A NON-LINEAR DISTRIBUTED FET-MODEL, FOR MILLIMETER-WAVE CIRCUIT DESIGN BY HARMONIC BALANCE TECHNIQUES

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ABSTRACT

In this paper, we propose a systematic procedure to derive a non-linear, distributed, FET model, which may be implemented in harmonic balance simulators for non-linear design at millimeter waves.

The model is derived from the knowledge of the conventional lumped non-linear equivalent circuit, and the geometrical dimensions of the FET.

A FET-finger is modeled by N sliced sections. Each section includes a nonlinear two-port, inserted between two linear four-port.

Element-values of the non-linear two-port are derived from the lumped model, by appropriate scaling rules. Element-values of the linear four-port are derived from an electromagnetic analysis of the transverse structure of the FET, which takes into account coupling and distributed effects along the electrodes.

The model has been applied to the non-linear analysis of a millimeter-wave FET, and compared to the lumped equivalent circuit.

I - INTRODUCTION

Non-linear millimeter wave circuit design needs accurate modelling of semiconductor devices. For very high frequencies applications, the distributed effects along the width of the FET-fingers must be taken into account, the more the device works at high input levels and harmonic frequencies are generated.

Recently [1], [2], [3] linear distributed FET models have been proposed. However they cannot be used in non-linear designs.

In this paper, we propose a systematic procedure to derive a non-linear, distributed, FET model, which may be implemented in harmonic balance simulators.

This accurate model is derived from the knowledge of the conventional (low frequency) lumped non-linear equivalent circuit, and the geometrical dimensions of the FET.

Note that the necessary informations may be obtained by conventional measurements.

II - NON-LINEAR, DISTRIBUTED FET MODEL : General description

Figure 1 shows the proposed non-linear distributed model of the FET. A FETfinger is modeled by N sliced sections shown in the figure.

Each section includes a non-linear two-port, inserted between two linear four-port.

- The non-linear two-port describes the active region (intrinsic FET) of the the section,
- The two linear two-ports describe the coupling between electrodes and the distributed effects along the width of the finger,
- The losses of a section are modeled by lumped resistances along the gate and drain lines, and across the width of the source,

III - DERIVATION OF ELEMENT-VALUES

Elements of the linear four-port

The electrical characteristics of an elementary linear four-port are derived from the transverse geometrical description of a unit FET-finger shown in figure 2: the drain and gate lines are assumed assymetrically coupled to the source line, which is taken as common ground. The electrical characteristics are found from a quasi T.EM. electromagnetic analysis of the structure, using a finit-eelement method.

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Figure 2 gives the resulting capacitances and inductances by unit length of the coupled-lines structure for the FET analysed. From this electromagnetic analysis a 4 x 4 [Y] or [Z] matrix is deduced to characterize a length : Lu of the structure. The relation between the total length L_f of a finger and the number N of elementary sections describing it, is : $L_f = 2\ N\ .\ Lu$.

Description of the non-linear active region

The element-values of the non-linear twoport which models the active region of an elementary section, are deduced from the conventional non-linear lumped equivalent circuit of the FET-finger which has been previously measured. Figure 3 shows the lumped circuit of a 32 µm FET-finger (bonding pads have been deembedded).

This circuit may be divided into two subcircuits representing :

- The losses of the gate, drain, and source represented by Rg, Rd, Rs.

- The intrinsic non-linear FET.

To deduce the elements of an elementary nonlinear section, the coupling capacitances : Cgde, Cdse, Cgse previously derived from the E.M. analysis, are first substracted from the corresponding Cgd, Cds and Cgs capacitances of the intrinsic FET.

The scaling rules are then applied to the resulting intrinsic FET, to slice it into N sections as shown in figure 3.

It must be noted that the same scaling rules cannot be applied to the Rg and Rd resistances. In fact this lumped resistances represent distributed resistances along the gate and drain electrodes, so their DC values must be calculated before application of the scaling rules. Let be $R_{g_{DC}}$ and $R_{d_{DC}}$ the corresponding DC resistances, we have [1] :

$$R_g = \frac{R_{g_{DC}}}{3} \qquad R_d = \frac{R_{d_{DC}}}{3}$$

It results that (see figure 1) :

$$\frac{R_{gu}}{2} = \frac{3\ R_g}{2N} \qquad \frac{R_{du}}{2} = \frac{3\ R_d}{2N}$$

where N is the number of unitary sections of one FET-finger

IV - RESULTS OBTAINED

The proposed procedure has been systematically applied to derive a non-linear distributed model of the XL THOMSON-FET, which a length : 0,3 µ m and a width : 2 x 32 µm.

One FET-finger (32 µm) has been firstanalyzed. It is modelled by seven elementary sections.

Its lumped and distributed models have been introduced in our spectral-balance simulator [5].

First at all, S parameters have been compared from 1 to 100 GHz. An excellent agreement is found from 1 to 60 GHz. At higher frequencies a small difference may be seen.

Then, the frequency of the input generator has been fixed at 47 GHz, and the input signal level increased, to obtain a non-linear behaviour.

The load-line of each elementary drain-current source is drawn in function of the gate and drain voltages which takes place in the corresponding section, in other words : Ids_k is drawn in function of V_{gs_k} and V_{ds_k}, with k = 1 to 7.

Figure 4 shows the waveform of the current and voltage in each unit section for an input voltagegenerator of 1,5 V and a FET bias : $V_{gso} = -2^V$, $V_{dso} = 2^V$.

The non-linear and distributed effects are clearly shown. This effects increase with the frequency and the level of the generator.

V - CONCLUSION

A systematic procedure has been given to derive an accurate non-linear distributed model of FET.

This model is extracted from its lumped lowfrequency equivalent circuit, and its geometrical configuration.

The model has been implemented in an harmonic-balance simulator. The results obtained have been compared with that of the lumped equivalent circuit at millimeter waves. It must be noted that the model allows the FET-designer to optimize the place of the gate and drain access-input along the width of the corresponding electrode, following the desired application (power amplification, frequency multiplication etc ....) at millimeter waves..

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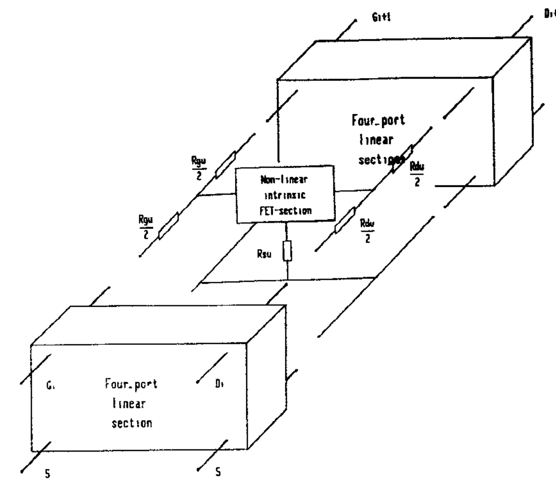
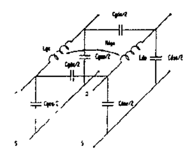
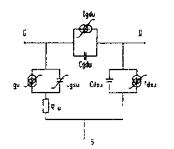


An elementary section of the distributed non-linear model.
A FET-finger is described by N cascaded sections

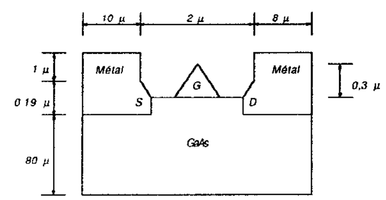


Equivalent circuit of an elementary four-port linear section derived from an E.M. analysis of the geometrical structure



Elementary, Non-linear, intrinsic FET-section

- Figure 1 -

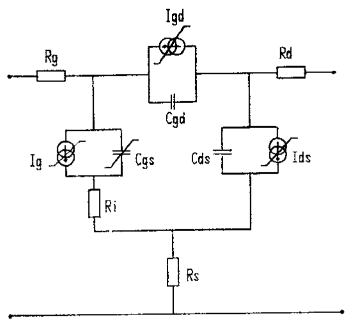


Electromagnetic structure analysed

Numerical results

CDSe = 1 477e-10 F/m	LDe = 2.29e-07 H/m
CGSe = 1 816e-10 F/m	LGe = 2 12e-07 H/m
CGDe = 1 475e 10 F/m	Mdge = 1 14e-07 H/m

- Figure 2 -



Linear elements

Rg = 557 Ω
Rd = 7,18 Ω
Rs = = 3,1 Ω
Cgd = 0,01 pf
Cds = 0,03 pf
Ri = 3,1 Ω

Non-Linear elements

expressions are given in reference [4]. Numerical coefficients for the FET analysed are the following.

Ids :

Idss	186.10-3
M	20.45
P	.073
A	.020
B	-.638
W	-.1.10-3
Vdsp	1652
Vphi	-.84
Vpo	.85
Tau	2.1.10-12

Ig :

Is	.56.10-5
alpha	7.00

Igd :

Iass	20.10-9
a	1.31
b	.183
c	12.99
d	.057
e	1.10

Qgs :

Qgsc	-.955.10-13
Vb	.0

Scaling rules for N sliced sections

$$Rgu = \frac{3\,Rg}{2\,N} \qquad Cdsu = \frac{Cds - Cdse}{N}$$

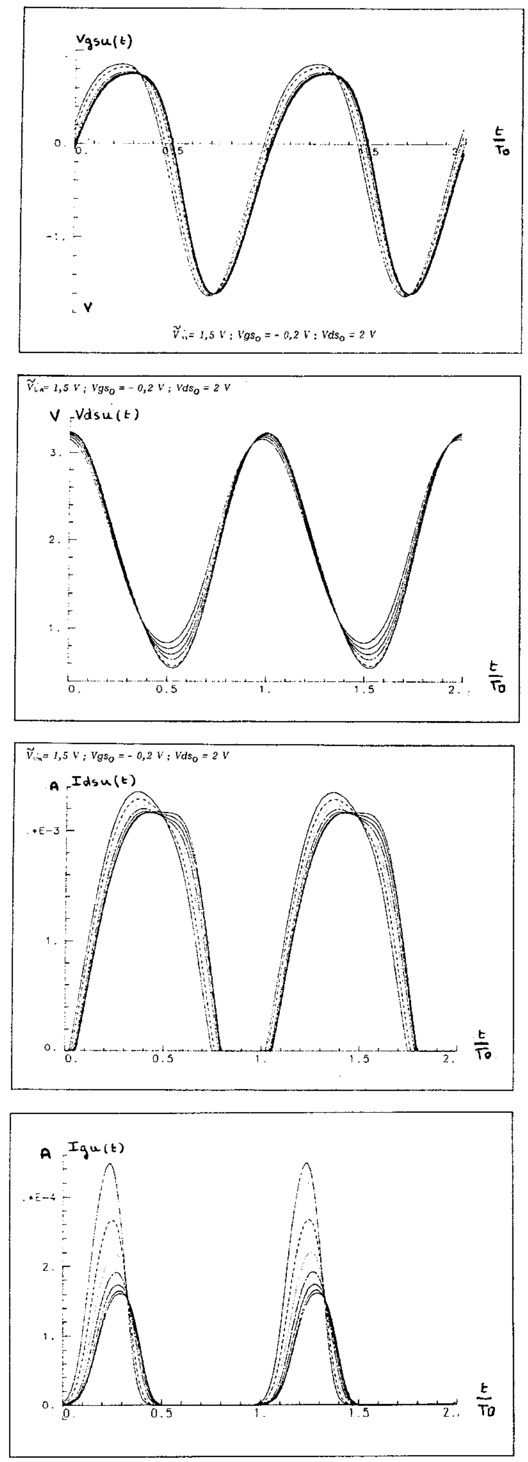
$$Rdu = \frac{3\,Rd}{2\,N} \qquad Cgdu = \frac{Cgd - Cgde}{N}$$

$$Riu = Ri.N \qquad Cgsu = \frac{Cgs - Cgse}{N}$$

$$Rsu = Rs.N \qquad Igu = \frac{Ig}{N}$$

$$Igdu = \frac{Igd}{N} \qquad Idsu = \frac{Ids}{N}$$

- Figure 3 : 32 µm FET-Finger -



- Figure 4 -