RELIABLE EXTRACTION OF SMALL-SIGNAL ELEMENTS OF A GENERALIZED DISTRIBUTED FET MODEL

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Abstract

This paper presents a new approach for the reliable determination of the small-signal parameter values of a generalized distributed FET model. For the first time it is shown that unique and physically relevant values for all parameters can be obtained, including the bias-dependent series resistances and the distributed parts of the effective gate-source and drain-source capacitance. The approach has been validated with respect to various FETs with different gate-lengths (0.5 μm - 0.12 μm) in different measurement environment (in-fixture, on-wafer). Exemplary results for a wire-bonded 0.5μm-gate MESFET and a MMIC 0.12μm-gate HEMT are presented and discussed.

Introduction

Accurate small-signal parameter extraction of microwave and millimeterwave FET models is very important for efficient nonlinear device modeling. The topology of common FET equivalent circuits can be partitioned into a linear extrinsic part covering the device parasitics, and a nonlinear intrinsic one which models the active region. Knowing the parasitics the nonlinear device modelling process is tremendously simplified and restricted to the inner part with a reduced number of model elements [1].

The extraction of physically meaningful equivalent circuits of FET devices from S-parameter measurements on the basis of optimization strategies is impeded by the local minimum problem. The problem becomes more severe with extended ultra-broadband equivalent circuits due to an increased number of model elements.

The problem of small-signal model parameter extraction from S-parameter measurements has been widely discussed in the literature for a long time ([2]-[12]). Various procedures have been proposed aiming at the consistent extraction of the parameter values. Recently the physical relevance of the derived values has been strengthened. This applies in particular to the less sensitive model parameters like the gate-, source-, and drain-resistance (R_g, R_s, R_d), the resistive elements in series with the gate-source and the gate-drain capacitance (R_i, R_{gd}), and to the distributed nature of the effective gate-source, drain-source, and gate-drain capacitance.

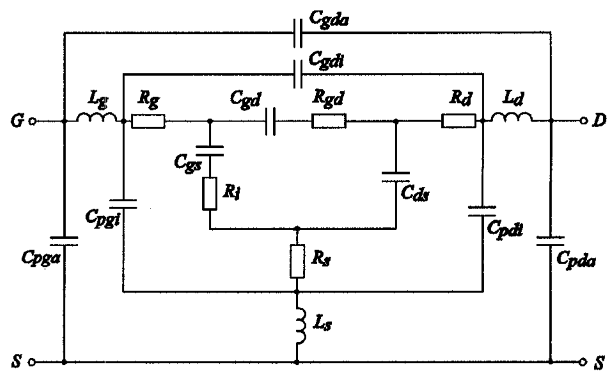

Fig. 1 Distributed pinched-FET equivalent circuit.

Unified FET model topology

A variety of model topologies are known from literature (e.g. [6],[11],[13]-[15]). The extracted model parameter values depend on the chosen equivalent network topology. Often obviously unphysical values (e.g. negative resistances) are extracted. To avoid the topology dilemma a generalized FET model (Fig. 1) is proposed. In the saturated regime the circuit is completed by the drain current source and channel conductance both in parallel to the drain-source capacitance C_{ds}. The external capacitances C_{gda} and C_{gdi} are very small and neglected. Most of the published FET model variations can simply be derived from the proposed one by excluding appropriate elements.

Determination of effective capacitances and inductances from pinch-off measurements.

Regarding lower frequencies the distributed capacitances at the input and output of the FET can be put together to an effective gate-source capacitance C'_{gs}, gate-drain capacitance C'_{gd}, and drain-source capacitance C'_{ds} (Fig. 2). Notice the primed effective gate, drain and source inductances are not equal to L_g, L_d, and L_s in Fig. 1. The inductance values in the distributed model depend strongly on the partitioning of the effective capacitances.

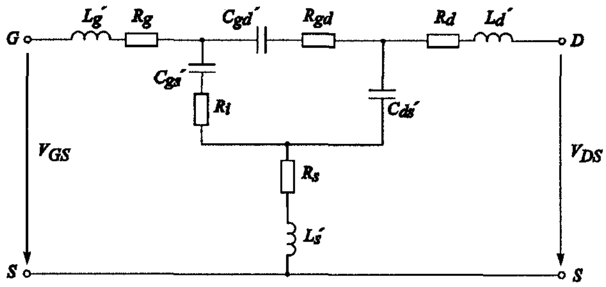

Fig. 2 Pinched-FET equivalent circuit with effective capacitances and inductances.

The effective capacitances can be determined from S-parameter measurements at frequencies lower than 10 GHz [16]; in this lower frequency range the FET model behaves like a capacitive network. With the effective capacitances known, the effective inductances can be derived from measured data including measurements at higher frequencies.

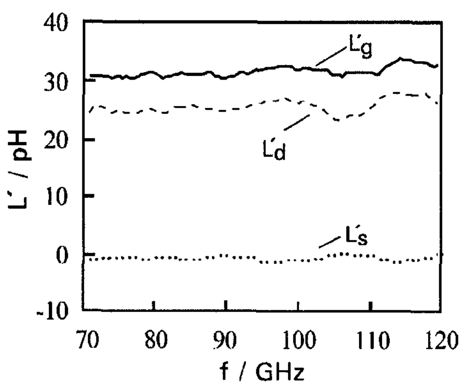

Fig. 3 Effective inductances for a 0.12μm-gate HEMT.

Because the extraction of inductance values from pinch-off seems to be very unusual (often said to be *impossible*), typical results of the proposed approach are given in Figs. 3 and 4 for demonstration. The observed monotonic increase of the L'_μ values with frequency originates from the resonance phenomena

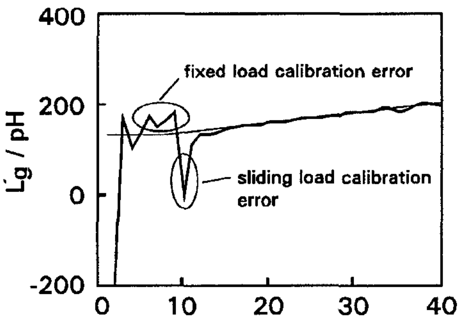

Fig. 4 Effective gate inductance of a 0.5μm MESFET.

of the external capacitances with the inductances. This is especially evident in the case of a wire-bonded 0.5μm-gate MESFET in Fig. 4. At lower frequencies some irregularities arise from measurement errors which can clearly be identified and eliminated by further calibration refinement. However, as the derived values are only utilized as starting quantities for the subsequent optimization process, the approximation indicated by the thin solid line is entirely acceptable.

Starting parameter values for the distributed FET model

We assume the following distribution of the effective capacitances: $C_{pda} = C_{pgi} = 0.5(C'_{gs} - C_{gs}) = C_{pda}$ and $C_{pdi} = C_{ds} = 0.5(C'_{ds} - C_{pda})$. With the distributed capacitance values defined, the inductance values of L_g, L_d, and L_s can approximately be determined from the effective inductive quantities (e.g. 0.12 μm-gate HEMT: $L_g \approx 1.20\, L'_g$, $L_d \approx 1.26\, L'_d$, $L_s \approx 4.40\, L'_s$; 0.5μm-gate MESFET: $L_g \approx 1.49\, L'_g$, $L_d \approx 1.69\, L'_d$, $L_s \approx 7.00\, L'_s$).

In conclusion, well-defined starting values for the distributed FET model have been found. They have been derived from measurements in only one operating point so that the initial capacitive and inductive values are well-correlated. It is known that the nearer the starting values of the model parameters are to the global minimum, the lower is the trapping probability in local minima.

Repetitive random optimization with adaptive starting intervall sizes.

Because trapping into a local minimum is a fundamental problem in optimization procedures, a statistical approach is preferred. The object function is probed near the expected minimum with a variety of carefully defined starting value vectors for the model elements. Extraction has been carried out as follows. 100 starting vectors based on uniformly distributed random model parameters within ± 20% of the derived starting values. The series resistors R_g, R_s, and R_d varied from 1Ω to 5Ω. R_i and R_{gd} were chosen within 10 Ω and 30 Ω. Optimization was started from each random vector using an improved Simplex algorithm. The extracted parameter values were then plotted with respect to increasing residual error of the object function (Fig. 5). Re-optimization is performed using reduced starting intervals according to the extracted value distribution of each parameter. After only a few re-optimization cycles the extracted parameter values stabilize. Optimization for the FET model parameter extraction is based on the concept of multiplane data-fitting and bidirectional search as described in Ref. [10].

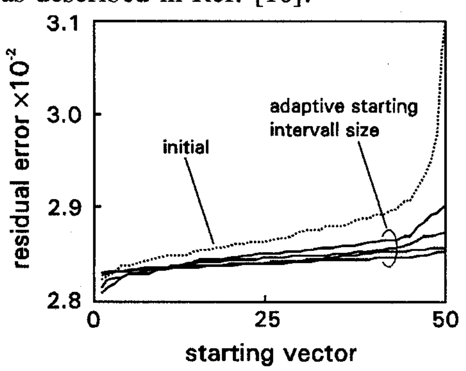

Fig. 5 Residual error of error function sorted according to size versus respective starting vector (0.12μm HEMT).

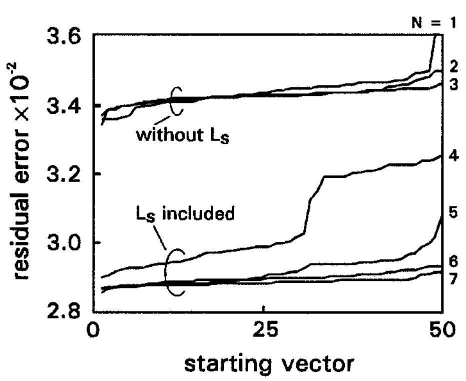

Fig. 6 Same as Fig. 5, but extraction is now based on arbitrarily chosen starting intervals.

Fig. 5 demonstrates the high efficiency of the new approach. The initial optimization yields already a very low residual error. Strongly monotonous increase of the error function signifies small value interchanges among the capacitances and inductances, respectively. For comparison, Fig. 6 shows a similar result based on arbitrarily chosen starting values [17]. Steps in the error function indicate significant value interchanges between capacitances and inductances which yield increased probability to trap into a local minimum. Simultaneous optimization of all parameters gives no satisfying results [17].

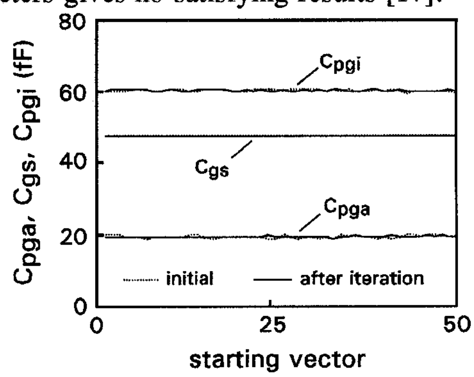

Fig. 7 MESFET capacitances at the gate-source port.

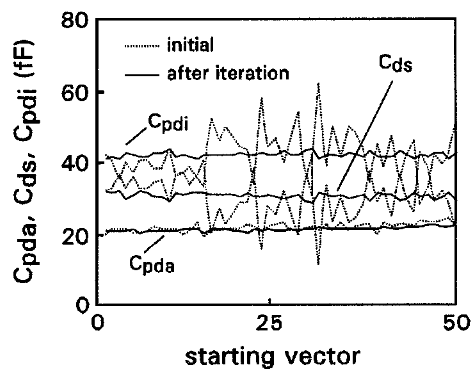

Fig. 8 MESFET capacitances at the drain-source port.

Figs. 7 and 8 show an example of the extracted capacitances for a 0.5μm-gate MESFET using the discussed procedure. Very stable extraction of the distributed capacitances at the gate-source side is possible right at the beginning, whereas at the output only C_{pda} turns out to be stable. Value interchanges are initially found between C_{pdi} and C_{pda}. After some iterations the partitioning becomes clear.

The investigations show that nearly all parameters can be extracted reliably. However, the extracted resistance values of R_s and R_d cannot generally be verified by physical inspection; uncertainty in the extracted values originates basically in the limited measurement accuracy. Therefore, the bulk series resistances are extracted together with all other bias-dependent parameters using a measurement-error sensitive two-frequency scanning method as described in Ref. [18].

Conclusions

This paper described a unified distributed FET model which incorporates most of published model variants. Unique extraction of the parameter values requires well-defined starting values for optimization avoiding trapping into local minima. These are found as follows. Firstly ignoring distributed effects, both effective capacitances and inductances as well are extracted from passive pinch-off measurements. Then partitioning of the effective capacitances into distributed ones is done under consideration of physical constraints. The starting values of gate, source and drain inductances are derived from the corresponding effective ones and the given values of the distributed capacitances. Final application of a new repetitive random optimization with adaptive starting intervall sizes yields unique results, especially for the three shunted capacitive elements at the FET input and output. The new extraction concept converges very fast. Guessing of suitable initial parameter values is omitted. A refined extraction method is needed to extract also the bias-dependent bulk series resistors.

Acknowledgements

The author thanks M. Novotny and J. Weide for their helpful discussions and generating the data used in this paper.

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