A New Scaleable Low Frequency Noise Model for Field-Effect Transistors Used in Resistive Mixers

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Abstract — **A new scaleable low-frequency noise model for cold-FETs ($U_{ds} \approx 0V$) is proposed. The model was tested using the Fujitsu HEMT FHC40LG in resistive mixer circuits where low-frequency noise (1/f-noise and generation-recombination noise) occurs due to self-mixing process. Describing the noise of the FET channel as resistance fluctuations the model explains the existence of noise in absence of a DC current. A method for implementing resistance noise in common CAE programs is also shown. The model yields excellent agreement with simulation results.**

I. INTRODUCTION

Low-frequency (LF-) noise performance of microwave field-effect transistors (MESFET, HEMT, PHEMT) became an important subject because it generates amplitude and phase noise in amplifiers and oscillators [1] and limits the sensitivity of direct-conversion receivers [2]. RF circuits can only fulfill the high standards of modern communication systems if their design takes LF-noise into account. In comparison to other active devices (namely HBTs) HEMTs exhibit very strong 1/f- (flicker) noise [4]. Therefore, sufficient models for computer aided optimization are highly needed and many proposals can be found in the literature [4]-[9]. They mostly contain noise current and/or voltage sources with dependencies on DC currents and/or voltages. This simple approach succeeds very well in active circuitry [3], [4]. However, it fails in cases (e.g. resistive FET mixers) that produce noise without DC current. Up to now, noise models for resistive mixers refer to high-frequency noise only [10].

The model in this paper implements fluctuations of the HEMT channel resistance, thus, yielding good simulation results with drain-source voltages around zero volts (ohmic channel bias regime) and physical background. If the operation is extended to active region the well known current dependent noise sources have to be added. In spite of different 1/f noise sources, the model may also be used for MESFET, MOSFET or JFET devices.

II. BASIC THEORIES

In contrast to noise sources like thermal noise or shot noise, up to now flicker noise is not fully understood. But it is a long known fact that 1/f- and generation-recombination (GR-) noise in electronic circuits stems from equilibrium resistance fluctuations [11]-[14]. Passing a DC current through the fluctuating resistance naturally causes voltage and/or current fluctuations to appear. But there are also physical systems that produce LF-noise power from noisy resistors without any DC current [14]. Even though the derivations in this article mainly refer to 1/f-noise, they fit in with GR-noise as well.

The origins of 1/f-noise are very fundamental and still a matter of research, as they differ from system to system. Fortunately, these problems don't affect the modeling of flicker noise. According to the popular Hooge formula [12] the normalized 1/f-noise spectra are:

$$\frac{S_R}{R^2} = \frac{S_G}{G^2} = \left.\frac{S_u}{U^2}\right|_{i=const} = \left.\frac{S_i}{I^2}\right|_{u=const} = \frac{\alpha}{N \cdot f} \quad (1)$$

where R is ohmic resistance, G ohmic conductance, U DC voltage, I DC current, S_x power spectral density (PSD) of the quantity x, N absolute number of charge carriers, α Hooge parameter, f frequency. The equality of the normalized noise spectra (resistance, conductance, voltage, current) is a necessary criterion for resistance fluctuations. Recent literature still discuses the nature of the Hooge parameter α. It appears to be dependent on material, lattice quality, temperature and charge mobility [12].

III. NOISY RESISTANCE IN CAE-PROGRAMS

At a first glance, implementing resistance noise in CAE (computer aided engineering) programs encounters severe problems as only current and voltage noise sources are available. One can overcome this limitation by using mathematical terms. The Hooge formula in time domain reads as follows [16]:

$$\frac{\Delta r}{R} = -\frac{\Delta g}{G} = \left.\frac{\Delta u}{U}\right|_{\Delta i=0} = -\left.\frac{\Delta i}{I}\right|_{\Delta u=0} = \Delta k \quad (2)$$

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where Δx is fluctuating part of the quantity x, the capital letters are non-fluctuating parts of the quantity and Δk represents the normalized fluctuation, whose PSD equals the right term in (1). A resistor exhibits fluctuations, if its created noise obeys the correct DC voltage and current dependences described by the Hooge equation (2):

$$i = \frac{u}{r} = \frac{u}{R + \Delta r} = \frac{u}{R \cdot (1 + \Delta k)} \quad (3)$$

where r is fluctuating resistance, R non-fluctuating part of r and i and u overall current and voltage, respectively (fluctuating plus non-fluctuating part). The equality (3) expresses nothing else as Ohm's law and Hooge formula in time domain, but now one is able to put this equation into almost every circuit simulator. Note that the voltage and the current in equation (3) are not necessarily DC values (as is of tremendous concern within the FET noise model).

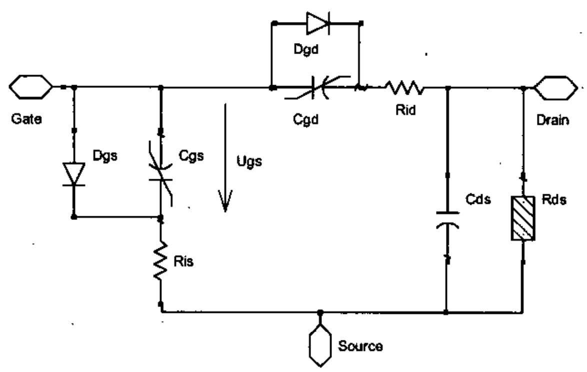

Fig. 1. Intrinsic equivalent circuit of Fujitsu HEMT FHC40LG valid for ohmic channel bias regime

IV. Modeling of FETs

We used a packaged Fujitsu HEMT FHC40LG (gate length $L_g \leq 0.15\mu m$, gate width $W_g = 280\mu m$) to verify the noise model. In order to simplify the modeling procedure, only the gate-source voltage dependencies are implemented. This is acceptable if compression of conversion gain and intermodulation are not of interest. Fig. 1 shows the intrinsic equivalent circuit. The drain-source resistance R_{ds} owns flicker noise (hatched area in the component schematic). Noise of the other resistors will be discussed in further publications.

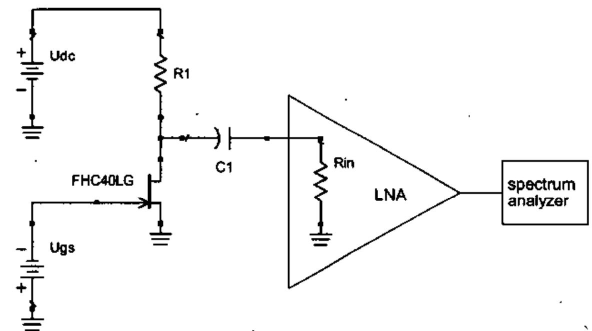

Fig. 2. Configuration for measuring low-frequency noise of field-effect transistors

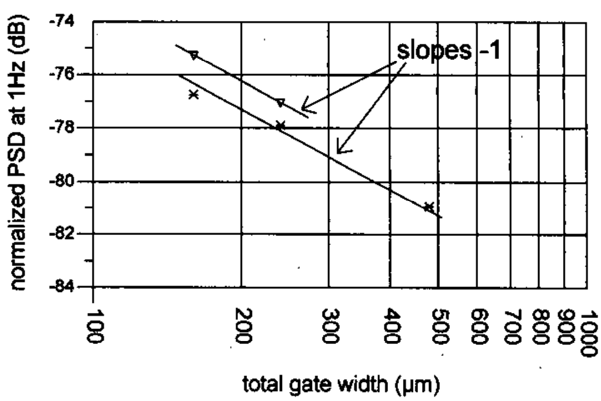

Fig. 3. Scaling of 1/f-noise properties for FET channel, example with two Infineon PHEMT chips (stars and triangles) at U_{gs}= -0.1V

Fig. 2 shows the measurement configuration for determining the noise parameter α/N (from Hooge equation). An electromagnetic shielded chassis protects the circuitry against disturbing signals. The low-noise amplifier (LNA), a Femto HVA-S, exhibits a noise floor of -164dBm/Hz at 50Ω. The spectrum analyzer (NI-4551) permits measurement from about 1Hz to 80kHz. A low-noise drain-source voltage of 30mV was applied to the HEMT, thus performing measurement in ohmic channel bias regime. One receives the α/N-parameter as follows:

$$\frac{\alpha}{N} = \frac{S_u(f = 1Hz)}{I^2 \cdot (R_{ds} \parallel R_1 \parallel R_{in})} \quad (4)$$

where I is drain-source DC current, R_{ds} drain-source ohmic resistance, R_l measurement resistor, R_{in} input resistance of the low noise amplifier and || parallel connection. The α/N-parameters of MESFETs or HEMTs steadily decrease with increasing gate-source voltage U_{gs}. The physical reason for the dependence is discussed in

[17], [18]. The noise parameter of the FHC40LG channel fits the empirical function

$$\frac{\alpha}{N} = -85dB - 25dB \cdot \tanh\left(\frac{3}{1V} \cdot U_{gs} + 0.165\right). \quad (5)$$

The Hooge formula (1) also expresses the scaling of the FET channel noise, because the number of charge carriers directly increases with gate area and the Hooge parameter, of course, remains constant. Fig. 3 shows measured noise properties of Infineon PHEMT chips (L_g=0.12µm) with different gate widths. Two samples are depicted with two and three FETs, respectively, taken from the same chip. A specimen variation of less than 2dB can be seen. The line with slopes of minus one excellently confirms the expected scaling. The same scaling holds for GR-noise.

V. Resistive Mixers

A single-ended resistive mixer should prove the correctness of the proposed HEMT model. In Fig. 4 the topology is depicted. The transistor was mounted on RF laminate and placed into a shielded chassis. Coaxial bias-Tees (HP33150A) feed the FET with signals and DC gate bias. They also separate IF (<1MHz) and RF (>1GHz) signals. The gate-source voltage sets the drain-source resistance R_{ds} to 50Ω, thus yielding broadband RF (radio frequency) and IF (intermediate frequency) matching without additional components.

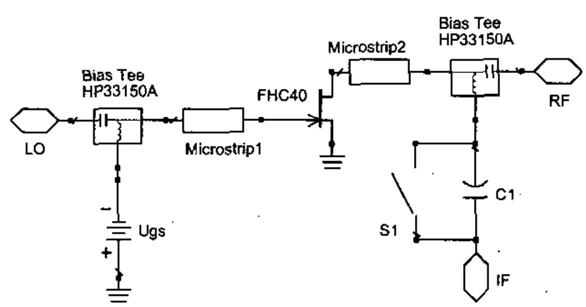

Fig. 4. Single-ended resistive HEMT mixer topology

A. The Mechanism of Creating LF-Noise

The non-balanced mixer strongly suffers from LO self-mixing: The gate-drain capacitance couples a fraction of the LO signal to the drain electrode. Being now at the RF port, this signal is mixed with the LO, i.e., it is mixed with itself. Of course, the resulting difference frequency equals exactly zero, that is, a drain-source DC voltage and 1/f-noise appear. Note that if the switch S_1 is open (Fig. 4), the capacitor C_1 prevents any DC current to flow. Nonetheless flicker noise can't be suppressed by this way: The resistance fluctuation of the HEMT channel superimposes itself upon the variations of drain-source conductance that produces the mixing process. Thus, transforming a tiny part of the LO energy to low-frequency noise. A strongly simplified calculation (without non-linearities and without not interesting mixing frequencies) should illustrate the mechanism. Applying the approach from (3), the following terms hold:

$$\begin{aligned} i_{IF} &= u_{LO,coupl} \cdot g_{ch} = u_{LO,coupl} \cdot G_{ch} \cdot (1 + \Delta k) \\ &= i_{DC} \cdot (1 + \Delta k) = i_{DC} + i_{noise} \end{aligned} \quad (6)$$

where i_{IF} is IF current, $u_{LO,coupl}$ LO voltage coupled from gate to drain, g_{ch} drain-source conductance, Δk normalized fluctuating part of g_{ch} and G_{ch} non-fluctuating part of channel conductance. Because G_{ch} varies with the same frequency as $u_{LO,coupl}$, the multiplication creates a DC current i_{DC} and an LF-noise current i_{noise}. The generated currents both are proportional to the same quantities, but they don't depend on each others!

Other noise sources, that disturb measurements, are down-converted amplitude noise of the local oscillator, self-mixing of the RF signal and gate current due to rectified LO power. Therefore, one has to be very careful to avoid all of these mechanisms.

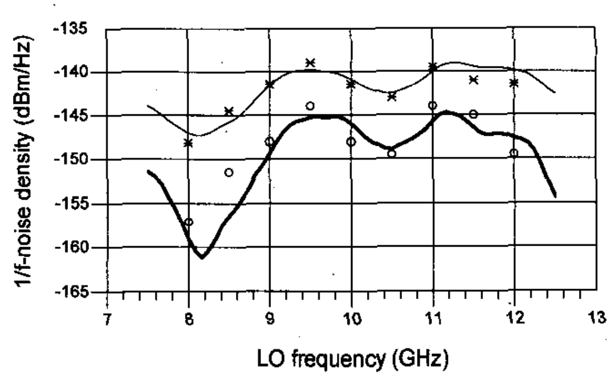

Fig. 5. 1/f noise density at 1kHz with 0dBm LO-power; simulation with (thick line) and without (thin line) DC path; measurement with (circles) and without (stars) DC path

B. Measurements and Simulation Results

All simulations published here were performed with ADS2002 (Agilent Technologies). Calculated conversion gain, AM- and PM-conversion factors and self-mixing DC current agree well with the measured ones. Fig. 5 and 6 show the comparison between noise simulation results and measurements with very good agreement. Note that if the IF capacitance (C_l in fig. 4) blocks the DC path and prevents the self-mixing current to flow, 1/f-noise increases by about 6dB. The reason for that will be explained in detail in further publications.

The increase of noise due to LO power can be seen in fig. 6. At low LO power there is a slope of +20dB per decade, because of increasing conversion gain (+10dB per decade) and increasing LO power coupling to the drain (+10dB per decade). At about -12dBm LO power the conversion starts to compress and the curve in fig. 6 flattens.

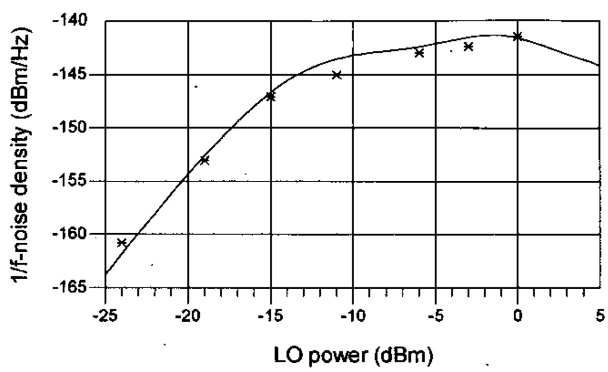

Fig. 6. 1/f noise density at 1kHz (LO frequency 9GHz), simulation (line) and measurement (stars)

VI. Conclusion

A new low-frequency noise model for microwave FETs in ohmic channel bias regime has been proposed. In contrast to previously published models the noise source is the fluctuating channel resistance. No active noise sources are present. Experimental investigations proved that the FET model fits very well the measured noise spectra.

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