Non-Quasi-Static Modeling of the Intrinsic Y_{22} for GaN, Si, and GaAs mm-Wave FET Technologies

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***Abstract*—The extraction of accurate transistor models is essential for a reliable and efficient design of transmit/receive modules, which in turn is a keystone for the development of active electronically scanned array radars. The present paper is aimed at analysing the implementation of non-quasi-static effects for advanced millimeter-wave FET models. The non-quasi-static phenomena can be neglected at few GHz but their contributions become more and more dominant by increasing the operating frequencies. In particular, this study is focused on the investigation of the non-quasi-static effects for modeling the intrinsic short circuit output admittance for FETs based on gallium nitride, silicon, and gallium arsenide technologies. Different model solutions are carefully compared and analysed in detail.**

I. Introduction

The transmit/receive (T/R) modules are at the heart of successful active electronically scanned array (AESA) radars, because these modules play a crucial role in determining the performance, reliability, size, weight, and costs of the entire system [1-3]. Reliable and efficient design of T/R modules requires accurate millimeter-wave models for transistors [4-16]. For that reason, the target of the present paper is to analyse different non-quasi-static (NQS) models for advanced millimeter-wave FETs based on gallium nitride (GaN), silicon (Si), and gallium arsenide (GaAs) materials. The attention is devoted especially to the intrinsic section of the small-signal equivalent circuit that is obtained after removing the extrinsic effects, which are assumed to be bias independent [4]. The intrinsic NQS contributions of the model have a more dominant effect at higher frequencies, since they are used to model the time constants representing the inertia of the intrinsic transistor in responding to rapid signal changes [5]. Depending on the specific device technology, some NQS phenomena can play a major role or can be even disregarded. As a consequence, a detailed and thorough study of the intrinsic admittance (Y-) parameters is mandatory for establishing the most appropriate intrinsic circuit topology for each investigated case. This analysis is of great importance also for determining accurate large-signal circuit models, which are oftentimes built by employing the multi-bias small-signal equivalent circuit as the cornerstone [6-8].

In particular, the present study is focused on analysing the NQS effects for modeling the intrinsic short circuit output admittance Y_{22} and their impact on S_{22} of the whole FET, which includes the extrinsic contributions. Although the accuracy in modeling Y_{22} can affect the simulation of all scattering (S-) parameters, typically Y_{22} has a stronger impact on the parameter S_{22}, which represents the output reflection coefficient by which port 1 is terminated by 50 Ω.

II. Non-Quasi-Static Effect Implementation

This section is organized into three subsections, which are respectively devoted to the analysis of the NQS intrinsic circuit models for a GaN HEMT, a Si FinFET, and a GaAs pHEMT. In order to reproduce accurately the behaviour of these three transistors, the small-signal equivalent circuit topology has been adapted to each specific case and then the circuit elements have been analytically extracted. Here, our analysis is dedicated to investigating the circuit model differences reflecting the diversities observed in the behaviour of the intrinsic Y_{22}.

A. GaN HEMT

Fig. 1 shows the equivalent circuit used for modeling the investigated 0.7x800 μm^2 GaN HEMT [8]. The intrinsic Y-parameters are extracted from S-parameters measured over 0.04 GHz - 40 GHz range, after removing the extrinsic effects with a ''cold'' FET extraction procedure. Such techniques are called "cold" because based on S-parameters at zero V_{ds} [11].

By adopting the QS assumption, which corresponds to neglecting the time constants, the real parts of the intrinsic Y-parameters should be frequency independent, while the imaginary parts of the intrinsic Y-parameters should be proportional to the frequency. Since the experimental data have shown clear evidence that this approximation is gracefully degraded by increasing the operating frequency, the intrinsic section of the small-signal model reported in Fig. 1 has been expanded with the NQS contributions associated to three circuit elements: R_{gs}, R_{gd}, and τ_{gs}.

As far as the intrinsic Y_{22} is concerned, the presence of the feedback resistance R_{gd} in series with C_{gd} leads to the following definition of this admittance parameter:

$$Y_{22} = g_{ds} + \frac{j\omega C_{gd}}{1 + j\omega R_{gd} C_{gd}} + j\omega C_{ds} \qquad (1)$$