for each measured bias point the transistor's S-parameters were measured at 20K in a probe station. The equivalent circuit was extracted for each bias point using the hot/cold FET method [6]. The transistor was mounted in a special test fixture with a pre-matching circuit and gate bias-tee, Fig. 4. The pre-match circuit is used to get a narrow band Γ_{opt} match. The increased gain caused by the pre-match circuit helps reducing error contributions of following stages. The noise temperature was measured at 20K for several bias points, Fig. 3. Finally the noise models were extracted for each bias point by using a circuit simulator in order to model the pre-match structure and transistor. A two stage LNA has been used to verify the model.

In order to simplify the design of low power LNAs the Chalmers model [4] has been extended to include noise sources. The noise source's bias dependence was modeled as a quadratic of I_d, using the PRC configuration of the noise sources. The coefficients of the model were found by fitting to measured noise temperature at 8GHz for a range of bias points.

Amplifier results

A prototype 4-8 GHz low noise amplifier (LNA) designed for the FIRST (Far InfraRed and Submillimetre Telescope) satellite project has been designed. The goal is a high performance, Gain ~25dB and

T_n < 5K, amplifier working at a low power consumption P_{dc}<4mW. The amplifier was designed for the MGF4419G, a GaAs PHEMT by Mitsubishi. The LNA, uses two transistors in common source configuration. The box measures 3x3x2 cm. The design has been tested with InP devices by just substituting them for the MGF4419G, since the devices are of comparable size the matching networks were approximately right. The results from these experiments are shown in Fig. 5. As can be seen in the figure the GaAs version does not meet the power requirements when Gain >25dB, T_n ~ 6K, and P_{dc}=22mW, while the InP version has Gain~25dB and T_n~3K at 4 mW. Even when reducing the power consumption to 2mW, V_{ds}=0.5V and I_d=2mA, the noise temperature was degraded by less than 0.5K and the gain was only reduced by about 1dB.

Conclusion

In this paper we have presented an overview of extraction methods for noise models. These methods are useful in different circumstances. If a simple model is to be extracted at one bias point there is little need for a direct extraction procedure to be implemented and a circuit simulator might as well be used. But if more complicated and especially bias dependent models are to be extracted or if one wants to study the bias behavior of noise model parameters then an automated direct extraction method is more attractive.

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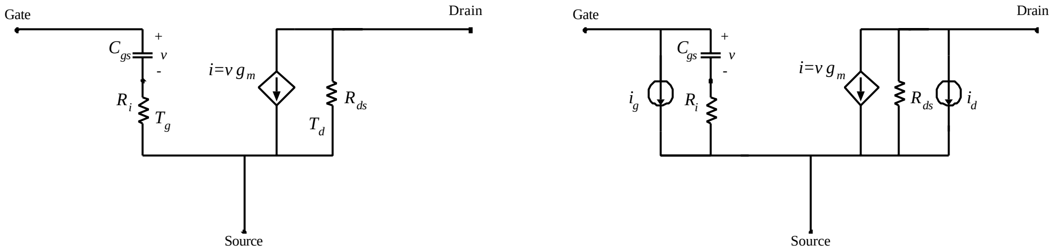


Fig. 1 Noise models for the FET, a) Pospieszalski and b) PRC respectively.

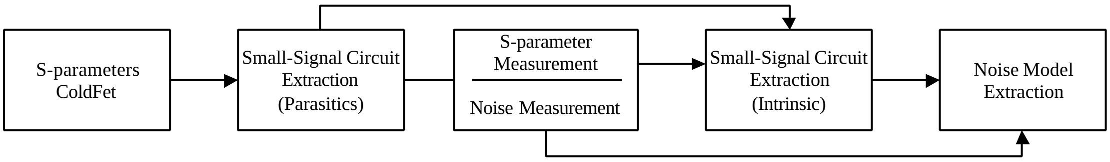
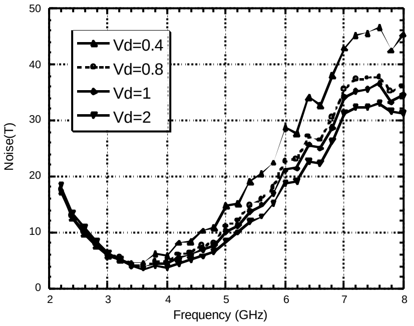


Fig. 2 Example of extraction procedure.



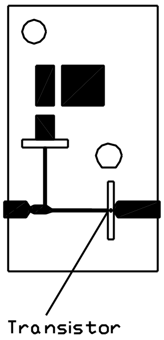


Fig. 3 Noise Temperature. Vd as parameter. I_d=5mA.

Fig. 4 Noise measurement pre-match circuit.

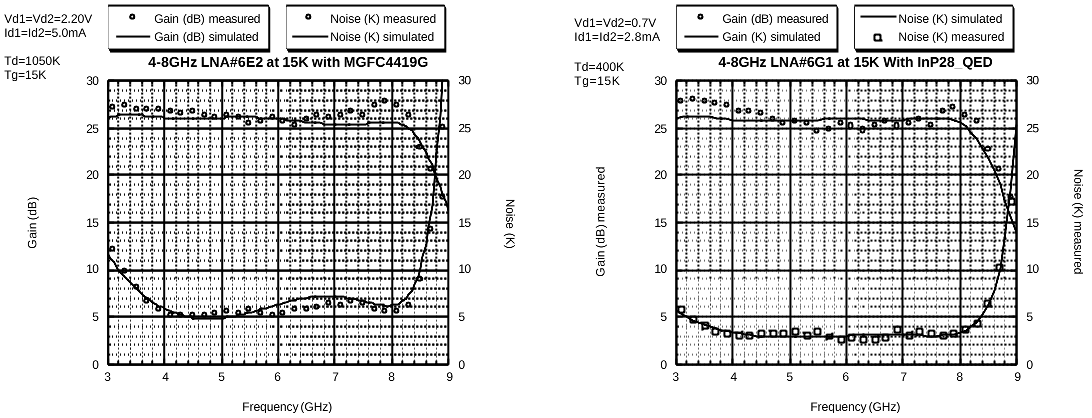


Fig. 5 Measuredand simulated results of LNA with GaAs (MGF4419G) and InP (Chalmers) transistor.