Relaxation-Time Modeling for NQS Phenomena Characterization in High-Frequency Diodes

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***Abstract*—A characterization methodology for nonquasi-static (NQS) phenomena in high frequency electron devices is carried out in this work. The proposed nonlinear diode model includes a S-parameters-based procedure for the estimation of the parasitic network, and the direct extraction of the nonlinear intrinsic state functions from single-tone measurements. This NQS proposal, based on a first-order electric charge source, was validated for some commercial diodes improving the prior QS model when frequency rises. A voltage-discretization analysis and some small signal (0.7-20 GHz) and waveforms (f_0 = 2 and 8 GHz) tests, prove the successful performance of these circuits and their frequency extrapolation possibilities versus foundry models.**

***Index Terms*—Nonquasi-Static Phenomena, Varactor, Schottky Diode, High-Frequency, Nonlinear Network Vector Analyzer.**

I. INTRODUCTION

It seems that state-of-the-art requirements in terms of user massive demand, high bandwidth needs, and low latency requests force to the new prototypes to go up in frequency. This fact poses several challenges for mmWave-designers nowadays and, undoubtedly, the proper characterization of nonquasi-static (NQS) high-frequency phenomena can be considered one of the most attractive in the development of modern communications circuits [1]. Indeed, the proper modeling of finite time required for electric charges redistribution when control voltage changes in electron-devices is becoming essential due to the emergence of innovative reconfigurable solutions based on active devices such as diodes, varactors, or transistors [2].

In accordance, the interest of these components in novel antennas was born because of their voltage-control capabilities leading to robust and automated designs based on a hardware-software interoperability. Therefore, it is justified to spend efforts for providing robust equivalent circuits in order to enhance co-design and system-level RF-architectures. This contribution presents the experimental validation of the quasi-analytical extraction technique formulated for one-port devices in [3] from a first-order NQS electric charge approach [4], and software-based tested in [5]. Specifically, two varactors and a Schottky diode equivalent models were extracted for verifying the intrinsic delay state functions over different technologies.

The technique, which combines a multi-bias S-parameters de-embedding for the extrinsic network estimation with an original strategy for the intrinsic modeling from frequency domain nonlinear measurements, has also been studied from the voltage discretization-performance tradeoff.

After this *Introduction*, *Section II* summarizes the formulation of the proposed extraction methodology which is based on the Nonlinear Function Sampling (NFS) [3], [5] operator. In *Section III*, the experimental validation of the technique over some commercial devices [6]–[8] evidences the advantages of the NQS equivalent model at high frequency versus the QS and Foundry alternatives. A discretization analysis from voltage intervals (N_v) is also included. Conclusions are in *Section IV*.

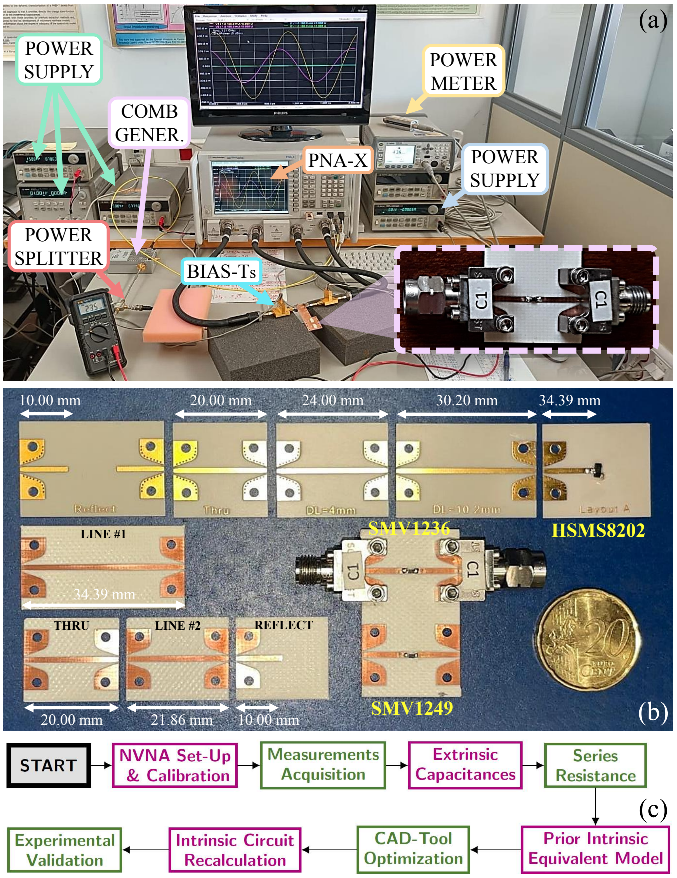
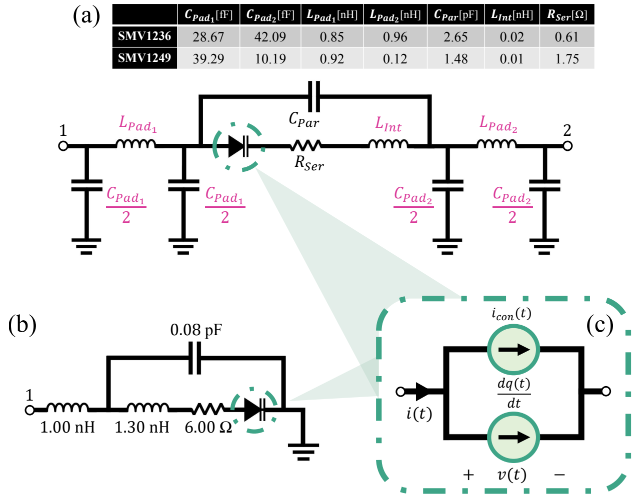


Fig. 1. (a) NVNA-based nonlinear single-tone setup including power, vectorial and phase calibrations. (b) Access lines and TRL cal-kits layouts for the DUTs. (c) Flowchart for extrinsic and intrinsic parameters extraction.

II. DIODE'S EQUIVALENT MODEL FORMULATION

The implementation of the equivalent diode model requires both multi-bias S-parameters and single-tone (f_0) waveforms measurements. Fig.1.a shows the NVNA PNA-X Agilent™ N5247A setup together with the two varactors under test (DUTs): the Skyworks™ SMV1236 [6] and SMV1249 [7],



	C_{Pad_1}[fF]	C_{Pad_2}[fF]	L_{Pad_1}[nH]	L_{Pad_2}[nH]	C_{Par}[pF]	L_{Int}[nH]	R_{Ser}[Ω]
SMV1236	28.67	42.09	0.85	0.96	2.65	0.02	0.61
SMV1249	39.29	10.19	0.92	0.12	1.48	0.01	1.75

Fig. 2. (a) Proposed equivalent varactor circuit and extracted values. (b) Avago™ HSMS 8202 linear elements. (c) Two-current-based intrinsic model.

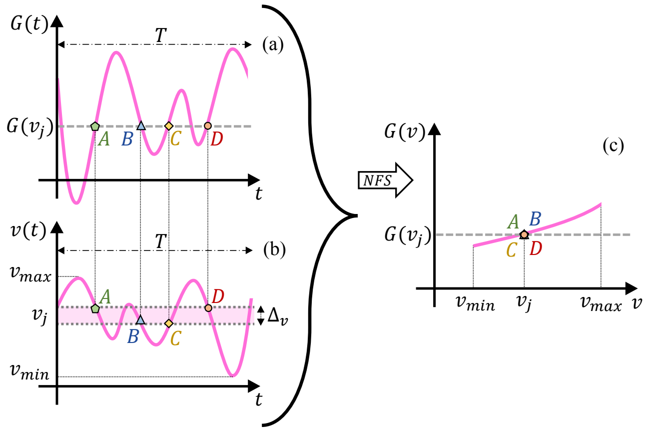


Fig. 3. (a-b) Samples A, B, C and D of a generic QS-function $G(t)$, which exclusively depends of a control voltage $v(t)$, are turned into a v_j (X axis) and $G(v_j)$ (Y axis) single value in the (c) voltage domain by the NFS operator if the Δ_v discretization is small enough to belong to a same voltage interval.

and the Avago™ HSMS8202 Schottky diode [8]. The varactors were tested "in transmission" (one port per terminal), and the Schottky diode with one grounded port in 20 mils microstrip FR4-CIF™ ($\varepsilon_{eff} = 4.32$ & $tan(\delta) = 0.014$), and RO4003C™ ($\varepsilon_{eff} = 2.84$ & $tan(\delta) = 0.0021$) substrates, respectively (Fig. 1.b). The extraction flowchart is described in Fig. 1.c.

A generic linear circuit with a π-access equivalent-line was proposed as high-frequency solution for varactors (Fig. 2.a). The process leads to the extrinsic capacitances and the series resistance from low-frequency S-parameters (1) at reverse and forward bias [3]. The inductances were obtained by a $M = 201$ frequency-samples ADS™-optimization from this cost function per bias: $(|S_{xy}^{model} - S_{xy}^{meas}|)^2/M \approx 0$. For the Schottky diode, datasheet values were used in tests (Fig. 2.b).

$$C_{Total}(v) = \frac{\mathfrak{Im}[-Y_{12}(v)]}{\omega} = \underbrace{C_{j0}\left(1 - \frac{v}{V_J}\right)^{-M}}_{C_j(v)} + C_{Par} \tag{1}$$

$$C_{Pad_1} = \frac{\mathfrak{Im}[Y_{11} + Y_{12}]}{\omega} \qquad R_{Ser} + R_j(v) \approx \frac{1}{\mathfrak{Re}[-Y_{12}(v)]}$$

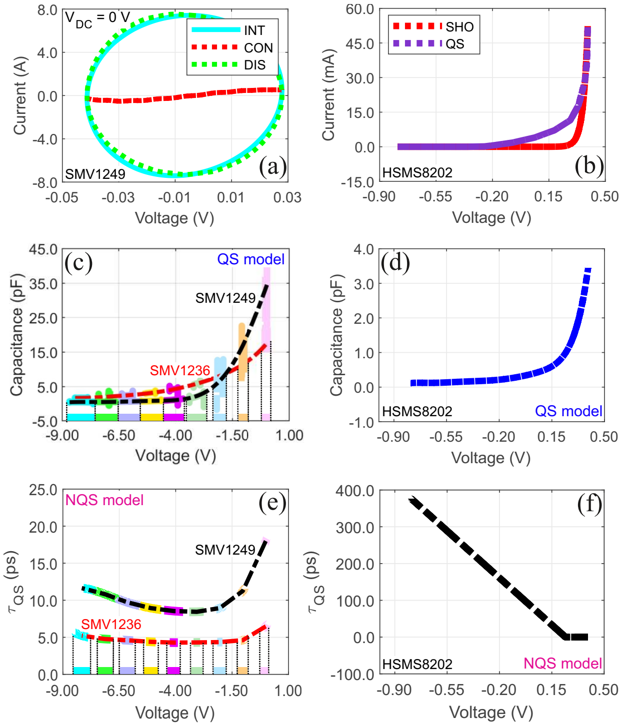


Fig. 4. (a) The assumption of $i_{con}(v) \approx 0$ A is valid for varactors. (b) Estimated $i_{con}(v)$ QS state function versus Shockley's Law typical approach for the Schottky diode. (c-d) Fitted capacitance $C_{QS}(v)$ for the QS-equivalent model. (e-f) Extracted delay function $\tau_{QS}(v)$ for the NQS-equivalent circuits.

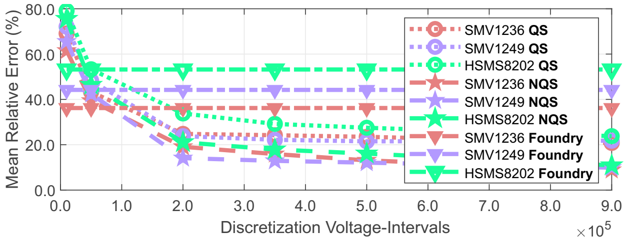


Fig. 5. Mean relative error (%) [3] in current and voltage experimental waveforms under test versus some N_v values of the DUTs' extracted-models.

The adopted first-order NQS charge (2) is the difference between the QS and NQS [4] nonlinear dynamic models (Fig. 2.c) where the total intrinsic current $i(t)$ is the sum both conduction $i_{con}(t)$ and displacement $i_{dis}(t)$ sources [3], [5]:

$$\begin{aligned} q_{NQS}(t) &= q_{QS}(v) - \tau_{QS}(v)\frac{dq_{NQS}(t)}{dt} \\ i(t) &= i_{con}(t) + i_{dis}(t) = i_{con}(v) + \underbrace{\frac{dq(t)}{dt}}_{\text{QS or NQS}} \end{aligned} \tag{2}$$

The NFS operator allows mapping involved waveforms into voltage domain by establishing useful conditions between the real and imaginary parts of the involved spectral coefficients (Fig. 3). This makes feasible to directly extract the unknown QS-magnitudes from the port currents and voltages: $i_{con}(v)$ and $q_{QS}(v) = C_{QS}(v)/dv$ (QS model), and $q_{QS}(v)$, and $\tau_{QS}(v)$ (NQS version, where $i_{con}(v)$ component must be earlier known [5]). A proper number of voltage-discretization intervals (N_v) is key for a low-error modeling, as in Fig. 5.

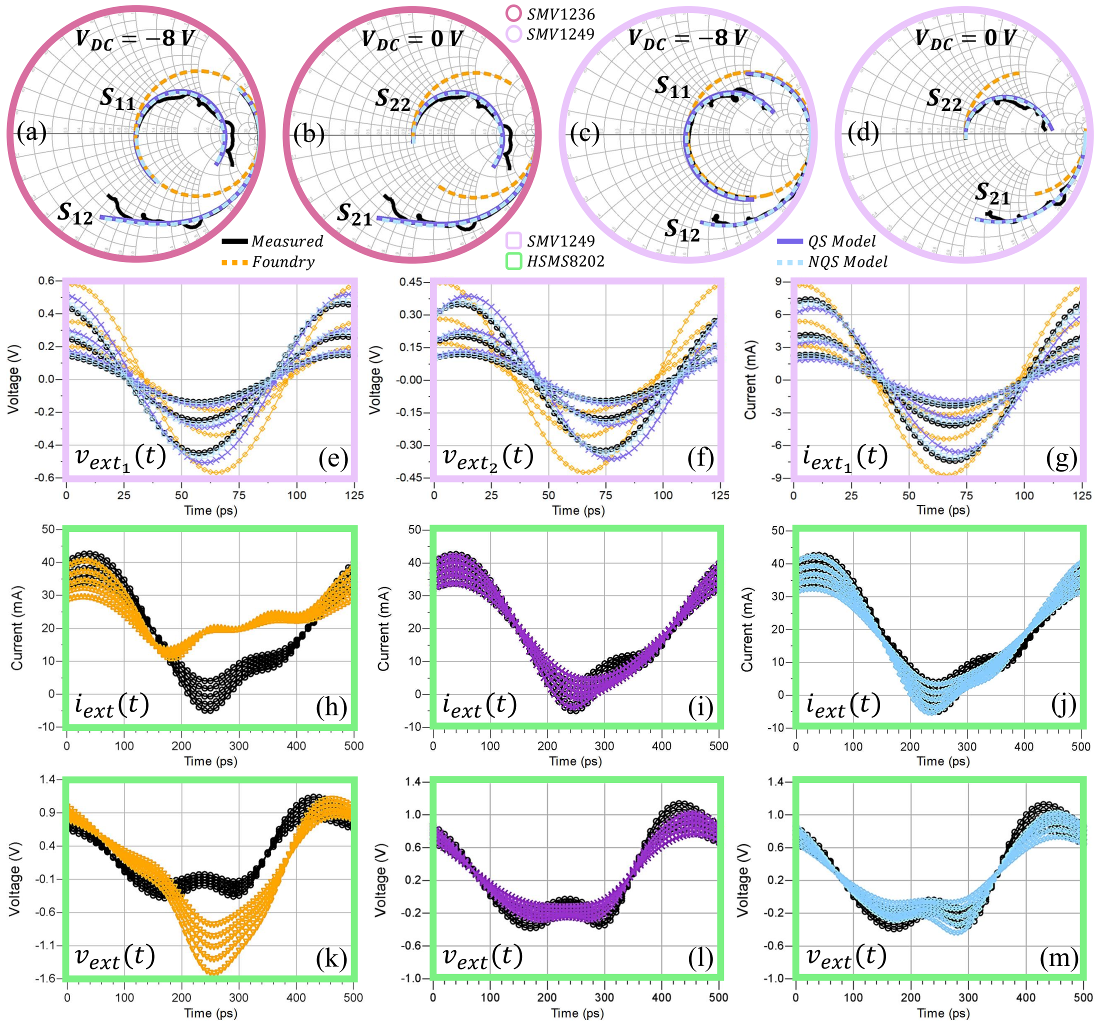


Fig. 6. (a-d) Measured S-parameters (black) versus Foundry (orange), QS (purple) and NQS models (blue) from 0.7-20 GHz at $V_{DC} = -8$ & 0 V for SMV1236 (pink), and SMV1249 (violet) varactors. Port voltage and current waveforms under single-tone injection for (e-g) SMV1249 varactor (violet) at $f_0 = 8$ GHz, $V_{DC} = 0$ V, $P_{RF} = [-5, 0, 5]$ dBm, and (h-m) HSMS8202 Schottky (green) at $f_0 = 2$ GHz, $V_{DC} = 0$ V, $P_{RF} = [9.7 : 1.3 : 15]$ dBm.

III. TESTS & EXPERIMENTAL VALIDATION

Figs. 4.a-b plot how the $i_{con}(v)$ is negligible for varactors and the QS-approach required for the Schottky diode NQS-model. Extracted state functions were fitted by n-order polynomials (Figs. 4.c-f) and varactors characterization were done in pieces due to current limitations. Fig. 6 small signal and waveforms tests confirm that varactors linear network works suitably and the mean relative error is, on average, better with the NQS circuit ($\bar{\delta} \approx 13.4\%$) versus the QS ($\bar{\delta} \approx 22.7\%$), and the Foundry ($\bar{\delta} \approx 41.9\%$) model. The proposal frequency response is adequate since the extraction was done at 1 GHz but verified at 8 GHz, when NQS phenomena seem noticeable.

IV. CONCLUSIONS

An equivalent nonlinear extracted model has been validated with commercial varactors and Schottky diodes. The extracted circuits, which include an own extrinsic parameters network and a first-order NQS-electric charge intrinsic source, have proven their high-frequency advantages under small and waveforms tests in comparison to the QS and Foundry alternatives.

ACKNOWLEDGMENT

This work is supported by the Universidad de Málaga (*PhD Grant-401*), and the *UMA20-FEDERJA-001* regional project.

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