# Millimeter-wave FET modeling based on a frequency extrapolation approach

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**ABSTRACT**
*An empirical distributed model, based on electromagnetic analysis and standard S-parameter measurements up to microwave frequencies, is shown to be capable of accurate small-signal predictions up to the millimeter-wave range. The frequency-extrapolation approach takes advantage from a physically-expected, smooth behavior of suitably defined elementary active devices connected to a passive distributed network. On this basis, small-signal millimeter-wave FET modeling becomes an affordable task in any laboratory equipped with a standard microwave vector network analyzer and electromagnetic simulation capabilities. In the paper, wide experimental validation of the proposed model up to 110GHz is presented for PHEMT devices with different sizes and bias conditions.*

**INTRODUCTION**

Lumped equivalent circuit models of electron devices become inappropriate at millimeter-wave frequencies due to complex distributed and coupling effects which may strongly affect the electrical performance. However, accurate electron device models for millimeter-wave frequencies would be a very useful tool for circuit designers to face off demanding low-cost requirements and increasing operating frequencies in many applications of the communication area.

In the last years, the progress in numerical device simulation and the development of electromagnetic analysis tools, together with the availability of powerful workstations, have led to modeling approaches aiming to the numerical solution of the electromagnetic and electron transport problems in a consistent way. Although potentially accurate, these models are still in a preliminary phase and their application to circuit simulation and design may be difficult, taking also into account their computational cost [1,3].

Recently, a circuit-design-oriented family of distributed models appeared in the literature. They are based on the common idea of an extrinsic passive network interconnecting a cascade of elementary active devices [4,5]. With respect to others, the empirical approach presented in [5], adopts a distributed description in terms of scattering parameters both for the active device area and for the extrinsic structure, which is consistent with simple scaling rules. In the present paper it will be shown how the considered modeling approach allows for a reliable frequency extrapolation method, which will be exploited for the small-signal performance prediction up to 110GHz of different P-HEMT devices.

**THE MODELLING APPROACH**

According to the FET distributed modeling approach presented in [5], the active area is partitioned, as shown in Fig.1, in a convenient number of *internal elementary devices* (or *active slices*) connected by means a *passive distributed structure*. The latter is characterized in terms of a multi-port scattering matrix computed by means of accurate electromagnetic simulations [6] on the basis of layout geometry and material parameters (usually available from the design rules and provided by the foundry). This kind of analysis enables the actual device geometry and material stratification, as well as losses in the dielectrics and metallizations, to be taken into account for any given device structure and size. Since electromagnetic propagation and coupling effects are accounted for by the passive structure, all the active slices can be described by the same, unique admittance matrix $Y^{AS}$. The latter can be identified from measured electron device S-parameters by means of closed-form algebraic manipulations involving the electromagnetic simulation results. The complete identification procedure is described in [5]. It is worth noting that model identification does not require either parameter optimization or complex measurement procedures.

**THE FREQUENCY EXTRAPOLATION APPROACH**

The proposed frequency extrapolation approach relies on the observation of the fairly smooth behavior versus frequency of the internal active slice admittances in comparison with the corresponding parameters evaluated at the device electrodes. For instance Fig.2 shows the measured admittance parameter Y21 (per unit width) versus frequency up to 110 GHz for a Philips Microwave Limeil (PML) 2x30μm GaAs-PHEMT ($L_G$=0.2μm) biased at Id=Idss, Vds=3V. In the same figure the corresponding admittance parameter $Y_{21}^{AS}$ of the internal elementary devices, obtained considering a single active slice per finger, is also reported. The resonant-like behavior of the measured admittance parameter in comparison with the quite regular, smooth, almost linear shape of the internal elementary device admittance can be observed also for the other admittance matrix elements and for a great variety of bias conditions. This is not surprising, since extrinsic parasitic effects cause very often such a kind of resonance in the Y-domain for most devices observed, while the regular frequency behavior of the "intrinsic device" admittance is consistent with physical hypothesis of short memory conditions, which usually hold for micro- and millimeter-wave devices [7]. Thus, frequency extrapolation of measured device scattering or admittance parameters would lead to very inaccurate prediction results. Instead, the almost linear behavior of the internal elementary device admittance suggests an alternative way to perform reliable frequency extrapolation. In fact, these internal admittance coefficients can be suitably approximated and extrapolated by means of low-order polynomial expressions, easily identifiable on the basis of least-square minimization algorithms in the frequency range used for device characterization. The extrapolated polynomial expression of the internal elementary devices can be used in conjunction with the distributed description of the extrinsic passive structure in order to predict the small-signal device behavior up to very high frequencies. To this aim, electromagnetic simulation must be obviously performed up to the highest frequency of interest.

Fig.3 shows the comparison between intrinsic admittance parameters and their associated linear regression evaluated in the range 0-50 GHz. It is worth to observe that the upper frequency used for polynomial coefficient extraction represents a trade-off between accuracy and instrumentation costs for device characterization, generally increasing for higher frequencies. In that case the boundary frequency of 50 GHz allows a reasonable parameter approximation up to 110 GHz and has been adopted in the following to verify experimentally the proposed frequency extrapolation procedure using Philips PHEMT devices.

In Fig.4 the comparison is shown between the S-parameters of the 2x30μm device directly measured[1] on wafer up to 110 GHz by using an HP8510XF network analyzer along with the corresponding predictions obtained by means of the procedure outlined above. An electromagnetic simulation was performed on the basis of foundry-provided parameters and device GDSII files, using the planar-3D *"em"* Sonnet electromagnetic simulator (sub-micron grid and quadruple precision were adopted for better accuracy). Then, the internal elementary device admittance $Y^{AS}$ was approximated through simple linear regression in the frequency range up to 50 GHz and extrapolated up to 110 GHz. The internal elementary devices characterized in this way were finally connected with the extrinsic passive device structure characterized by means of an "extended" electromagnetic simulation up to 110 GHz. Small-signal predictions in Fig.4 were obtained with the proposed model after implementation within the HP-MDS CAD-tool for microwave circuit design. Finally, in Fig.5 measured and predicted parameters are shown in admittance form for a 6x30μm PHEMT biased near pinch-off. It is worth noting that, as shown in Fig.5, the model is capable of predicting resonant-like effects occurring in the extrapolated frequency range (50 to 110GHz). This feature confirms the "physical" correctness and consistency of the proposed approach.

## CONCLUSION

An empirical distributed approach to the modeling of millimeter wave FETs has been used to predict small-signal PHEMT performance up to 110 GHz on the basis of scattering parameters measured up to only 50 GHz. The proposed frequency extrapolation method takes advantage from the physically-expected, fairly smooth behavior of the admittance parameters of a suitably defined internal elementary device, whose admittance response can be easily extrapolated by means of low-order polynomials. Experimental results confirm the validity of the proposed approach.

### REFERENCES


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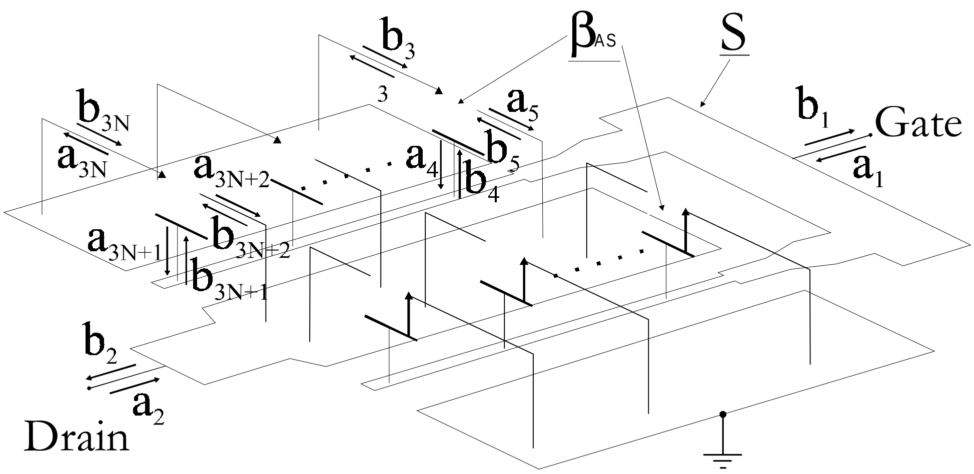


Fig.1: Structure of the empirical distributed model.

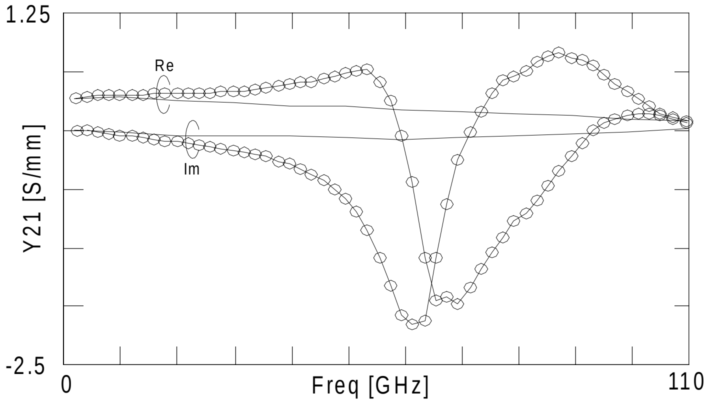


Fig.2: Measured admittance Y21 per unit width (symbols) for a PML 2x30μm GaAs-PHEMT biased at Id=Idss, Vds=3V. Continuous lines represent the corresponding admittance parameter $Y_{21}^{AS}$ of the internal elementary devices.

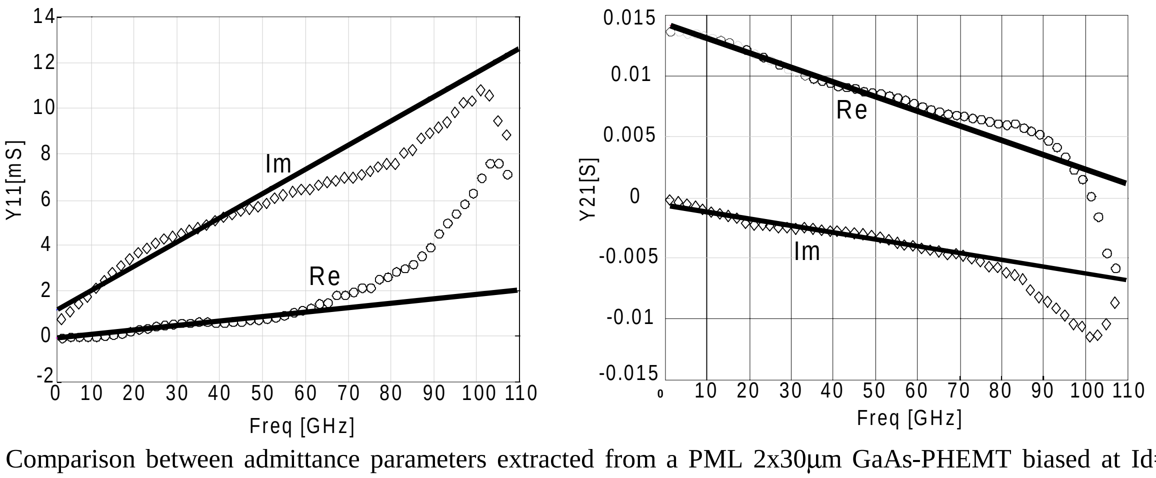


Fig.3: Comparison between admittance parameters extracted from a PML 2x30μm GaAs-PHEMT biased at Id=Idss, Vds=3V and the corresponding linear regressions. The approximation is fitted in the 0-50 GHz frequency range.

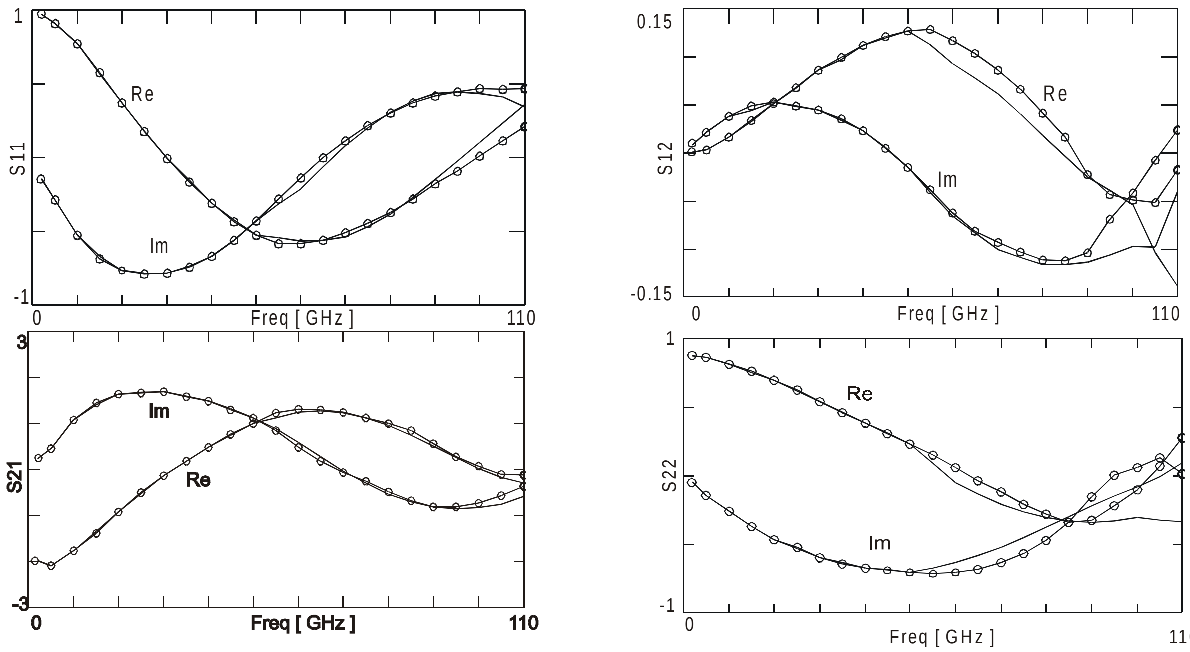


Fig. 4: Measured (symbols) and predicted through frequency extrapolation above 50 GHz (lines) scattering parameters for a PML 2x30μm GaAs-PHEMT at Id=Idss, Vds=3V.

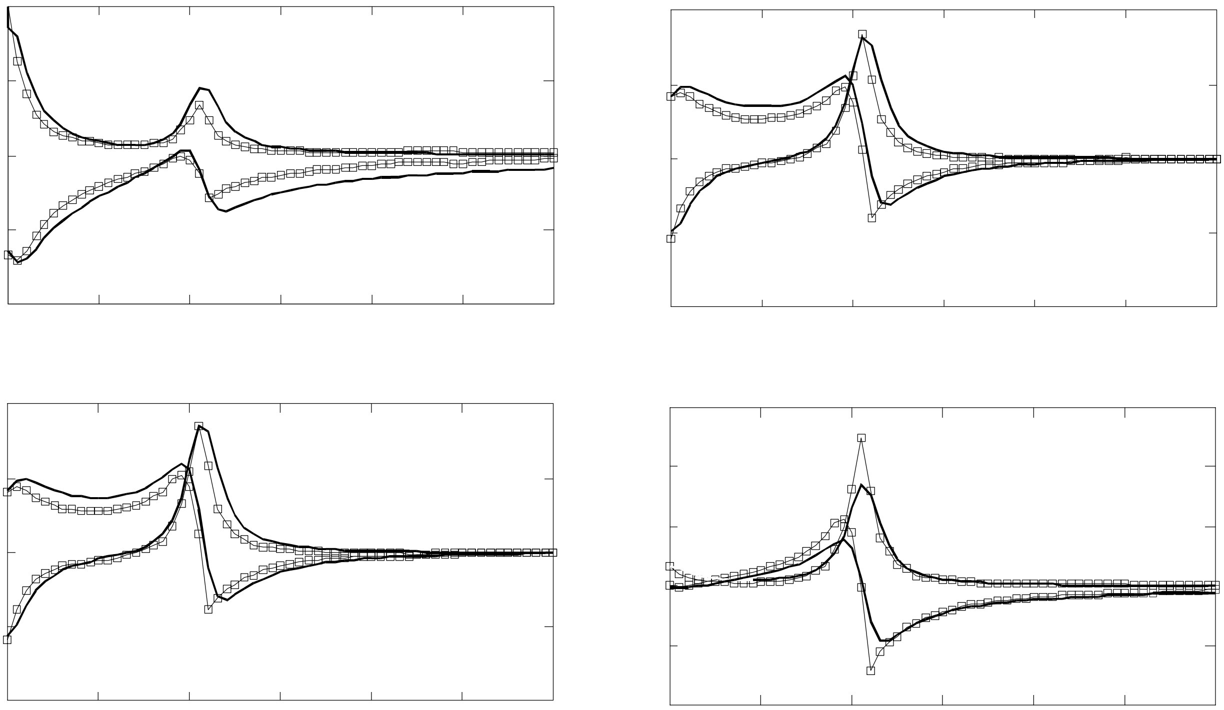

Fig. 5: Admittance parameters obtained from measurements (symbols) and predicted through frequency extrapolation above 50 GHz (lines) for a PML 6x30μm GaAs-PHEMT at Vgs=-1V, Vds=3V.