A UNIFIED, CAD-ORIENTED APPROACH FOR THE PHYSICS-BASED LARGE-SIGNAL CONVERSION AND NOISE MODELLING OF MICROWAVE AND mm-WAVE SEMICONDUCTOR DEVICES

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ABSTRACT

The paper presents a new, CAD-oriented approach for the physics-based conversion and noise modelling of a nonlinear semiconductor device operated in (quasi) periodic regime in the microwave and mm-wave range. After a short review of the physics-based frequency conversion and noise theory, results are presented for a varactor diode frequency multiplier and compared with circuit models derived from small-signal and DC simulations.

INTRODUCTION

The physics-based large-signal analysis of conventional and compound semiconductor devices for RF, microwave and mm-wave applications operating in the (quasi) periodic regime has been the object of great interest during the last few years [1]. Harmonic Balance (HB) techniques have been applied with success to the solution of discretized 1D or 2D physical models, although the computational intensity of the method is still very high.

In the present paper we address a further topic in the physics-based characterization of semiconductor devices, corresponding to the so-called Small-Signal Large-Signal (SSLS) analysis [2], leading to the Conversion Matrix characterization of the active device. Several applications exploit the SSLS analysis; perhaps the best know is the simulation of non-saturated mixers. However, the SSLS analysis is also the basis for noise analysis in LS operation, as well known from noisy circuit theory [3].

In the present paper, we propose a complete, CAD-oriented, physics-based conversion and noise characterization of a nonlinear device under (quasi) periodic operation by means of the HB analysis technique and of a full generalization of the Impedance Field Method to the analysis of multidimensional devices through a drift-diffusion model, according to the theory outlined in more detail in [4]. After a short outline of the underlying theory, a practical example based on a varactor diode frequency multiplier is presented, and the physics-based model is compared to simpler, circuit-oriented approaches.

THEORY

The basis for the present approch is the application of the HB method to the physics-based modelling of active semiconductor devices. Starting from the HB solution, the SSLS analysis is carried out by linearizing the device model around the instantaneous working point, and by applying a small-amplitude harmonic signal. As well known, the small-change device response is linear, and is made of a set of sidebands of the original LS spectrum deriving from frequency mixing by the linearized system, which is time-varying. As usual, we define as upper or lower sidebands of the LS spectrum ω_i a set of frequencies $\omega_{\pm k}$ such as $\omega_{\pm k} = \omega_i \pm \omega$, respectively. An input signal belonging to the sideband set is shown to be converted into an output signal belonging to the same sideband set. More generally, a set of sideband input signals generates a set of sideband output signals. The linear relationship between the complex amplitudes of the input and output sideband signal is given by the so-called conversion matrix (CM), and the resulting representation of the device is often referred to as a multi-frequency, multi-port device [2], see Fig.1. Notice that each port is associated to a specific sideband, and that the CM generally depends on ω.

The physics-based noise analysis of semiconductor devices in (quasi) periodic large-signal conditions can be interpreted as a generalized SSLS analysis, wherein the small-amplitude, harmonic signal actually is a stochastic fluctuation (the microscopic noise sources) arising within the device, rather than a deterministic, externally applied source. In fact, carrier density (generation-recombination noise, GR) or velocity (diffusion noise) fluctuations occurring in the device volume can be interpreted as small perturbations of the LS (quasi) periodic steady state, thus enabling the device response to be evaluated by means of a linear model.

With respect to conventional, small-signal noise analysis, the LS case is also made complex by the fact that microscopic noise sources are periodically amplitude-modulated by the instantaneous working point. Such a modulation implies a frequency conversion process of the noise sources [5]. Because of this process, each harmonic component of the unmodulated noise in converted into a set of correlated sidebands. The resulting noise spectrum can be therefore described by means of a sideband correlation matrix (SCM); noise components which do not have the same frequency separation from two harmonics of the LS steady state are uncorrelated. The same characterization also applies to the noise generators appearing in the multifrequency equivalent circuit of the nonlinear device under SSLS operation, see Fig.1. In order to evaluate the SCM of a set of noise generators appering in the multifrequency linear equivalent circuit, the classical Impedance Field Method for noise analysis [6] can be conveniently extended. Such an extension was first proposed by Cappy *et al.* [7] with reference to a quasi-2D FET model.

As a basis for the physical analysis, we make use of a bipolar drift-diffusion physics-based model discretized through the conventional finite-box approach and we solve an equation set including both the discretized model and the external circuit equations by means of the HB method. The so-called random sampling technique was exploited, allowing for non-commensurate sources (see e.g. [2]). After the HB solution, the sideband conversion matrix of the device is evaluated through linearization and the sideband correlation matrix of noise generators is computed according to the Generalized Impedance Field theory described in [4]. More specifically, the modulated microscopic noise source distribution is computed from the steady-state solution according to the main noise mechanisms (diffusion noise and generation-recombination noise) in terms of a space-dependent SCM. As usual, the spatial correlation of microscopic noise sources is neglected. Then, the external response of the linearized device to a microscopic noise source located in an internal point $\vec{r}$ is computed through SSLS. This means that a set of sideband microscopic noise sources (with SCM given by $\overleftrightarrow{\mathbf{K}}_{\delta\vec{J}_\alpha\delta\vec{J}_\alpha}$ for diffusione noise and $\mathbf{K}_{\gamma_\alpha\gamma_\beta}$ for GR noise) induces, on the external device terminals, a set of sideband noise generators whose second-order statistical properties (the SCM) can be computed through a conversion-matrix Green's function approach as follows:

$$\mathbf{S}_{\delta i_i \delta i_j}(\omega) = \sum_{\alpha=n,p} \int_\Omega \vec{\mathbf{G}}_{\alpha,i}(\vec{r},\omega) \bullet \overleftrightarrow{\mathbf{K}}_{\delta\vec{J}_\alpha\delta\vec{J}_\alpha}(\vec{r}) \bullet \vec{\mathbf{G}}^\dagger_{\alpha,j}(\vec{r},\omega)\,\mathrm{d}\vec{r} + \sum_{\alpha,\beta=n,p} \int_\Omega \mathbf{G}_{\alpha,i}(\vec{r},\omega) \cdot \mathbf{K}_{\gamma_\alpha\gamma_\beta}(\vec{r}) \cdot \mathbf{G}^\dagger_{\beta,j}(\vec{r},\omega)\,\mathrm{d}\vec{r}$$

where Ω is the device volume. Without loss in generality, we consider the SCM of the short-circuit current fluctuations, $\mathbf{S}_{\delta i_i \delta i_j}(\omega)$. Once the SCM of the noise generators has been evaluated, the device noise model is completed by the admittance conversion matrix [2], which is again obtained by linearization of the LS model around the instantaneous working point, see [4]. A full multifrequency conversion and noise representation of the device is thus obtained.

RESULTS

As a case study, we analyzed a varactor diode frequency doubler. The circuit structure, shown in Fig.2, is conventional, and provides input and output matching together with suppression of unwanted harmonics through the idler resonators. The reverse-biased microwave *pn* diode is described by a drift-diffusion bipolar physical model. The HB simulation was carried out through a mixed-mode approach, in which the linear elements connected to the diode are included into the physical model as boundary conditions. The element values were optimized so as to achieve optimum frequency conversion (60% conversion gain at 10 dBm input power). For an input frequency of 1 GHz, the physics-based HB simulation was carried out with 350 grid points and 4 harmonics plus DC.

In Fig.3, the conversion matrix elements of the diode are compared with those derived from a simple large-signal equivalent circuit characterized through DC and small-signal AC simulations. The equivalent circuit basically consisted of a nonlinear capacitance, whose behaviour was fitted against AC physics-based simulations. Excellent agreement can be observed between the physics-based and the equivalent circuit model.

The same agreement can be noticed when comparing the correlation matrix of the external diode noise sources, as derived from the physics-based analysis, with those obtained from the generalized Nyquist theorem. These include standard shot and thermal noise generators, as discussed in [5]. The comparison is shown in Fig.4.

Finally, Fig.5 shows the total noise spectrum on the load resistor due to the diode and to the noisy source resistor; an input signal generator with zero phase and amplitude noise was assumed. The noise contribution at the higher harmonics is found to be suppressed by the idler resonators, while, at the second (output) harmonic, the device contribution is slightly smaller than the generator resistance contribution, thus yielding an operating noise figure around 1.5. As expected, the same result is obtained through the noisy equivalent circuit model.

CONCLUSIONS

A full, physics-based multi-frequency conversion (SSLS) and noise characterization of a microwave nonlinear active device operating in (quasi) periodic regime has been demonstrated. Preliminary results on a simple structure (*pn* varactor diode) show good agreement with simpler, circuit-oriented models.

ACKNOWLEDGEMENTS

This work was partly supported by the Italian Ministery of Foreign Affairs through the Italian-Lithuanian project "Research and development cooperation in submicron electronics".

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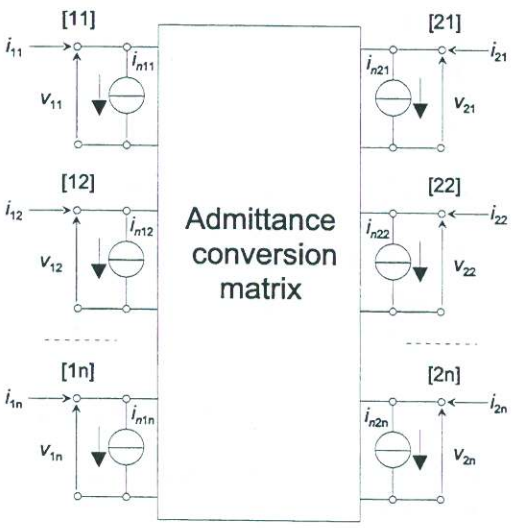

Figure 1: Multifrequency SSLS representation of noisy two-port.

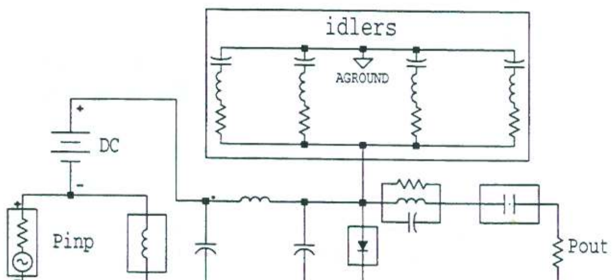

Figure 2: Circuit scheme for the varactor frequency doubler.

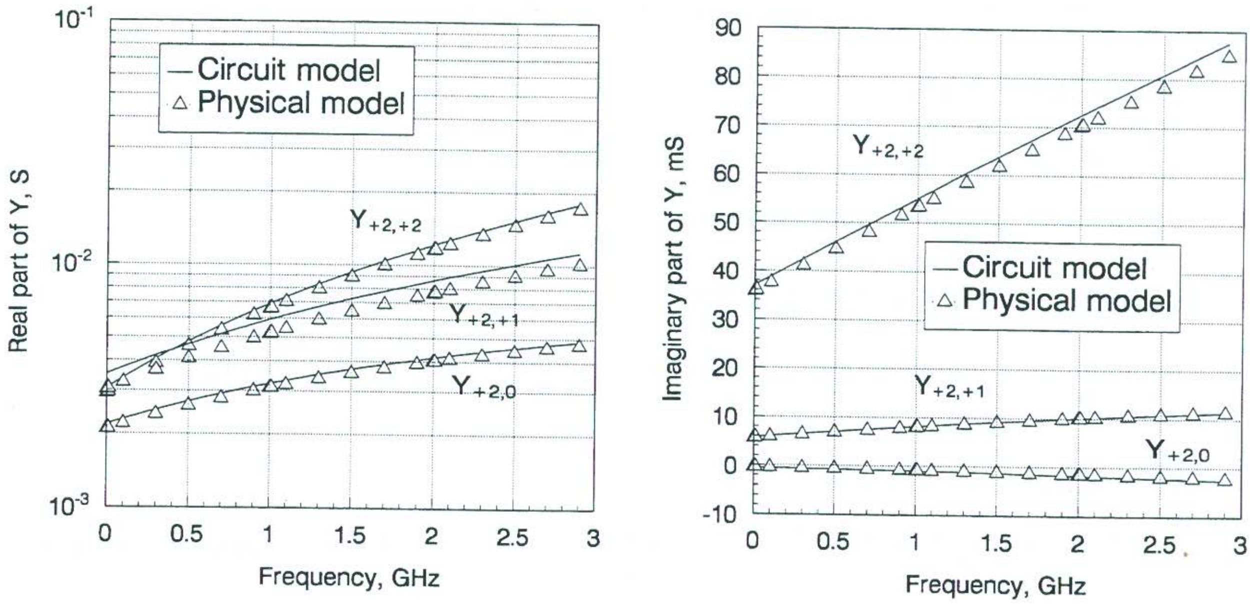

Figure 3: Frequency dependence of the real (left) and imaginary (right) part of the elements $Y_{+2,+2}$, $Y_{+2,+1}$ and $Y_{+2,0}$ of the varactor admittance conversion matrix. The full line is the result from circuit analysis, the triangles from the physical model. The absolute frequency corresponding to the sideband angular frequency ω of sideband $\pm n$ is $n\omega_0 \pm \omega$.

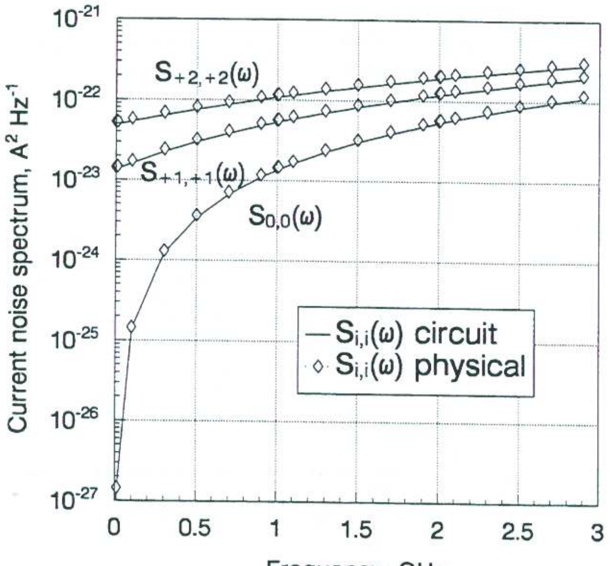

Figure 4: Comparison between the frequency dependence of the diode current noise correlation spectra evaluated through circuit and physics-based analysis. Only the power spectra of sidebands $(+2,+2)$, $(+1,+1)$ and $(0,0)$ are shown.

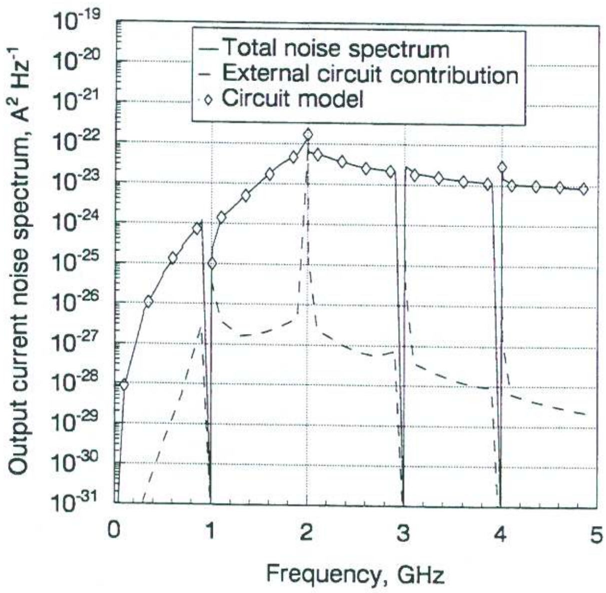

Figure 5: Load current noise spectrum for the varactor frequency doubler.