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Measurement-based nonlinear integral modelling of microwave diodes

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Abstract. *In this paper, the Nonlinear Integral Model is applied for the large-signal performance prediction of a Varactor Diode. It is shown as a very simple parasitic de-embedding procedure can be efficiently adopted to improve the accuracy of the model. As an example of application, the design of a varactor frequency doubler operating at the fundamental frequency of 10 GHz is presented.*

Introduction

The Nonlinear Integral approach has been successfully applied for the nonlinear modelling of microwave GaAs MESFETs [1..3]. Such an approach, which is based on nonlinear system theory, falls within the category of measurement-based models [4]. The main purpose of these modelling methodologies is the accurate computation of the large-signal dynamic device response directly on the bases of conventional measurements, without need for technology-dependent, analytically approximated equivalent circuit components and optimisation-based parameter extraction procedures. In particular, the Nonlinear Integral Model (NIM) [1..3] is a purely mathematical (i.e., black-box) model which can be directly identified on the basis of conventional measurements (DC characteristics and small-signal bias/frequency dependent AC parameters). The basic assumption of the NIM is that the electron device to be modeled is characterised by short-term nonlinear memory effects [1] when described in voltage-controlled form. This implies that the device current response to voltage pulses vanishes in a time much shorter than the period associated to the operating frequency. This assumption is normally verified in the presence of negligible parasitic effects. However, as far as microwave diodes operating at relatively high frequencies are concerned, the nonlinear memory effects may be not negligible due to the presence of important parasitics. A typical example is represented by Varactor Diodes, where the device current/voltage response is slowed down by the presence of important nonlinear resistive parasitic effects. In fact, in [5] it has been shown that the accuracy of the NIM for the large-signal performance prediction of a varactor frequency doubler is relatively poor. In this paper it is shown as a very simple de-embedding procedure for parasitic effects can be efficiently adopted for the NIM applied to a Varactor Diode.

The Nonlinear Integral Model

For a single-port electron device the current/voltage expression of the NIM is:

$$i(t) = F_{dc}\{v(t)\} + \sum_{k=-M}^{M} \widetilde{Y}\{v(t), \omega_k\} V_k e^{j\omega_k t} \qquad \text{with } \widetilde{Y}[v,\omega] = Y[v,\omega] - Y[v,0] \tag{1}$$

where V_k are the harmonic components of $v(t)$ and $\omega_k = k2\pi/T$. In the above equation, F_{dc} is the dc characteristic of the device, while $\widetilde{Y}$ is a frequency and *voltage-dependent nonlinear dynamic admittance* [1] which describes only the purely dynamic part of the device response, since $\widetilde{Y}[v,0] = 0$ according to eqn. (1).

The nonlinear voltage controlled dynamic admittance $\widetilde{Y}$ can be **directly** identified according to (1) in terms of conventional small-signal admittance parameters[1] measured under different bias conditions and within the frequency range of interest, without requiring numerical fitting procedures. Only a discrete characterisation of the electron device, in the space of the controlling variable v and ω_k,

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[1] The admittance parameters can be obtained through simple transformations of scattering parameters which are more easily measured at microwave frequencies.

can be carried out (i.e., the DC characteristics F_{dc}, including also the DC differential conductances Y[v,0], and the admittance parameters Y[v,ω] are measured for a discrete set of bias conditions and frequencies). Then the measured data are stored in look-up tables, which are used, together with suitable interpolation algorithms, to compute the values of the nonlinear dynamic admittance for each set of controlling variables occurring during the Harmonic Balance (HB) analysis. On such a basis eqn. (1) can be directly used to predict the device large-signal dynamic response in the framework of a HB analysis programme.

An important property of the NIM is to be intrinsically exact in DC and small-signal operations. In such conditions, in fact, the model simply coincides, respectively, with the measured DC characteristics and admittance parameters.

Equation (1) is derived from a more complex multidimensional, Volterra-like integral series [1] which represents a rigorous, general model for nonlinear dynamic systems. This nonlinear integral series can be truncated to the first term (which, applying well-known properties of the Fourier Transform, leads to eqn. (1)), under the reasonable assumption that the duration of nonlinear memory effects in an electron devices is much shorter than the inverse of the typical operation bandwidth. Under this hypothesis, the validity of the NIM is not limited to the case of weak nonlinearities as happens for other Volterra-based approaches.

Modelling the Varactor Diode

The main purpose of the modelling methodology presented is the accurate large-signal performance prediction of a Varactor Diode at high operating frequencies even in the presence of important parasitic effects. At high operating frequencies, in fact, parasitic phenomena become more important as they can strongly affect the device behaviour. In particular, the dynamic response becomes much slower with respect to the intrinsic device, so that the basic short-term nonlinear memory hypothesis of the NIM may not be satisfied.

In this paper it is shown as a very simple de-embedding procedure for parasitic effects can be efficiently adopted for the Nonlinear Integral Modeling of Varactor Diodes. In order to put in evidence the improvement in large-signal performance prediction, the same procedure of [5] is adopted.

More precisely, a physics-based model (PBM) of a Varactor Diode (see Fig.1), operating under reverse bias, is considered as the "reference" test device whose large-signal dynamic performance has to be compared with the performance predicted by the NIM. This procedure is particularly useful since enables the accuracy properties of the NIM to be evaluated by prescinding from measurement errors of a true experimental validation. Moreover it is sufficiently significative, since the physics-based model, apart from problems concerned with its identification, represents a good description of an actual Varactor Diode.

The brute-force application of the NIM to the diode in Fig.1 necessarily leads, in strongly nonlinear operation at high frequencies, to a relatively poor accuracy of large-signal performance prediction as it has been shown in [5]. This is quite obvious, since the presence of a large nonlinear series resistance, associated to the neutral region, is responsible for memory effects with long duration. In such conditions, a suitable de-embedding procedure of the series resistance should be adopted before applying the NIM approach. A possible strategy could be based on bias-dependent measurements of the device impedance in order to identify the series resistance behaviour before applying the NIM to the nonlinear depletion capacitance. However, simulated results have shown that this is not necessary, since a sufficiently accurate model can be obtained by simply de-embedding from a constant (i.e., linear) value of the series resistance. In particular, Fig.2 shows the rms error $\sqrt{\sum_{k=0}^{8} |I_{PBMk} - I_{NIMk}|^2 / \sum_{k=0}^{8} |I_{PBMk}|^2}$ between the PBM and NIM current responses, under large-signal sinusoidal voltage excitation at different frequencies, plotted as a function of the de-embedded linear resistance R_s (I_{PBMk} and I_{NIMk} being the current harmonic components of the PBM and the NIM, respectively). It is evident that a minimum of the error, substantially independent of the operating frequency, can be found. It is worth noting that the optimal linear resistance value is practically coincident with the neutral resistance value corresponding to the diode bias condition ($V_B = -10V$). Thus the de-embedding procedure simply requires to measure the real part of the device low-frequency impedance at the operating bias point.

This simple de-embedding procedures, which normally is not very effective in equivalent circuit approaches where an accurate parasitic identification is needed, gives good results for the NIM since, in order to verify the basic assumption of the model, it is sufficient to reduce the duration of the memory effects, by "extracting" a suitable part of the parasitic resistance.

In order to verify the accuracy of the NIM for the varactor diode, the same frequency doubler circuit used in [5] has been adopted (see Fig.3). In particular, the varactor is biased at $V_B = -10V$ and the fundamental frequency is 10GHz. Fig.4 shows the 2nd-harmonic component associated to the output power of the frequency doubler computed through the PBM and predicted using the NIM with and without resistance de-embedding (the latter case corresponds to the results presented in [5]). It is well evident the great accuracy improvement obtained through the simple de-embedding procedure adopted. The same accuracy improvement can be seen in Fig.5, which shows the comparison between the spectrum of the Varactor Diode current computed through the PBM and the performance predicted through the NIM for an input power of 18dBm.

Conclusion

The response of a physics-based model of a Varactor Diode operating under reverse bias has been compared with the performance predicted by the NIM under strongly nonlinear operating conditions. As an example the application to a frequency doubler has been considered.

Simulation results have shown that the brute-force application of the NIM is valid for relatively mild nonlinear operations, due to the parasitic series resistance associated to the neutral region that is responsible for memory effects with long duration. It has been shown that accuracy of the large-signal performance prediction of the model can be improved by adopting a very simple de-embedding procedure of the parasitic effects, before applying the NIM to the intrinsic device.

When considering an "actual" device (in a more realistic approach), parasitic modelling is more complicated due to the external connections and/or package and would involve more complex parasitic extraction procedures. In such a condition, an approach [6,7] (which represents a development of the NIM) "more robust", with respect to uncertainties in parasitic de-embedding, can be applied.

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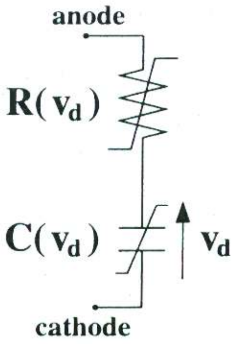

$$R(v_d) = R_0 \left(1 - \frac{(1 - v_d/V_0)^\alpha - 1}{(1 + V_L/V_0)^\alpha - 1}\right)$$

$$C = \frac{C_0}{(1 - v_d/V_0)^\alpha}$$

Fig.1: PBM model of a Varactor Diode. $R_0 = 20\Omega$, $V_L = 40V$, $V_0 = 4V$, $\alpha = 3$, $C_0 = 10pF$.

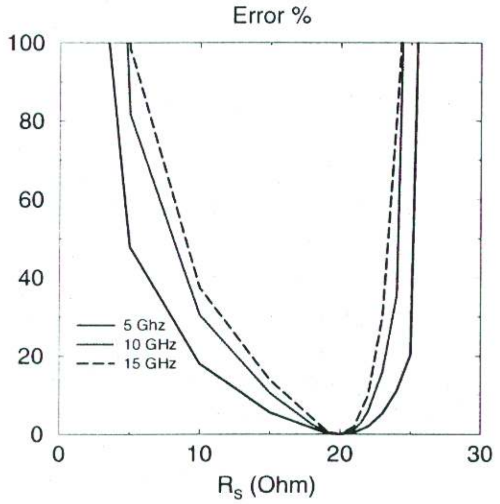

Fig.2: RMS error between the PBM and NIM currents as a function of the de-embedded resistance R_s.

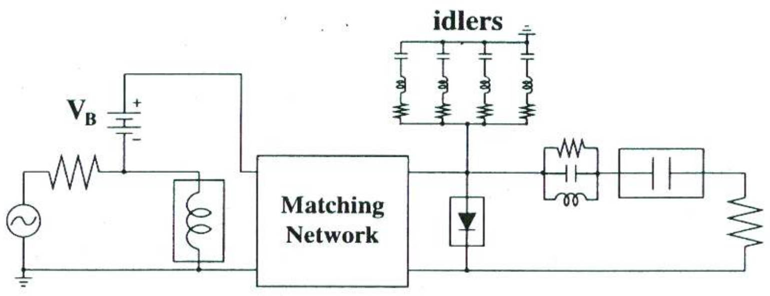

Fig.3: Electrical schematic of the frequency doubler.

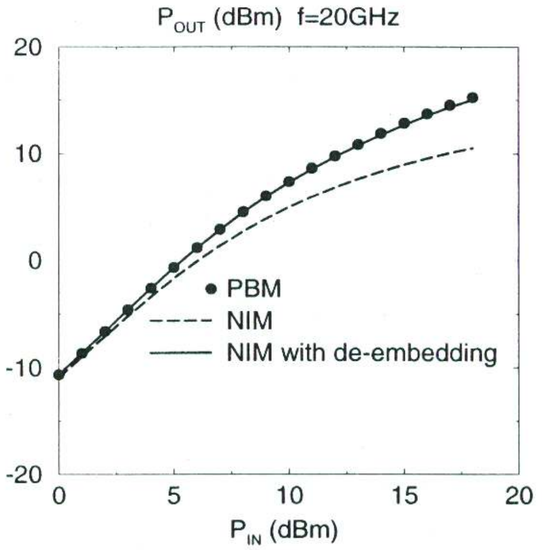

Fig.4: Output power at 20GHz as a function of the available input power for the PBM, the NIM and the NIM with de-embedding.

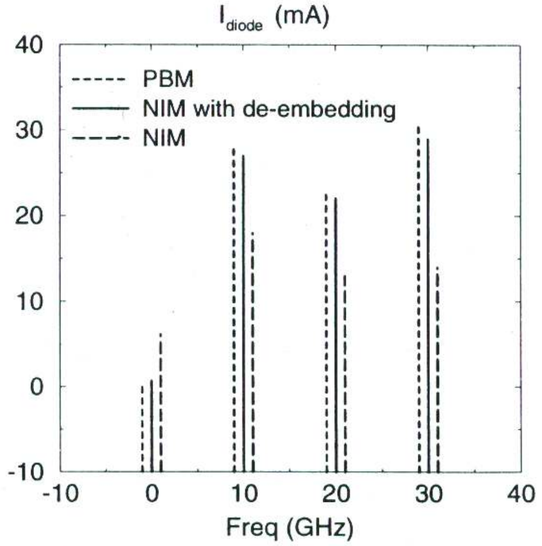

Fig.5: Spectrum of the diode current computed through the PBM and predicted by the NIM and the NIM with de-embedding ($P_{IN} = 18dBm$).