MODELING THE GAAS NONLINEAR MICROWAVE CIRCUITS USING THE CIA PROGRAM

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Abstract — **An original software tool called CIA (Circuit Interactive Analyzer) for general analysis and optimization of electronic circuits is briefly introduced. A built-in somewhat more accurate model of CIA GaAs FET is presented. An analysis of the microwave 3.8 GHz distributed oscillator by means of that model is performed in comparison with a SPICE3 analysis.**

I. INTRODUCTION

The author of the paper has constructed an original software tool called CIA (Circuit Interactive Analyzer) for general analysis and optimization of electronic circuits. The tool may also be used in effective way for modeling the nonlinear microwave circuits. It has built-in SPICE3 compatible models of BJT, JFET and MOSFET and a somewhat more accurate model of GaAs FET in comparison with that program. It has one universal routine for defining the circuit equations in static, frequency, time, and poles-zeros analyses and entirely different set of mathematical algorithms. The program also contains non-standard modes of actions - steady-state analysis or optimization, for example. Some of the progressive features of that system will be presented.

II. BUILT-IN GAAS FET MODEL

The CIA equations of the GaAs FET are based on the Sussman-Fort, Hantgan, and Huang model on principle [1]. However, the very important dependency of the threshold voltage on the drain-source voltage has also been incorporated - see schema in Fig. 1:

$$V_{th} = V_{to} - \sigma V_{ds}, \tag{1}$$

$$I_{10} = \begin{cases} 0 & \text{if } V_{gs} \le V_{th} \\ \beta\left(V_{gs} - V_{th}\right)^n \left(1 + \lambda V_{ds}\right)\tanh\left(\alpha V_{ds}\right) & \text{if } V_{gs} > V_{th} \end{cases} \tag{2}$$

if $V_{ds} \ge 0$ and

$$V_{th} = V_{to} + \sigma V_{ds}, \tag{3}$$

$$I_{10} = \begin{cases} 0 & \text{if } V_{gd} \le V_{th} \\ \beta\left(V_{gd} - V_{th}\right)^n \left(1 - \lambda V_{ds}\right)\tanh\left(\alpha V_{ds}\right) & \text{if } V_{gd} > V_{th} \end{cases} \tag{4}$$

if $V_{ds} < 0$.

All the parameters were defined in [1] with the exception of σ: this is a new CIA model parameter - coefficient of threshold voltage dependency on drain-source voltage.

Naturally, the basic current source of the model defined by the equations (1) till (4) must be surrounded by the standard passive elements - see schema in Fig. 1.

The Schottky-barrier gate-source diode (currents numbered by 4, 6, and 8) and gate-drain diode (currents numbered by 5, 7, and 9) are defined in the standard way [1] by means of well-known Shockley equation with entirely different saturation currents and emission coefficients. The resistances of the contact regions (currents numbered by 1, 2, and 3) are also included. The current source numbered by 10 defined above may be assumed to be the main part of the static model.

The dynamic part of the model contains strongly nonlinear gate-source and gate-drain capacitances controlled by gate-source and gate-drain voltages, respectively [2], and a linear drain-source capacitance - see Fig. 1 and 2:

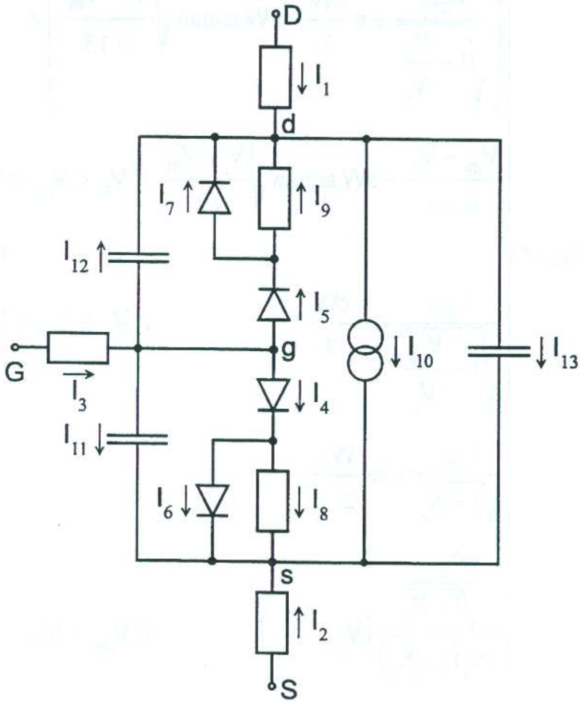

Fig. 1. GaAs FET equivalent circuit.

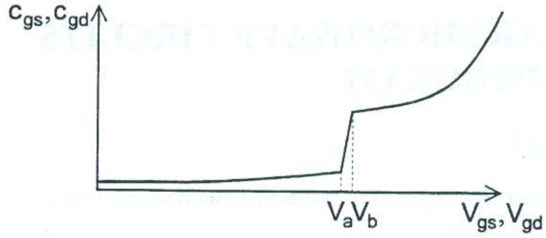

Fig. 2. Modified model of junction capacitance.

Note that the capacitance drop is not included in many analytical programs - they often use simple formulae that are typical for the JFET modeling. Thus, the capacitances for under-threshold values of gate-source or gate-drain voltages are unrealistic and transient analyses of such programs may be enough inaccurate.

The transitional region between subthreshold and junction capacitance formulae is defined in empirical way [1]:

$$V_a = V_{th} - 0.15, \tag{5}$$

$$V_b = V_{th} + 0.08. \tag{6}$$

The CIA complete capacitance formulae are slightly modified in comparison with the original ones. Thus, the program uses the following formula for c_{gs}:

$$c_{gs} = \begin{cases} \varepsilon W \arctan\sqrt{\dfrac{V_j - V_{th}}{V_{th} - V_{gs}}} & \text{if } V_{gs} \le V_a, \\[2ex] \left(\dfrac{c_{gso}}{\sqrt{1 - \dfrac{V_b}{V_j}}} + \pi\dfrac{\varepsilon W}{2} - \varepsilon W \arctan\sqrt{\dfrac{V_j - V_{th}}{0.15}} \right) \times \\ \dfrac{V_{gs} - V_a}{0.23} + \varepsilon W \arctan\sqrt{\dfrac{V_j - V_{th}}{0.15}} & \text{if } V_a < V_{gs} < V_b, \\[2ex] \dfrac{c_{gso}}{\sqrt{1 - \dfrac{V_{gs}}{V_j}}} + \pi\dfrac{\varepsilon W}{2} & \text{if } V_b \le V_{gs} \le V_c, \\[2ex] \dfrac{c_{gso}}{\sqrt{1 - X_j}} + \pi\dfrac{\varepsilon W}{2} + \\ \dfrac{\dfrac{c_{gso}}{\sqrt{1 - X_j}}}{2V_j(1 - X_j)}\left(V_{gs} - V_c\right) & \text{if } V_{gs} > V_c, \end{cases} \tag{7}$$

where

$$V_c = X_j V_j \tag{8}$$

is an auxiliary voltage used by the CIA program to linearize abrupt growth when the gate-source voltage is near by junction voltage V_j - the other parameters are given in [1].

III. GAAS FET MODEL IDENTIFICATION

To demonstrate the advantage of the improved static model of Sussman-Fort, Hantgan, and Huang by means of the CIA equations (1) till (4), let to identify the output characteristics of the Plessey GAT6 GaAs FET [3]. The identification will also be performed for the standard SPICE3 Statz model [4] to illustrate the accuracy of the CIA model.

The identification was performed by a CIA optimization technique that will be discussed later. First, the standard Statz equation has been used as a CIA *user-defined* model:

$$I'_{10} = \begin{cases} 0 & \text{if } V_{gs} \le V_{to}, \\ I'_{ds}\left[1 - \left(1 - \alpha\dfrac{V_{ds}}{3}\right)^3\right] & \text{if } V_{gs} > V_{to} \wedge 0 \le V_{ds} \le \dfrac{3}{\alpha}, \\ I'_{ds} & \text{if } V_{gs} > V_{to} \wedge V_{ds} > \dfrac{3}{\alpha}, \end{cases} \tag{9}$$

where

$$I'_{ds} = \frac{\beta}{1 + b\left(V_{gs} - V_{to}\right)}\left(V_{gs} - V_{to}\right)^2\left(1 + \lambda V_{ds}\right). \tag{10}$$

All the parameters in these equations are discussed in [4]. Second, the CIA equations (1) till (4) have been used as a CIA *built-in* model. The results of both identifications are drawn in Fig. 3 and 4 - the crosses represent the measured values, the solid lines represent the Statz and CIA models, respectively. Corresponding model parameters are written in Tables I and II:

TABLE I: IDENTIFIED PARAMETERS OF THE STATZ MODEL

V_{to}	α	β	λ	b
-1.43	1.65	.164	.0727	4.18
V	V^{-1}	AV^{-2}	V^{-1}	V^{-1}

TABLE II: IDENTIFIED PARAMETERS OF THE CIA MODEL

V_{to}	α	β	λ	n	σ
-1.42	2.29	.0301	-.0705	1.77	.132
V	V^{-1}	AV^{-n}	V^{-1}	1	1

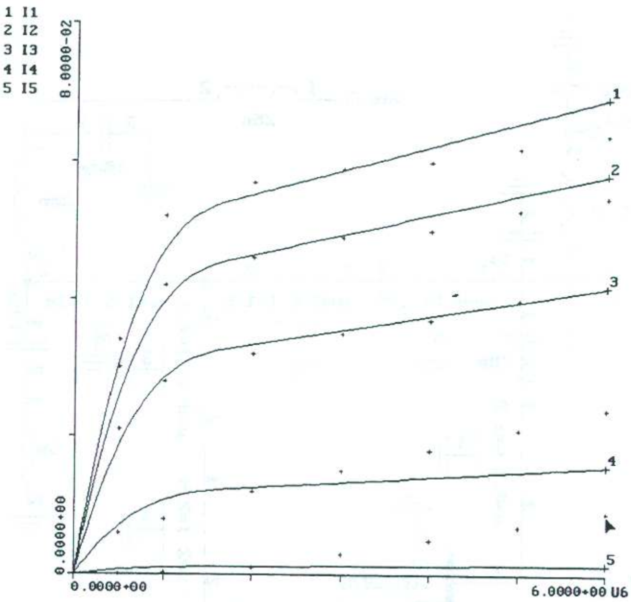

Fig. 3. Identification of the GAT6 for the SPICE3 model.

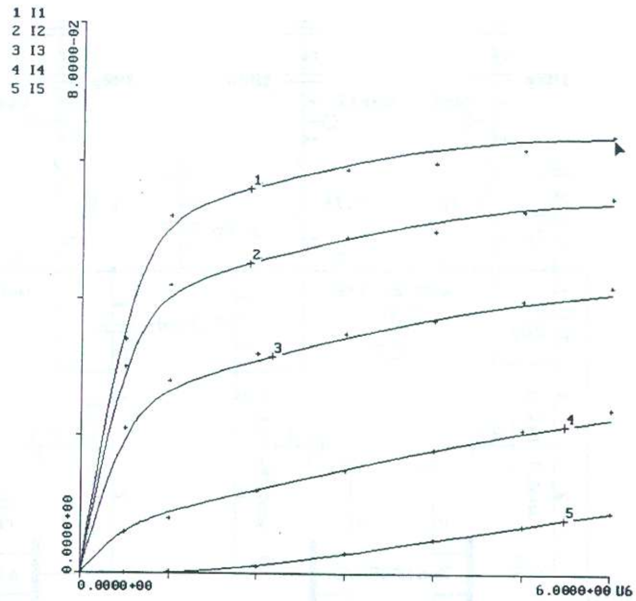

Fig. 4. Identification of the GAT6 for the CIA model.

The SPICE3 model is not too appropriate for modeling such devices as the Plessey GAT6 GaAs FET. The crucial difficulty is marked by an arrow in Fig. 3 - the measured curve grows here much more rapidly than the identified one. However, if the model of threshold voltage dependent on drain-source voltage according to the equations (1) and (2) is used then the approximation is enough accurate - see analogous place in Fig. 4.

Furthermore, the slopes of the characteristics are not also identified correctly for larger values of drain current - see upper part of Fig. 3. Likewise the previous paragraph, the CIA model is also more accurate in this aspect.

In the place marked by the arrow in Fig. 4, a negative slope of the characteristics may even occur [5]. The CIA model is also able to create a characteristic with partially negative output conductance.

As we can see in Fig. 3 and 4, the transistor has been identified in the scope of drain-source voltage from zero to 6 V - note that the CIA program uses symbol "U" as the sign of voltage. The five output characteristics 1, 2, ... , 5 are controlled by the gate-source voltage - respective values were 0, -0.2, -0.5, -1, and -1.5 V. The drain and source resistances (see Fig. 1) were estimated both to the value 2 Ω and were not identified.

IV. MICROWAVE DISTRIBUTED OSCILLATOR

Consider a microwave tunable distributed oscillator [6] in Fig. 5. The oscillator has been developed and realized at the Department of Electromagnetic Field of Czech Technical University and the necessary analyses have been carried out by both SPICE3 [7] and CIA programs.

The oscillator is based on the idea of distributed amplification. Therefore, it is tunable over a relative wide interval of frequencies. Our analyses have been performed for the case of function at 3.8 GHz.

Granted static parameters of the Statz model are written in Table III. These parameters have been recalculated for the CIA model by optimization technique. The resultant CIA parameters are written in Table IV. Granted drain and source resistances were 0.62 Ω and 1.38 Ω, respectively. Both SPICE3 and CIA have used these values. However, the CIA has nonzero gate resistance as default.

Granted dynamic parameters of the Statz model were 0.3 pF for zero-bias gate-source capacitance, 50 fF for zero-bias gate-drain capacitance, and 1 V for gate junction potential. The same values have been used by the CIA program; the other CIA parameters have been set to their default values, i. e. $\varepsilon W = 5$ fF and $X_j = 0.5$.

TABLE III: GRANTED STATIC PARAMETERS OF THE STATZ MODEL FOR ATF35376

V_{to}	α	β	λ	b
-1	2	.08	0	0.3
V	V^{-1}	AV^{-2}	V^{-1}	V^{-1}

TABLE IV: IDENTIFIED STATIC PARAMETERS OF THE CIA MODEL FOR ATF35376

V_{to}	α	β	λ	n	σ
-.931	1.66	.0727	-.0242	1.64	.00129
V	V^{-1}	AV^{-n}	V^{-1}	1	1

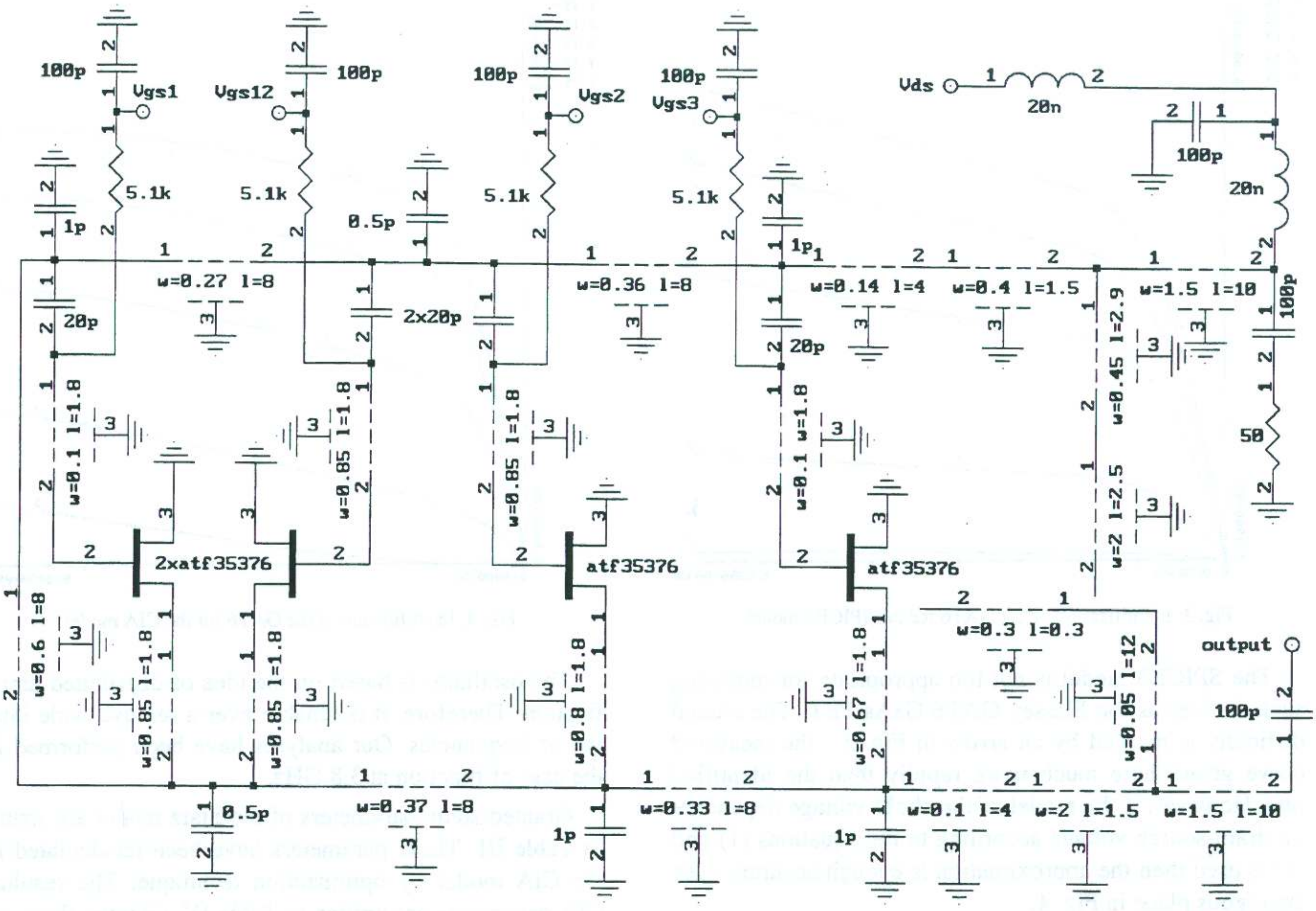

Fig. 5. Microwave distributed oscillator.

The results of transient analyses are presented in Fig. 6 and 7. As we can compare, the frequencies of the oscillations are the same. In both cases, approximately 15 periods correspond to the last 4 ns of the analyses, i. e. the frequency of the oscillations is about 3.75 GHz. The magnitudes of the oscillations are also analogous - about 1 V.

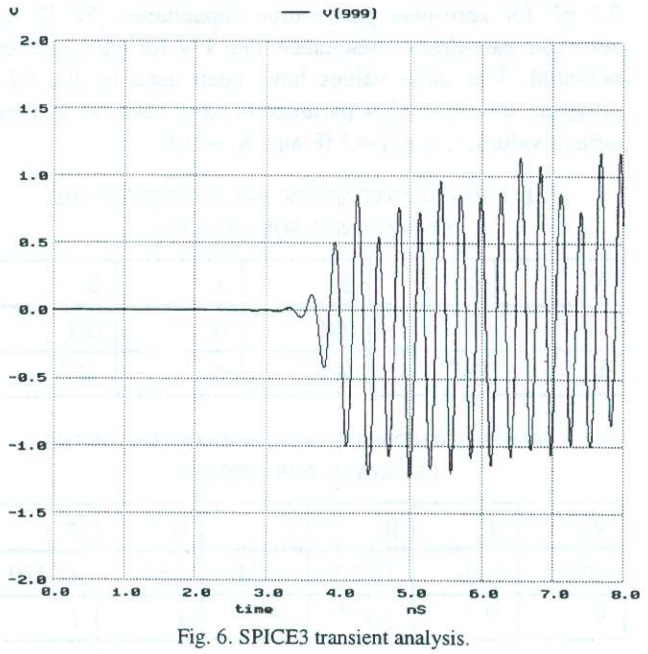

Fig. 6. SPICE3 transient analysis.

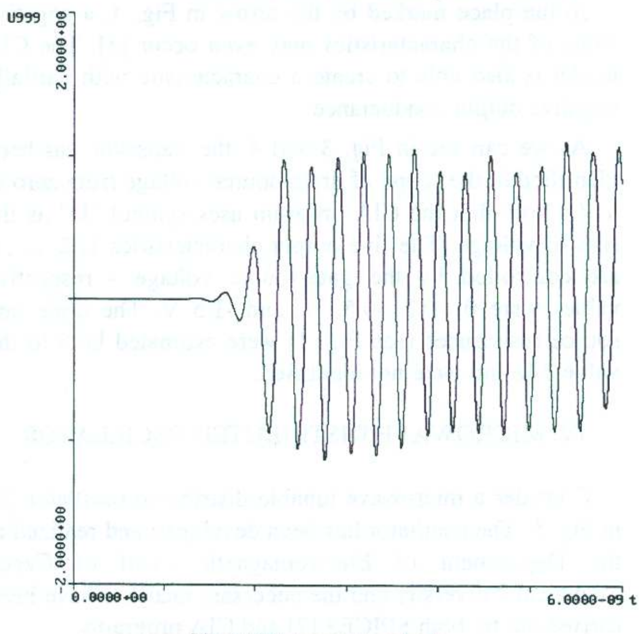

Fig. 7. CIA transient analysis.

The only difference between those analyses consists in the interval that necessary to obtain the full magnitudes of the oscillations. In the case of SPICE3, the value about 4 ns is necessary; in the case of CIA, the value about 2 ns is necessary. That deviation can be explained by the different capacitance equations of the Statz [4] and CIA models. I have also tested that the transient analysis is very sensitive on the gate resistance mentioned above.

All the transmission lines in the schema of the oscillator in Fig. 5 are modeled by standard lossy form - see Fig 8.

V. CIA OPTIMIZATION TECHNIQUE

The CIA optimization algorithm seeks to find up to 25 unknown parameters of the circuit for fulfillment of user-specified requirements. The algorithm starts the same analyses sequentially and changes sophistically those parameters after each of them to fulfill the requirement gradually.

Let assume that two circuit outputs are to be monitored in three points - see Fig. 9. Circles mark user-specified requests for the outputs and squares mark values of those outputs obtained after an analysis. The algorithm seeks to minimize the sum of squares of differences between them:

$$S(x_1,\ldots,x_n)=\sum_{k=1}^{m}R_k^2(x_1,\ldots,x_n),\ n\le m, \quad (11)$$

where unknown optimized parameters of a circuit are marked by $x_1,\ldots,x_n$ and R_k, $k=1,\ldots,m$ are the differences.

An extreme of the function of n variables (11) may be found in the standard way, i. e.:

$$\nabla S=\sum_{k=1}^{m}2R_k\nabla R_k=\mathbf{0}. \quad (12)$$

After some steps, classical quasi-Newton method can be obtained from (12):

$$\mathbf{J}^t\mathbf{J}\Delta\mathbf{x}^{(l)}=-\mathbf{J}^t\mathbf{r},\ \mathbf{x}^{(l+1)}=\mathbf{x}^{(l)}+\Delta\mathbf{x}^{(l)},\ l=1,\ldots,l_{max}, \quad (13)$$

where l is the iteration number and

$$r_k=R_k\left[\mathbf{x}^{(l)}\right],\ \frac{\partial r_k}{\partial x_i}=\frac{\partial R_k}{\partial x_i}\left[\mathbf{x}^{(l)}\right],\ \mathbf{J}=\begin{bmatrix}\frac{\partial r_1}{\partial x_1} & \cdots & \frac{\partial r_1}{\partial x_n}\\ \vdots & & \vdots\\ \frac{\partial r_m}{\partial x_1} & \cdots & \frac{\partial r_m}{\partial x_n}\end{bmatrix},$$

$$k=1,\ldots m,\ i=1,\ldots,n. \quad (14)$$

The quasi-Newton method is very fast, but insufficiently reliable. For this reason, the method is combined with the classical gradient one

$$\Delta\mathbf{x}^{(l)}=-2\mathbf{J}^t\mathbf{r},\ l=1,\ldots,l_{max} \quad (15)$$

to the following Levenberg-Marquardt modification:

$$\left[\mathbf{J}^t\mathbf{J}+\lambda^{(l)}\mathbf{1}\right]\Delta\mathbf{x}^{(l)}=-\mathbf{J}^t\mathbf{r},\ \mathbf{x}^{(l+1)}=\mathbf{x}^{(l)}+\Delta\mathbf{x}^{(l)},$$

$$l=1,\ldots,l_{max}, \quad (16)$$

where $\mathbf{1}$ is the unit matrix and $\lambda^{(l)}$ is a scalar iteration-dependent factor. The CIA method seeks to minimize that factor sequentially (i. e. to make the quasi-Newton method more influential):

$$\lambda^{(1)}=1,\ \lambda^{(l+1)}=\frac{\lambda^{(l)}}{5}. \quad (17)$$

The monotone decay must be interrupted (and the gradient method must be made more influential) when the method seems to diverge:

$$\text{if } l>1\wedge S^{(l)}\ge\min_{j=1}^{l-1}S^{(j)} \text{ then}$$

$$\mathbf{x}^{(l)}\leftarrow\mathbf{x}^{(l-1)},\ \lambda^{(l)}\leftarrow\lambda^{(l)}5^2, \quad (18)$$

where the first multiplication by 5 compensates the division by 5 in (17) and the second multiplication by 5 increases that scalar factor.

Unfortunately, the method described above is insufficient for the majority class of the circuit optimization problems. Thus, an improved method has been implemented to the CIA program.

The improvement consists in the following steps:

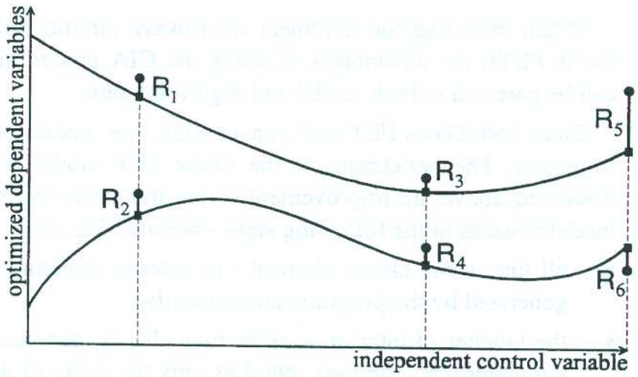

Fig. 9. Optimization.

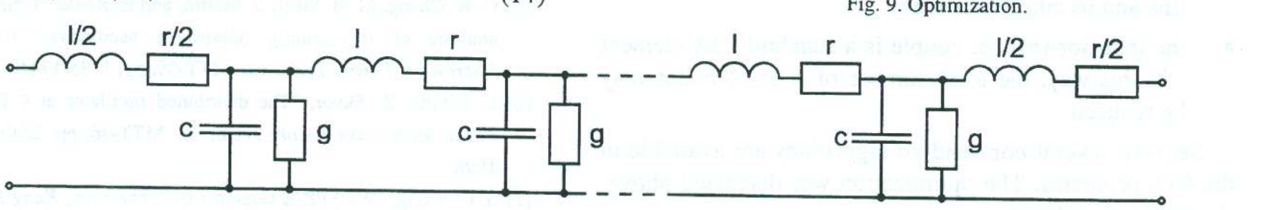

Fig. 8. Transmission line model.

- the differences r_k defined in (14) *must* be normalized
- those differences may also be weighted
- the Jacobian $\mathbf{J}$ in (14) *must* be normalized too
- that Jacobian may quickly be evaluated by sensitivities
- evaluating the Jacobian not necessary in each iteration
- possible divergence of iterations (16) can be damped
- dangerous difference $\Delta\mathbf{x}^{(l)}$ is reduced logarithmically

Let us illustrate the optimization convergence ability by means of the identification of the GAT6 transistor mentioned above from various starting estimation points. Five starting vectors were chosen - they are written in Table V. In the last column of the table, necessary numbers of iterations (numit) for fulfillment of convergence are also written. Note that all the optimizations were constrained in the intervals <-4, -1>, <.2, 20>, <.001, .05>, <-.5, .5>, <1, 5>, and <.02, 10> for V_{to}, α, β, λ, n, and σ, respectively.

All the five optimizations were converged to the solution vector that is written in Table II. Therefore, it seems to be a *global* minimum of the objective function (11). However, it may be shown that the function has also some *local* minima. Usage of the more starting vectors is therefore very important.

The optimization is one of the important advantages of the CIA program in comparison with the SPICE3 one. The total number of optimized unknown circuit parameters is now limited to 25. However, there is no problem to increase that number arbitrary. The optimization may be applied upon the operation point, direct current transfer, frequency, and even transient analyses.

VI. OTHER CIA IMPROVEMENTS

When modeling the nonlinear microwave circuits with GaAs FETs, the advantages of using the CIA procedures can be parceled to both model and algorithm parts.

First, both GaAs FET and transmission line models are improved. The betterment of the GaAs FET model was discussed above; an improvement of the transmission line model consists in the following steps - see also Fig. 8:

- all line is *one* circuit element - its interior structure is generated by the program automatically
- the number of interior sections may also be generated automatically - the user specifies only the delay of the line and its cutoff frequency
- the inductor-resistor couple is a standard CIA element - in this way, the total number of interior nodes may be reduced

Second, several nonstandard algorithms are available in the CIA programs. The optimization was discussed above; the others are following:

TABLE V: CONVERGENCE OF THE CIA OPTIMIZATION ALGORITHM

$V_{to}^{(1)}$	$\alpha^{(1)}$	$\beta^{(1)}$	$\lambda^{(1)}$	$n^{(1)}$	$\sigma^{(1)}$	numit
-2	5	.02	.01	2	.2	7
-3	2	.05	.02	3	.05	38
-1	3	.005	.05	1	.1	7
-4	5	.05	.01	5	.2	26
-1	.2	.001	-.1	1	.02	8
V	V^{-1}	AV^{-n}	V^{-1}	1	1	

- a new reliable algorithm for solving the nonlinear circuits in both static and dynamic cases is included - the algorithm converges even for GaAs FET and BJT microwave amplifiers with extreme feedback.
- sensitivity analyzes can be performed in static, static transfer, frequency, and even transient domains
- a steady-state algorithm has also been included - the algorithm is also able to determine the unknown period of autonomous microwave circuits automatically

VII. CONCLUSIONS

In this paper, identification of a more precise modified GaAs FET model was fulfilled. Transient analysis of a distributed oscillator at 3.8 GHz was also performed. Moreover, optimization and some other novel feature of GaAs FET circuit modeling by the CIA program were presented.

VIII. REFERENCES

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