

Systematic Compact Modeling of Correlated Noise in Bipolar Transistors

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Abstract—A systematic method for the integration of correlated shot-noise sources into compact models (CMs) is presented, which significantly improves the accuracy of predicted high-frequency noise in transistors. The developed method relies on a system theory approach, and hence, is not limited to specific CM or device type. In this paper, the method is applied to the CM HICUM, which serves a vehicle for verification purposes. The method and its implementation were verified for SiGe heterojunction bipolar transistors based on measured data for frequencies up to 50 GHz, as well as on device simulation data up to 500 GHz, obtained from simulations of both hydrodynamic and a Boltzmann transport model.

Index Terms—Boltzmann transport equation (BTE), compact modeling, correlated noise, heterojunction bipolar transistor (HBT), high-frequency (HF) noise, hydrodynamic (HD) model, minimum noise figure (NF).

I. INTRODUCTION

FOR implementing a high-frequency (HF) system, the design effort and cost of the associated HF front-end circuit modules represent a significant bottleneck. Hence, efficient circuit design and simulation requires so-called compact models (CMs), which capture very accurately the device characteristics over a wide bias, frequency, temperature, and geometry range [1], including such characteristics as noise and distortion that are important figures-of-merit for HF and power applications [2].

The most recent silicon-germanium (SiGe) heterojunction bipolar transistor (HBT) process technology development has

spurred rapidly increasing interest in millimeter-wave and terahertz applications (e.g., [3]). As a consequence, the accurate description of HF noise correlation in CMs has become important for circuit design. However, commercial circuit simulators can only handle uncorrelated noise sources for large-signal models, and access to simulator code by model developers is usually restricted. Some simulators (such as Advanced Design System (ADS) and MWOoffice) offer the definition of a frequency-independent noise correlation factor for two-ports, but even this option cannot be applied to CMs with frequency-dependent noise correlation. Since today's advanced CMs are being released in Verilog-A (VA) format, several approaches for implementing HF noise correlation using adjunct networks in large-signal CMs have been published over the past few years [4]–[8]. Unfortunately, these models still exhibit a variety of issues that makes them either inconvenient to use or inaccurate at high frequencies. The approach presented in this paper overcomes these issues in a general way and has been verified against data from both measurements up to 50 GHz and advanced device simulations up to 500 GHz.

This paper is organized as follows. After a detailed review of existing HF noise correlation models in Section II, the fundamentals of describing noise in electrical networks are briefly summarized in Section III. The latter concludes with the pitfalls in existing circuit simulators and provides the basics for deriving a systematic and general approach for integrating correlated noise sources in Section IV. This approach is applied to bipolar transistors in Section V with the details of the implementation shown in Section VI. Finally, model verification results are presented in Section VII.

II. REVIEW OF THE CORRELATED NOISE REALIZATION IN LARGE-SIGNAL MODELS

Generally, VA enables a much faster model development compared to the (classical) coding within a simulator. However, the implementation of certain equations, such as those for non-quasi-static (NQS) effects and correlated noise, into a CM using VA is not straightforward since it has to be done through adjunct networks. To our best knowledge, the first implementation of noise correlation in a CM using VA was presented in [4]. However, the realization of the imaginary part of the correlation factor (σ) did not allow a frequency-dependent analysis and made the approach inconvenient for practical applications.

Another solution based on a T-equivalent circuit (EC) was published in [7] using collector charge partitioning. However, the latter causes the magnitude of the transconductance, and thus also the power spectral density (PSD) of the collector current, S_{ic} , to increase with frequency rather than to decrease [8], [9].

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