Analysis of Noise Up-Conversion in Microwave Field-Effect Transistor Oscillators

Jacques Verdier, Olivier Llopis, Robert Plana, and Jacques Graffeuil

***Abstract*— The conversion process of the low frequency noise into phase noise in field-effect transistors (FET) oscillators is investigated. First, an evaluation of the baseband noise contribution to the oscillator phase noise is provided from the analysis of the baseband noise and the frequency noise spectra. A distinction is made within the different components of the low frequency noise contributions to close-in carrier phase noise. Next, the frequency noise of the oscillator circuit is analyzed in terms of the FET's low frequency noise multiplied by the oscillator's pushing factor. Though this product usually provides a good evaluation of the phase noise, experimental results presented here show the inaccuracy of this method at particular gate bias voltages where the pushing factor decreases to zero. To account for these observations, a new nonlinear FET model involving at least two noise sources distributed along the channel is proposed.**

I. Introduction

OSCILLATOR phase noise is an essential parameter which limits the performances of many modern telecommunication systems. Consequently, there has always been a great interest in identifying the origins of random phase fluctuations and get them reduced. In solid state microwave oscillators, the phase noise is generally attributed to the active device low frequency (LF) noise that upconverts via a mixing process into frequency fluctuations around the carrier signal. This LF noise is used as an input parameter in nonlinear simulators to compute the oscillator frequency fluctuations, either by the conversion matrices formalism or by direct modulation (or sensitivity) analysis [1]–[4].

For FET devices, the LF noise is generally described by an equivalent input voltage generator measured on the non-oscillating device. This classical approach leads to computed phase noises usually lower than the measured ones [5], [6]. Indeed, we have already described how the device LF noise can be modified by the self-biasing due to the nonlinear oscillation and how it is difficult to find equivalent measurement conditions for the non-oscillating device [7]. Therefore LF noise measurements on the oscillating device are mandatory. But, even if the LF noise is measured under oscillation, some differences may still be found between the computed and the measured phase noise [7]. We believe that these differences are essentially due to an inadequacy of the classical FET models used to describe the noise conversion process.

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In this paper, we analyze the noise conversion process first through a comparison of the oscillator frequency noise and the equivalent input LF noise voltage measured under oscillation. Indeed, if a direct frequency modulation process is involved, these two noises should be strongly correlated. The frequency noise is also compared to the product of the input LF noise and the pushing factor (which represents the oscillator frequency sensitivity to a change in the dc gate bias). It is concluded that modeling problems are occurring in the vicinity of special bias conditions where the pushing drops down to zero. Finally, a possible solution is proposed to circumvent these problems, based on a distributed gate effect.

II. Oscillator Design and Measurement Technique

The parallel feedback topology has been selected for our investigations since it is easy to interchange the active device with this topology and consequently to compare the phase noise of different oscillating devices. Each commercial FET device (a conventional GaAs MESFET, an AlGaAs/GaAs HEMT, and an AlGaAs/InGaAs pseudomorphic HEMT's) is embedded in a microstrip fixture in a grounded source configuration. The bias conditions are $V_{ds} = 2$ V, $V_{gs} = 0$ V (HEMT and PHEMT) or $V_{ds} = 3$ V, $V_{gs} = 0$ V (MESFET). The oscillation is established through a resonator with a loaded quality factor Q_L of 160 at 4 GHz. This small Q-value (with regard to the high quality factor of a dielectric resonator) facilitates the phase noise measurements. The control of the loop gain and the loop phase shift is achieved by inserting a variable attenuator and a variable length line into the feedback loop.

The schematic diagram of the microwave oscillators phase noise test set is shown in Fig. 1. It is a delay line frequency discriminator with an improved sensitivity provided by the two phase detectors that allows us to perform a cross correlation analysis. Low phase noise levels such as −125 dBc/Hz at 10 kHz offset of a 4 GHz carrier can be measured in this way.

III. Phase Noise and Conversion Process

To evaluate the effect of baseband noise on the oscillator phase noise it is useful to introduce a pushing factor K_p (in $\mathrm{MHz/V_{RMS}}$) which can be obtained either by modifying lightly the dc gate bias or by superimposing a white noise of known spectral density through the bias tee on the FET gate dc bias. Indeed, for most of the devices tested, a white

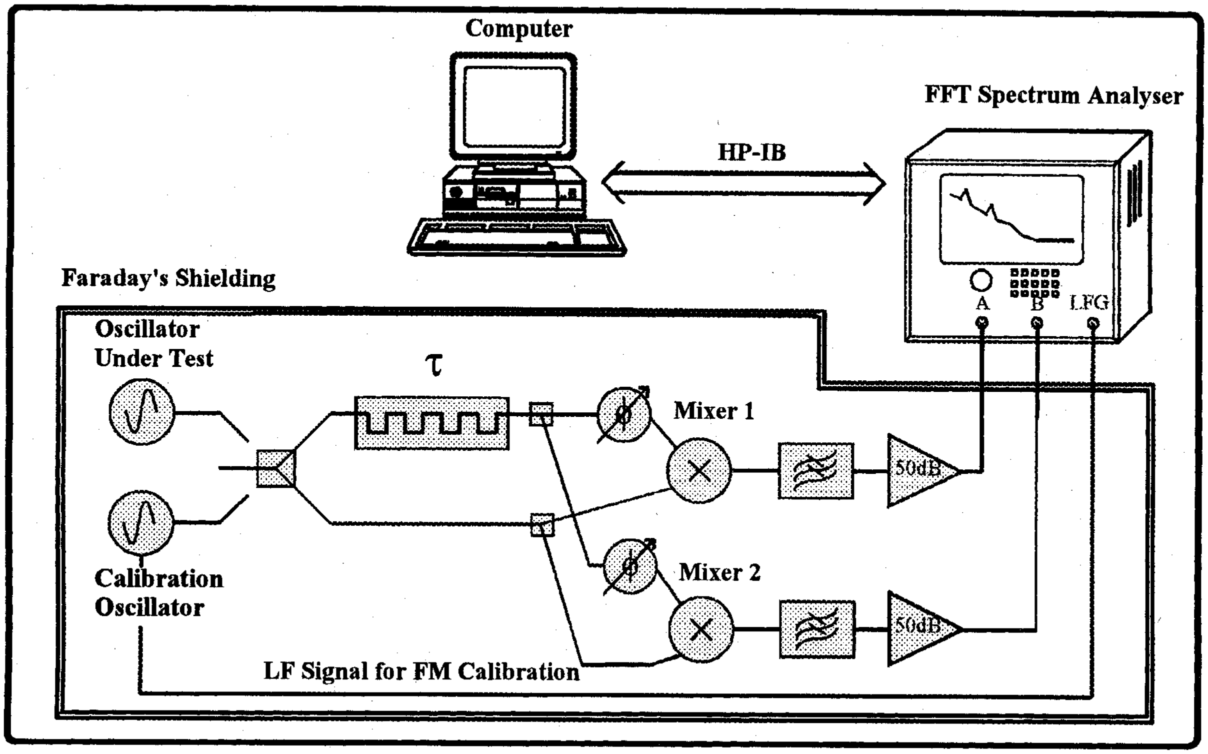

Fig. 1. Schematic diagram of the microwave oscillators phase noise test set.

noise on the gate translates into a white frequency noise of the oscillator and the ratio of these two noises is exactly equal to the dc pushing factor (at least up to 100 kHz which is the limit of our LF noise and phase noise test sets). This means that the FET's LF dispersion effects, such as the output conductance frequency dispersion [8], have no influence on the conversion of the gate voltage fluctuations into frequency fluctuations. Therefore, a good agreement is usually found between the frequency noise of the FET oscillator and the product of the device input referred low frequency voltage noise by the pushing factor providing that the LF noise is measured under the oscillation conditions [7]. Indeed, the FET equivalent input noise voltage is strongly modified by the self-biasing under nonlinear oscillation: the rectification of the microwave signal creates new measurement conditions by changing the $(V_{gs_{\mathrm{dc}}}, V_{ds_{\mathrm{dc}}}, I_{ds_{\mathrm{dc}}})$ triplet. An example of this behavior is depicted on Fig. 2 where the measured phase noise of a PHEMT oscillator is compared to the phase noise calculated from the pushing factor and the equivalent input low frequency noise. It is obvious that the phase noise calculated from the noise measured on the non-oscillating device is much lower (about 10 dB) than the actually measured phase noise. On the contrary, the phase noise evaluated using the LF noise observed under oscillation perfectly fits the measurement. The strong correlation between the phase noise and the LF input noise is also clearly shown on the plot of the oscillator frequency fluctuations spectrum which can be directly compared to the equivalent input voltage fluctuations spectrum. These two noise spectra are plotted on Fig. 3 and the shapes are obviously identical.

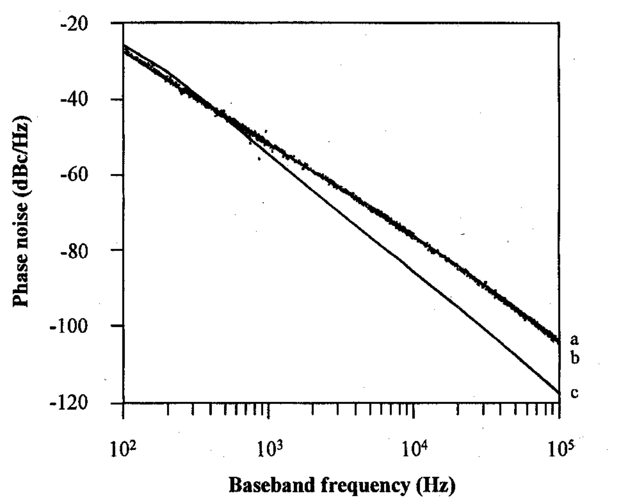

Fig. 2. PHEMT 4 GHz oscillator phase noise. a) Experimental data, b) calculated data from the oscillating LF noise, and c) calculated data from the quiescent LF noise.

However, for the HEMT oscillator (Fig. 4), we can observe that the agreement is not so good since differences appear below and above the generation-recombination (g-r) bulge (in the 10 kHz range). These differences are more clearly visible on the combined plot of the LF and frequency noise spectra (Fig 5). It is not surprising since the correlation factor (between the LF noise and the frequency fluctuations) [9], [10] measured for the HEMT oscillator is as low as 40%, whereas it is higher than 80% for the PHEMT's (Figs. 2 and 3). A possible explanation of the discrepancy observed may rely on different conversion processes for the different components

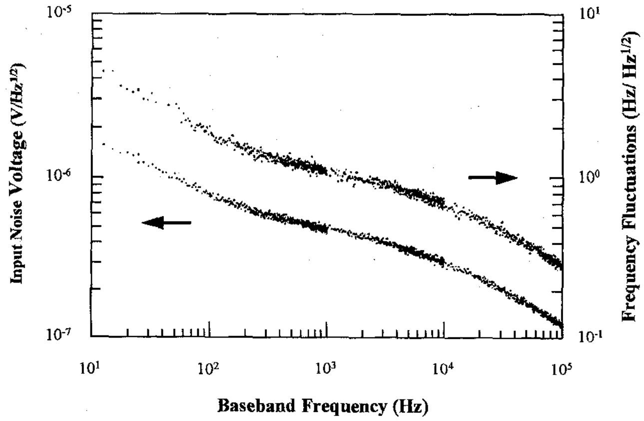

Fig. 3. PHEMT 4 GHz oscillator frequency noise compared to the input referred LF noise.

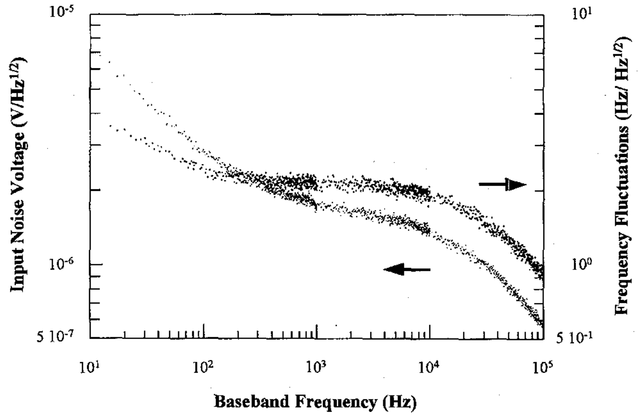

Fig. 5. HEMT 4 GHz oscillator frequency noise compared to the input referred LF noise.

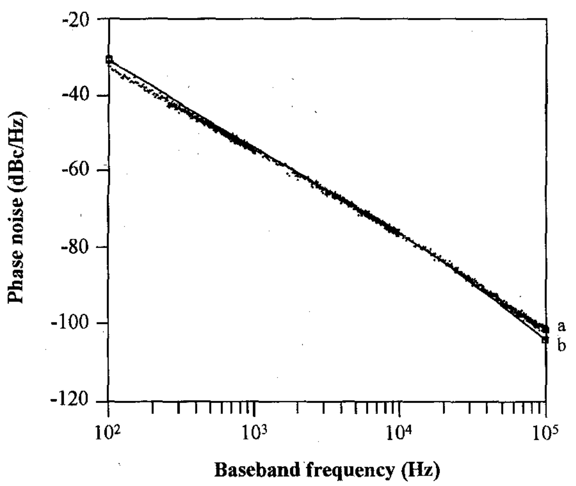

Fig. 4. HEMT 4 GHz oscillator phase noise. a) Experimental data and b) calculated data from the oscillating LF noise.

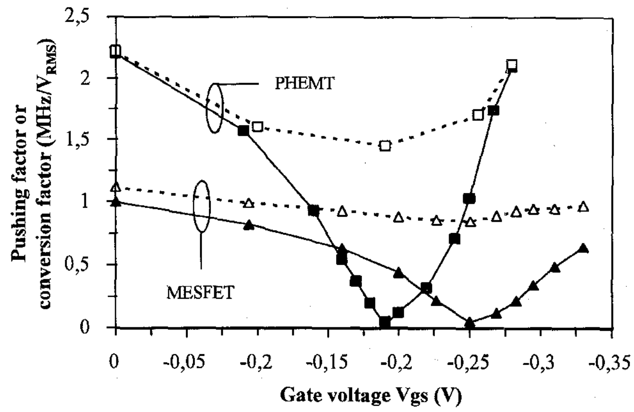

Fig. 6. Comparison between the magnitude of the pushing factor (■) and the conversion factor (— — □— —) for two 4 GHz oscillators versus dc gate bias.

of the low frequency noise. As an example, fluctuations in the gate depletion region caused by electron trapping on deep centers can be directly related to gate-source capacitance (C_{gs}) fluctuations and are therefore strongly converted into phase noise (C_{gs} being one of the major nonlinear element able to translate the low frequency noise into phase noise [11]). On the contrary, other processes in the channel or near the drain electrode may have a comparatively reduced influence on the phase noise (see Section IV).

Finally, with regard to these results, it is clear that the product of the pushing factor and the input referred low frequency noise (measured on the oscillating device) gives a fairly good evaluation of the oscillator frequency noise. However, in most of the FET oscillators we have tested, a bias point where the pushing drops down to zero may be found. Nearby this point, a decrease of the phase noise is generally observed but (unfortunately) the phase noise does not totally cancel like the pushing factor [12]. Such a disagreement is clearly shown on the simultaneous plot (Fig. 6) of the pushing factor and of the conversion factor versus the dc gate voltage; the conversion factor K_c being the ratio of the frequency fluctuations by the input referred LF noise voltage. Indeed, one can note that the pushing coefficient depends on the dc gate voltage and features a sharp minimum where it drops down to zero (at $V_{gs} = -0.25$ V for the MESFET's and at $V_{gs} = -0.19$ V for the PHEMT's). On the contrary, the conversion factor remains fairly high at this bias point. Therefore, the evaluation of the conversion process through a single gate control voltage is not sufficient to predict the phase noise at the zero pushing $V_{gs_{\mathrm{dc}}}$ value. Nearby this bias point, another up-conversion process takes place. In the next section, we propose a possible explanation of this behavior based on a modification of the classical FET nonlinear modeling.

IV. Noise Model and Simulation

The LF noise behavior of a FET can be modeled by two generators: a voltage noise source and a current noise source on the gate [13]. In most FET's, at frequencies under 100 kHz, the equivalent input current noise source contribution is negligible and only the input referred voltage noise source has to be considered.

In the classical approach, this low frequency noise source is associated to a large signal FET model such as the one depicted on Fig. 7. Three essential nonlinearities have been considered in our model: the drain current generator described by Curtice's expressions [14], the gate diode and the gate-

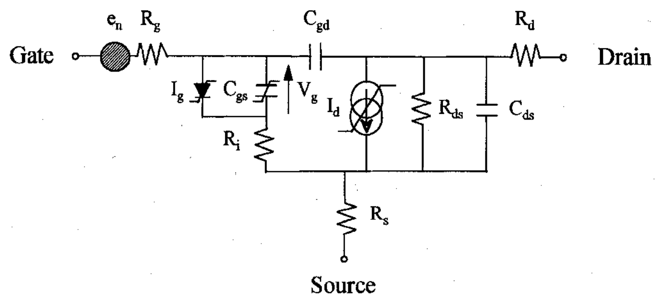

Fig. 7. Classical nonlinear FET model topology.

source capacitance nonlinearities. The low frequency noise is represented by a single noise voltage generator on the gate. On Fig. 7, the model has been simplified in order to make easier the comparison with the more sophisticated model described in the next paragraphs of this paper. Phase noise simulations have been performed by using the Hewlett-Packard simulation software MDS.

The theoretical investigations presented in this paragraph have been carried out on a MESFET device because the large signal model of this device had already given good results in MMIC design, and because the simulated value of the pushing factor at $V_{gs_{dc}} = 0$ V fits well with our experimental data. The phase noise plots are shown on Fig. 8 for this device. A satisfactorily agreement is observed between the measured and simulated phase noise versus gate voltage as long as the gate bias is far from a critical point approximately corresponding to $V_{gs_C} = -0,20$ V. At this point, which corresponds to the zero pushing point of Section III, the simulated phase noise drops down to levels 40 dB lower than the measured phase noise. Besides, the bias points corresponding to the minimum of the simulated and measured phase noises are not exactly the same. These differences are due to the large sensitivity of the computed V_{gs_C} point with regard to several electrical parameters in the active device and the feedback loop. Indeed, a 50 mV shift of this optimum V_{gs_C} value can be contributed either by a 10% variation of the gate-drain capacitance or by a 0.35 dB increase of losses in the feedback loop. Finally, not only the exact location of the phase noise minimum is very difficult to predict but also its computed value is different by many orders of magnitude from the measured one.

Therefore the classical FET model with a single input noise source is not able to provide an accurate description of the oscillator phase noise. Consequently other simulations have been performed with different FET noise models. The first attempts were based on a current noise generator located on the output, in parallel with the current source Ids. Considering only the LF noise, it makes no difference between a description by a gate referred voltage generator or a drain referred current generator. It is therefore interesting to check the ability of a drain referred noise model to overcome the problems found with the gate pushing factor modeling. Unfortunately, the conversion of this drain current noise into phase noise has been found to be very weak and the phase noise values obtained in such a way are at least 20 dB lower than the measured ones. This is consistent with the fact that the unilaterality

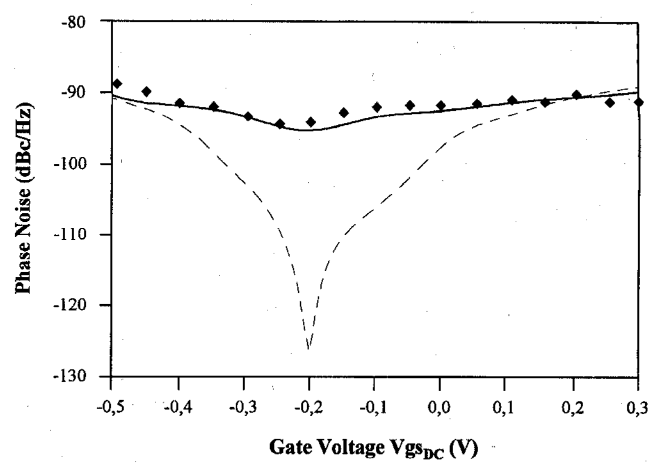

Fig. 8. MESFET 4 GHz oscillator phase noise (at 10 kHz from the carrier). "♦" measured data, "- -" simulated data from the classical nonlinear FET model, "—" simulated data from the distributed nonlinear FET model.

of FET's devices in the low frequency range prohibits the random fluctuations of the drain current from affecting the C_{gs} nonlinearity which has been found to be essential in the LF noise into phase noise conversion process. Consequently, the conversion process is probably gate related but the classical FET modeling has to be modified to prevent the simulated phase noise to drop down to non physically acceptable values such as those shown on Fig. 8.

We therefore suggest that the simulation predicts no phase noise at a given critical point because only a single LF noise source is considered. We think that such a behavior is not possible when different and uncorrelated noise sources along the active region of the device are taken into account. Indeed, a different conversion process is related to each of these noise sources and, because of the lack of correlation, the total contributed phase noise cannot cancel exactly. We have therefore investigated this type of modeling by taking into account the distributed effects along the gate using two uncorrelated noise sources. The equivalent circuit of the device is depicted on Fig. 9. It consists on a more accurate description of the channel region which separates the ohmic and the saturated regions [15]. The nonlinear capacitances C_1 and C_2 have been chosen to be equal to half of the total gate to source capacitance C_{gs} value. The other extrinsic and intrinsic elements have been adjusted to keep unchanged the S parameters values. The two uncorrelated noise voltage generators (e_{n1} and e_{n2}) have been serie connected to these two capacitances. The magnitude of these generators has been chosen equal and such that their combined effect produces a LF drain current noise equal to the LF drain current noise created by the unique noise source in the previously described model. The new simulated phase noise results are reported on Fig. 8. At the dc gate voltage where the pushing factor exhibits a dip, the phase noise computed with this model remains high and keeps values close to the measured ones. Other simulations performed with different active devices have shown a similar behavior. However, the drawback of this approach is the difficulty to evaluate the noise generators e_{n1} and e_{n2} since a single LF

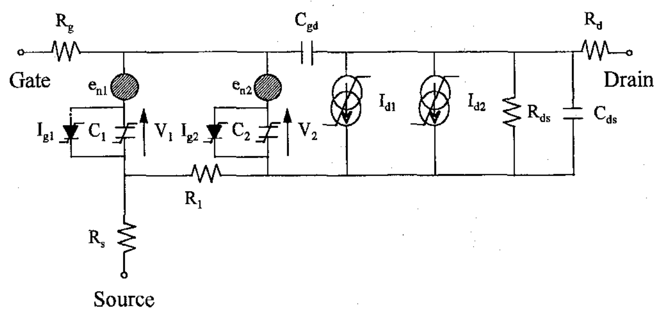

Fig. 9. Distributed nonlinear FET model topology.

noise measurement is insufficient to provide the necessary data. Investigations are in progress to determine a more appropriate measurement procedure. Anyway, even if such a procedure is not yet available, our approach gives a fairly good qualitative agreement between theory and measurement and prevent the calculation of optimized phase noise levels much lower than what can effectively be obtained on the physical circuit.

V. Conclusion

An extensive experimental analysis of up-conversion process in microwave FET oscillators has been presented. We have observed that a precise evaluation of the phase noise requires low frequency noise measurements under oscillation conditions. This evaluation is performed from the product of the pushing factor and the device's baseband noise. However, we have shown that a good agreement between the measured and computed phase noise can be observed only at gate bias far from a critical V_{gs_C} value where the pushing factor decreases to zero. At such a critical gate bias value we have observed up to 40 dB difference between the computed phase noise and the measured phase noise. The classical FET model incorporating a single LF noise source in the gate is therefore not valid in the whole gate bias range. A new approach based on a distributed gate effect has been proposed and has proven to be able to explain, at least qualitatively, the observed discrepancy. Besides, this new model prevent the calculation of physically unacceptable values for the phase noise. Additional work is in progress to identify the different parameters values needed in this model for a future very accurate phase noise prediction.

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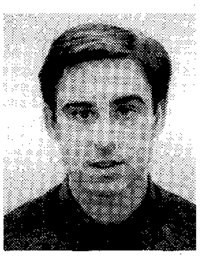

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