SIMULATION OF THE ACCURATE NEAR-CARRIER PHASE NOISE IN MICROWAVE MESFET OSCILLATORS

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ABSTRACT

The paper presents a new and efficient approach to the simulation of accurate near-carrier phase noise in free-running microwave MESFET oscillators. A kind of noise analysis model of the oscillators is introduced, in which a complete nonlinear noise model of the MESFET is included. An efficient algorithm is proposed to predict the accurate near-carrier phase noise in the microwave MESFET oscillators by nonlinear current method. Comparison between simulations and measurements proves that this approach is suitable for microwave CAD and is excellent in both efficiency and precision in predicting SSB phase noise of the microwave MESFET oscillators.

INTRODUCTION

Phase noise is a very important figure of merit in microwave oscillators. Accurate simulation of noise behavior has become an important part of general-purpose microwave CAD. Over the last few years, various methods for phase noise analysis in the microwave MESFET oscillators have been developed [1, 2, 3]. Yet these methods are not very suitable for the general-purpose CAD. With the development of CAD techniques for nonlinear microwave circuits, harmonic balance (HB) and Volterra series become the most popular methods used in analyzing steady-state of nonlinear microwave circuits. HBM has found successful applications in simulating the phase noise of the microwave MESFET oscillators [4, 5], but phase noise analysis through HB usually needs much CPU time. Nonlinear Current Method (NCM) is a very efficient method based on Volterra series that has been widely used to simulate steady-state of the oscillators [6], yet there is not any report in literature about its application in phase noise analysis of oscillators. The work presented here represents an attempt to fulfill this gap.

In this paper, we'll present a new method to predict accurate near-carrier phase noise in the free-running microwave MESFET oscillators by the nonlinear current method. A kind of noise analysis model of the oscillators that contains a complete nonlinear noise model of the MESFET will be introduced. An efficient algorithm will be stated which can predict the accurate near-carrier phase noise in the oscillators. Examples of application of the theory will also be given to demonstrate its high efficiency and precision

BASIC THEORY

In order to simulate the phase noise in the microwave MESFET oscillators, we introduce here the nonlinear equivalent noise model of the MESFET and a kind of noise analysis model of the oscillators. Fig. 1 is the noise analysis model for simulating the near-carrier phase noise of the oscillators. Inside the dashed frame in Fig. 1 represents the intrinsic nonlinear equivalent noise model of the MESFET, where all its nonlinear elements can be described by the following power series:

$$Q_{Cgs}(V_{gs}) = C_{gs1}V_{gs} + C_{gs2}V_{gs}^2 + C_{gs3}V_{gs}^3 + \dots \quad (1)$$

$$Q_{Cdg}(V_{dg}) = C_{dg1}V_{dg} + C_{dg2}V_{dg}^2 + C_{dg3}V_{dg}^3 + \dots \quad (2)$$

$$Q_{Cds}(V_{ds}) = C_{ds1}V_{ds} + C_{ds2}V_{ds}^2 + C_{ds3}V_{ds}^3 + \dots \quad (3)$$

$$I_{gs}(V_{gs}) = G_{gs1}V_{gs} + G_{gs2}V_{gs}^2 + G_{gs3}V_{gs}^3 + \dots \quad (4)$$

$$I_{dg}(V_{dg}) = G_{dg1}V_{dg} + G_{dg2}V_{dg}^2 + G_{dg3}V_{dg}^3 + \dots \quad (5)$$

$$I_{ds}(V_{gs}, V_{ds}) = G_{10}V_{gs} + G_{20}V_{gs}^2 + G_{30}V_{gs}^3 + G_{01}V_{ds} + G_{02}V_{ds}^2 + G_{03}V_{ds}^3 + G_{11}V_{gs}V_{ds} + G_{21}V_{gs}^2V_{ds} + G_{12}V_{gs}V_{ds}^2 + \dots \quad (6)$$

There are some noise sources in Fig. 1, where **Ing**, **Ind**, **Ins** and **Ini** are thermal noise corresponding to **Rg**, **Rd**, **Rs** and **Ri**; I_{nf} and I_{nL} represent thermal noise of the feedback circuit and the load, respectively; **Ings**, **Indg** and **Inds** are shot noise sources; and **En** represents the equivalent **1/f** noise source at the gate of the MESFET. The noise analysis model of the oscillators contains all

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kinds of noise sources in the circuit. All of these noise sources are up-converted or modulated to the carrier due to nonlinearities in the MESFET, and symmetrical noise sidebands are generated around the carrier in the output spectrum.

As stated in [4, 5], the noise sources in Fig. 1 are much smaller than the carrier signal and can be considered as pseudo-sinusoids. Then we can analyze the phase noise behavior of the oscillators by the nonlinear current method. The algorithm to simulate the accurate near-carrier phase noise in the oscillators is outlined as follows:

(I) Analyze the steady-state response of the noise-free oscillators by the nonlinear current method. Split the nonlinear noise-free oscillator circuit into a linear sub-circuit and a nonlinear sub-circuit. Each nonlinear element is then equalized by a linear component and a series of nonlinear current sources. Then the circuit becomes a linearized one that is driven by these nonlinear current sources. According to the theory of the NCM, accurate nonlinear current sources generated by the nonlinear elements can be calculated and be used to simulate the accurate steady-state of the oscillators. Assume the calculated oscillating frequency is *fo*, the steady-state voltage vector of the noise-free oscillator is $\overline{V}(kf_o)$(k=1~N_H), and the voltages across **Cgs**, **Cdg**, **Cds** and Z_L are ***Vgs(kfo)***, ***Vdg(kfo)***, ***Vds(kfo)*** and ***Vout(kfo)***, respectively.

(II) Compute the response at the noise sidebands of the oscillators by the nonlinear current method. All the noise sources in the circuit can be considered as very small drives. When the linearized oscillator circuit is excited only by those noise sources, the corresponding base-band response can be obtained through nodal analysis. Assume the response due to these noise sources is $\overline{V_n}(f_m)$, and the noise voltages across **Cgs**, **Cdg** and **Cds** are ***Vngs(fm)***, ***Vndg(fm)*** and ***Vnds(fm)***, respectively, where ***fm*** is the frequency deviation from carrier. Then the first order voltage response of the circuit can be obtained as

$$\overline{V_{1n}} = \overline{V}(kf_o) + \overline{V}(f_m) \tag{7}$$

From the theory of the nonlinear current method, the second order nonlinear current vector can be calculated:

$$\overline{I_{2n}}(kf_o + f_m) = \left[I_{2nCgs}, I_{2nCdg}, I_{2nCds}, I_{2ngs}, I_{2ndg}, I_{2nds}\right]^T \tag{8}$$

where

$$I_{2nCgs} = j4\pi(kf_o + f_m)C_{gs2}V_{gs}(kf_o)V_{ngs}(f_m) \tag{9}$$

$$I_{2nCdg} = j4\pi(kf_o + f_m)C_{dg2}V_{dg}(kf_o)V_{ndg}(f_m) \tag{10}$$

$$I_{2nCds} = j4\pi(kf_o + f_m)C_{ds2}V_{ds}(kf_o)V_{nds}(f_m) \tag{11}$$

$$I_{2ngs} = 2G_{gs2}V_{gs}(kf_o)V_{ngs}(f_m) \tag{12}$$

$$I_{2ndg} = 2G_{dg2}V_{dg}(kf_o)V_{ndg}(f_m) \tag{13}$$

$$I_{2nds} = 2G_{20}V_{gs}(kf_o)V_{ngs}(f_m) + 2G_{02}V_{ds}(kf_o)V_{nds}(f_m) + G_{11}\left[V_{gs}(kf_o)V_{nds}(f_m) + V_{ds}(kf_o)V_{ngs}(f_m)\right] \tag{14}$$

The corresponding second order voltage response of the circuit can then be solved:

$$\overline{V_{2n}}(kf_o + f_m) = Y^{-1}(kf_o + f_m)\,\overline{I_{2n}}(kf_o + f_m), \tag{15}$$

where **Y** is the nodal admittance matrix of the linearized circuit. Because the noise sources are very small, higher order nonlinear current sources and corresponding voltage response contribute little to the response at the noise sidebands ***kfo+fm*** and may be omitted. So $\overline{V_{2n}}(kf_o + f_m)$ is the voltage vector at the noise sidebands. Assume the output voltage at ***kfo+fm*** is ***Vnout(kfo+fm)***.

(III) Compute the loaded quality factor Q_L of the oscillators by frequency-pulling method [7] and the nonlinear current method. The oscillating frequency *fo* of the oscillator was obtained through NCM analysis in the first step of the algorithm while the load was Z_L. Here a very small perturbation is introduced to the load Z_L and its corresponding VSWR can be calculated. Then the oscillating frequency of the oscillator will be perturbed with respect to the effect of load-frequency pulling. The pulling figure of the oscillators can be obtained by re-analyzing the circuit through the NCM, and the loaded quality factor Q_L of the oscillators may be calculated easily.

(IV) As shown in Fig. 1, the feedback network of the circuit model is equivalent to a low pass filter, the transfer function of which can be expressed as follows [1, 8]:

$$H(f_m) = \left[1 + j2f_m Q_L(kf_o)/(kf_o)\right]^{-1} \tag{16}$$

where $Q_L(kf_o)$ is the loaded quality factor of the oscillators at *k*-th harmonic and may be calculated efficiently by the method stated in step (III).

(V) Calculate the single-sideband (SSB) phase-noise-to-carrier ratio $L(f_m)$. According to definition of the SSB phase-noise-to-carrier ratio, it gives:

$$L(f_m) = 20\log\left[\frac{V_{nout}(kf_o + f_m)}{V_{out}(kf_o)}\frac{1}{|1 - H(f_m)|}\right] \quad \text{(dBc/Hz)} \qquad (17)$$

This formula is very simple and the algorithm stated above is suitable for microwave CAD. The recursion and analyticity of the NCM make the algorithm very efficient. The accurate near-carrier SSB phase noise in the oscillators can be predicted because all of the noise sources mixed with the carrier signal have been taken into account in the nonlinear noise analysis model of the oscillators.

EXAMPLES OF APPLICATION

The above theory has been used to analyze the near-carrier phase noise of two oscillators shown in Fig. 2 and Fig. 3. For the oscillator circuit shown in Fig. 2, Fig. 4 gives comparison between results simulated here and calculated by the following widely used formula [1]:

$$L(f_m) = 10\log\left[\frac{FKT}{2P_{avs}}\left(\frac{f_c f_o^2}{4f_m^3 Q_L^2} + \frac{f_o^2}{4f_m^2 Q_L^2} + \frac{f_c}{f_m} + 1\right)\right] \quad \text{(dBc/Hz)} \qquad (18)$$

The solid line in Fig. 4 represents the simulated SSB phase noise of the circuit, and the dashed line corresponds to the results calculated by (18). The errors between them are less than 3.5 dB over the frequency range from 1 kHz to 100 MHz.

For the second oscillator shown in Fig. 3, the results simulated by our method and measured and simulated by HBM [5] are depicted in Fig. 5, where the solid line represents the simulated results in this paper. Fig. 5 shows that the accuracy of our method with respect to the experiment is better than that of the method given by [5]. Errors between our simulation and the measurement are under 3 dB while the frequency deviation ***fm***<1 MHz, and errors between the simulation in [5] and the measurement were up to 5 dB. The CPU time needed for a PC386 to calculate 50 points of the SSB phase noise by our method is only about a few seconds, while a HP9000 workstation needed about 6 seconds by the method proposed in [5]. All these indicate clearly that the method stated here is better both in accuracy and efficiency.

CONCLUSIONS

This paper presented a new method to simulate the accurate near-carrier SSB phase noise in free-running microwave MESFET oscillators. A kind of noise analysis model of the oscillators was introduced, and an efficient algorithm for phase noise analysis was stated. Examples of application prove that the new method is suitable for the microwave CAD and is excellent in both efficiency and precision in predicting the near-carrier SSB phase noise of the microwave MESFET oscillators. The theory presented in this paper can also be applied to other kinds of microwave oscillators.

REFERENCES

[1] Dieter Scherer, "Generation of low phase noise microwave signals", *RF and Microwave Measurement Symp. and exhibition*, HP Corp., May 1981.

[2] B. T. Debney, J. S. Joshi, "Theory of noise in GaAs FET microwave oscillators and its experimental verification", *IEEE Trans. on Electronic Devices*, Vol. ED-30, No. 7, July 1983, pp. 769-776.

[3] H. J. Siweris, B. Schieck, "Analysis of noise upconversion in microwave FET oscillators", *IEEE Trans. on Microwave Theory and Techniques*, Vol. MTT-33, No. 3, Mar. 1985, pp. 233-242.

[4] V. Rizzoli, F. Mastri, D. Masotti, "A general-purpose harmonic-balance approach to the computation of near-carrier noise in free-running microwave oscillators", *1993 IEEE MTT-S Int. Microwave Symp. Digest*, San Diego, pp. 309-312.

[5] W. Anzill, P. Russer, "A general method based on harmonic balance techniques to simulate noise in free-running oscillators", *1993 IEEE MTT-S Int. Microwave Symp. Digest*, San Diego, pp. 655-658.

[6] K. K. M. Cheng, J. K. A. Everard, "A new and efficient approach to the analysis and design of GaAs MESFET microwave oscillators", *1990 IEEE MTT-S Int. Microwave Symp. Digest*, May 1990, pp. 1283-1286.

[7] J. Obregon, A. P. S. Khanna, "Exact derivation of the nonlinear negative-resistance oscillator pulling figure", *IEEE Trans. on Microwave Theory and Techniques*, Vol. MTT-30, No. 7, July 1982, pp. 1109-1111.

[8] B. Leeson, "A simple model of feedback oscillator noise spectrum", *Proc. IEEE*, Vol. 54, Feb. 1966, pp. 329-330.

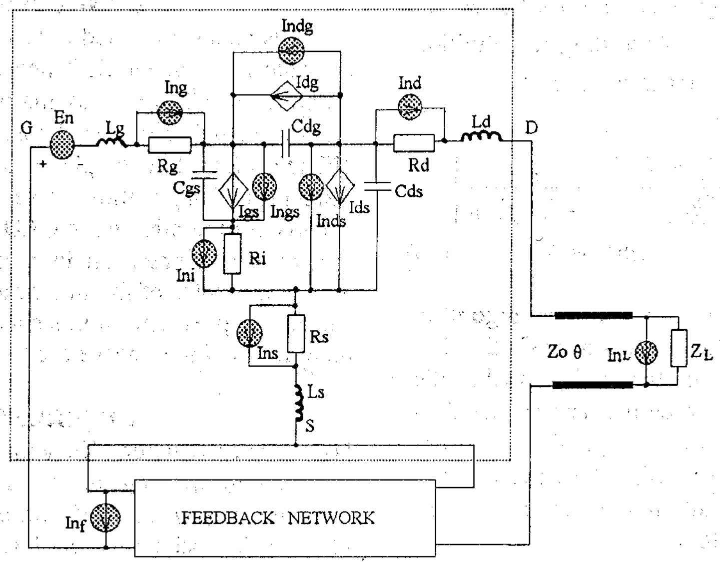

Fig. 1. Noise analysis model of MESFET oscillators

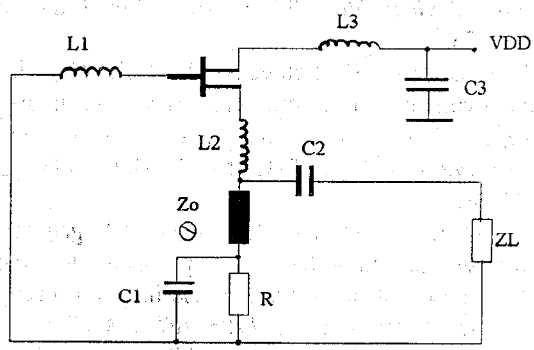

Fig. 2. Circuit of the first oscillator

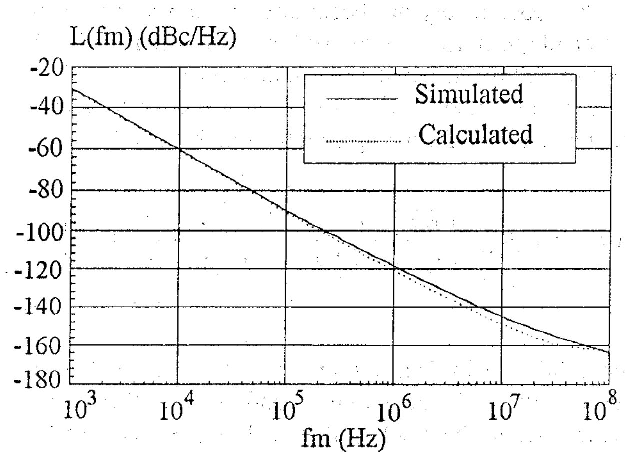

Fig. 4. SSB phase noise of the first oscillator

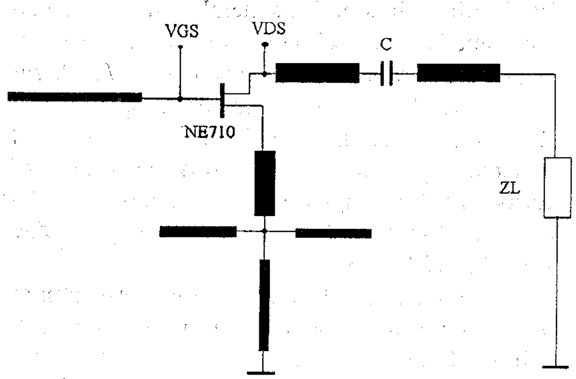

Fig. 3. Circuit of the second oscillator

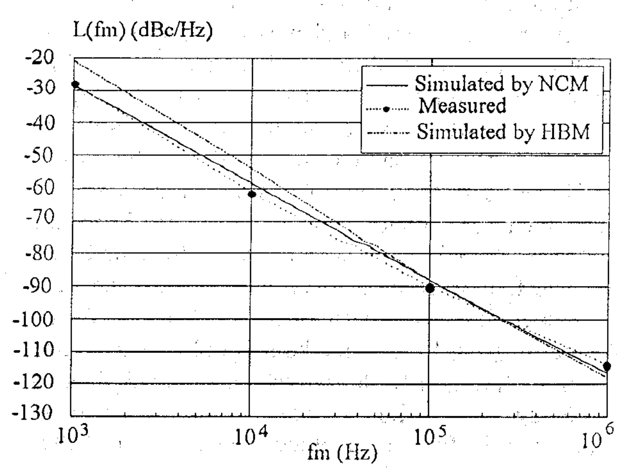

Fig. 5. SSB phase noise of the second oscillator