Parameters Extraction for Pseudomorphic HEMTs Using Genetic Algorithms

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***Abstract*—**A proposed small-signal model parameters for a pseudomorphic high electron mobility transistor (PHEMT) is presented. Both extrinsic and intrinsic circuit elements of a small-signal model are determined using genetic algorithm (GA) as a stochastic global search and optimization tool. The parameters extraction of the small-signal model is performed on 200-μm gate width AlGaAs/InGaAs PHEMT. The equivalent circuit elements for a proposed 18 elements model are determined directly from the measured S- parameters. The GA is used to extract the parameters of the proposed small-signal model from 0.5 up to 18 GHz.

***Keywords*—**PHEMT, Genetic Algorithms, small signal modeling, optimization.

I. INTRODUCTION

GAAS-BASED pseudomorphic HEMTs (PHEMTs) are used in microwave technology, high speed digital circuits and applications that require low noise figures and high gain, particularly at millimeter-wave frequencies. A HEMT, operating at high frequencies, can be represented by a modified circuit diagram as shown in figure 1. The 18 elements of the circuit can be divided into two parts: intrinsic and extrinsic elements.

a) The elements outside the dotted box (R_g , R_s ,R_d , L_g, L_s, L_d, C_{pg} and C_{pd}) are the extrinsic parasitic elements, and can be considered constant with bias.

b) The elements inside the dotted box (C_{gd} , C_{gs}, Cds, R_{gd} , R_i, g_{ds} , g_m and tau) are the intrinsic elements, changing with bias and thus are considered nonlinear.

In figure (1), the elements (R_t and C_t) are introduced to represent the transit time effect.

It is convenient to use the admittance Y-parameters when dealing with intrinsic elements, because they exhibit the pi topology and to remove the pad capacitances. These components can be found by measuring the S-parameters of the device at each bias of interest, and then using the Dambrine method [1] to extract the component values from the S-parameters, then the Y-parameters are converted back to Z-parameters to remove R_g , R_d , R_s , L_g , L_d , and L_s.The final step is to convert back to Y-parameters.

II. SMALL SIGNAL MODEL ANALYSIS

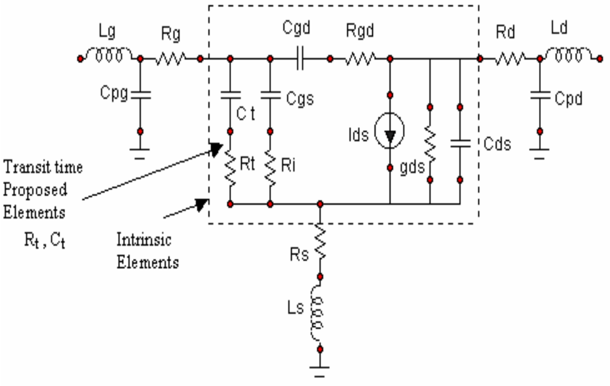

Fig. 1 Schematic Diagram of the proposed small-signal model

The traditional HEMT model (gate - drain resistor model) [2,3], is modified by introducing an impedance Z_t in parallel with the gate source capacitance C_{gs} and the charge resistance R_i as shown in figure (1). This impedance represents charge transfer transit time effect due to drift velocity depredating on bias voltage and frequency [4].

III. THE PROPOSED MODEL

The intrinsic y-parameters for the charge transfer transit time effect Z_t can be deduced as follows:
S-parameters are taken at the concerned bias point at different frequencies, and placed into an "S2P" file format. These parameters are converted into Y-parameters after de-embedding the extrinsic elements using equations 1 to 4:

$$y_{11}=(\omega^2 c_t^{\,2} R_t + \omega^2 c_{gs}^{\,2} R_i + \omega^2 c_{gd}^{\,2} R_{gd}) + j\omega(c_{gs}+c_{gd}+c_t) \quad (1)$$

$$y_{12}=-\omega^2 c_{gd}^{\,2} R_{gd} - j\omega c_{gd} \quad (2)$$

$$y_{21}=g_m(1-(R_i(j\omega c_{gd})(\frac{Z_t}{Z_t+Z_{gs}})) - j\omega c_{gd} - \omega^2 c_{gd}^{\,2} R_{gd} \quad (3)$$

$$y_{22}=(g_{ds}+\omega^2 c_{gd}^{\,2} R_{gd}) + j\omega(c_{ds}+c_{gd}) \quad (4)$$

$$Z(\tau)=\frac{1+j\omega\, c_t\, R_t}{j\omega\, c_t} \quad (5)$$

$$Z_{gs}=\frac{1+j\omega c_{gs} R_i}{j\omega c_{gs}} \quad (6)$$

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Taking into account the following approximations:

$$\omega^2 c_{gs}^2 R_i^2 << 1 \quad and \quad \omega\tau << 1$$

Equations 1 to 4 represent the four Y-parameters and the eighteen unknowns of the introduced equivalent circuit model.

IV. CIRCUIT ELEMENTS OPTIMIZATION

An error or objective function E_f can be defined in this work as the difference between the measured S-parameters and the simulated S-parameters (from the optimization process) through a certain frequency range and this error function can be shown as:

$$E_f = \frac{1}{n}\sum_{f_1}^{f_n} w_1\left|\overset{m}{S_{11}} - \overset{mod}{S}_{11}\right|^2 + w_2\left|\overset{m}{S_{21}} - \overset{mod}{S}_{21}\right|^2$$

$$+ w_3\left|\overset{m}{S_{12}} - \overset{mod}{S}_{12}\right|^2 + w_4\left|\overset{m}{S_{22}} - \overset{mod}{S}_{22}\right|^2 \qquad (7)$$

where n is the is the number of measurements at different frequency points, and S^m , S^{mod} are the measured and calculated (or modeled)S-parameters, respectively .The coefficients w_1 to w_4 are weighting factors that empathize (or deempathize) a specific portion of the error function and are equal to unity as a default value. If the modeled S-parameters were perfect, this equation would reach a minimum value as possible. For this purpose a genetic algorithm optimizer (GA) is used when the objective function is to be minimized.

The GA optimization method is working according the following steps [5,6]:

Step 1: Represent the problem variable domain as a chromosome with population size *N* of fixed length; the crossover probability *Pc* and the mutation probability *Pm*.

Step 2: Define a *fitness function* to measure the performance of an individual chromosome in the problem domain.

Step 3: Randomly generate an initial population of size N: *X1 , X2 , X3 , …….,*X_N

Step 4: Calculate the fitness of each individual chromosome *f (X1) , f (X2) , f (X3), ……, f* (X_N)

Step 5: Select a pair of chromosomes for mating from the current population. Parent chromosomes are selected with a probability related to their fitness. High fit chromosomes have a higher probability of being selected for mating than less fit t chromosomes.

Step 6: Create a pair of offspring chromosomes by applying the genetic operators.

Step 7: Place the created offspring chromosomes in the new population.

Step 8: Repeat Step 5 until the size of the new population equals that of initial population, *N.*

Step 9: Replace the initial (parent) chromosome population with the new (offspring) population.

Step 10: Go to Step 4, and repeat the process until the termination criterion is satisfied.

V. MODEL IMPLEMENTATION AND EXPERIMENTAL RESULTS

The device under test is The LP7512, it is an (AlGaAs/InGaAs) PHEMT, utilizing an Electron-Beam directwrite 0.25 µm by 200 µm Schottky barrier gate with “mushroom” gate structure [7].

The S-parameters measurements were taken from 0.5 GHz to 18 GHz, where the device is active ($v_{ds} \neq 0$). The GA has been introduced into the extraction of model parameters for PHEMT.

Figure (2) shows the optimization procedures in which the 18 unknowns are varied until a minimum difference between the measured S-parameters and the introduced model S-parameters is obtained. After determining the optimized variables (circuit elements), the obtained results of the introduced model are compared with the measured S-Parameters values.

Table (1) indicates the initial values for the circuit elements .The corresponding model optimized parameters are indicated in table (2). Some form of trial-and-error tuning was necessary for each particular instance of optimization problem. In this work, some trials have been achieved, to change the main GA’s parameters values. The population size *Np* is chosen as 100.The crossover probability *Pc* and the mutation probability *Pm* are chosen as 0.95 and 0.05, respectively.

The selection method that determines which of the individuals will survive and continue in the next generation (iteration), is *roulette wheel* selection.

The root mean square “ rms “ errors ε_{ij}, between the introduced model and the measured S-parameters are compared by [8]:

$$\varepsilon_{ij} = \sqrt{\frac{\sum_N \left| S_{ij}^{mod}(\omega_n) - S_{ij}^{m}(\omega_n) \right|^2}{\sum_N \left| S_{ij}^{m}(\omega_n) \right|^2}} \qquad (8)$$

where Sij^{mod} is the predicted S-parameters and Sij^{m} is the measured S-parameters. Figure (3) shows the good agreement between the measured S-parameters and modeled ones on smith chart, using the proposed model.

TABLE I

INITIAL VALUES FOR OPTIMIZATION

Circuit Elements	Lower Bound	Upper Bound
Rg (Ω)	0.01	4
Rs (Ω)	0.01	4
Rd (Ω)	0.01	4
Lg (pH)	0.001	10
Ls (pH)	0.001	10
Ld (pH)	0.001	10
Cgd (f F)	0.001	100
Cgs (f F)	0.001	100
Cds (f F)	0.001	100

Gds (mS)	0	90
Ri (Ω)	0.1	30
gm (mS)	0	100
Tau (ps)	0	10
Rgd (Ω)	0	1
Rt (Ω)	0.1	30
Ct (F)	0.001	500
Cpg (f F)	0	1000
Cpd (f F)	0	1000

TABLE II
EXTRACTED PARAMETERS
OF 18 ELEMENTS MODEL

Extrinsic Circuit	**Optimized values**
Rg (Ω)	1.9601
Rs (Ω)	1.4702
Rd (Ω)	1.5581
Lg (pH)	5.21
Ls (pH)	7.73
Ld (pH)	4.7
Cpg (f F)	130
Cpd (f F)	180
Intrinsic Circuit	**Optimized values**
Cgd (f F)	49.8
Cgs (f F)	31
Cds (f F)	79
Gds (mS)	3.041
Ri (Ω)	9.4981
gm (mS)	68.531
Tau (ps)	4.64
Rgd (Ω)	0.19425
Rt (Ω)	14.635
Ct (f F)	210

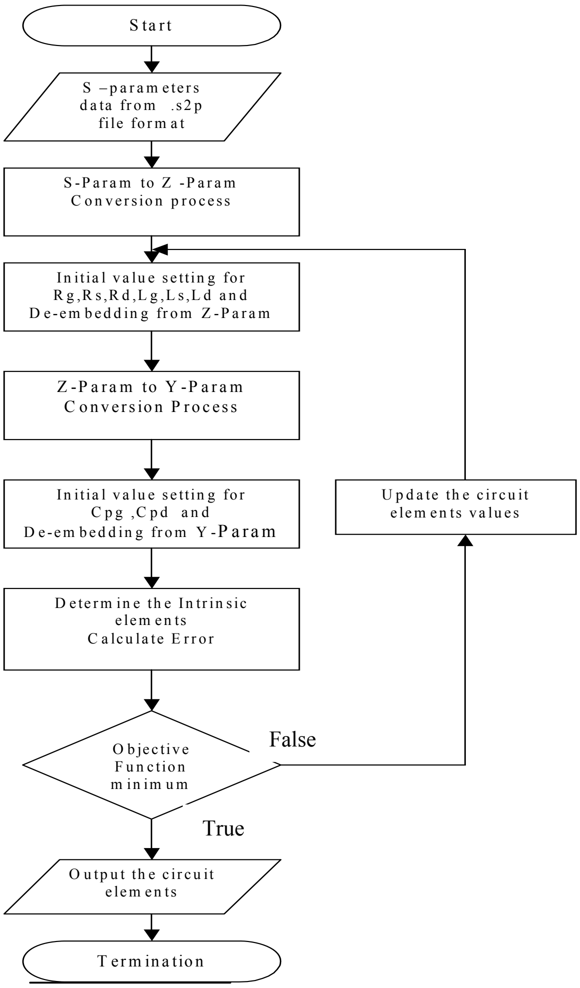


Fig. 2 Flow chart for the iterative algorithm to determine the equivalent circuit elements of PHEMT

The previous model gives approximately 2% relative error between measured and predicted S-parameters as indicated in table (3). Figure (3) shows the good agreement between the measured S-parameters and modeled ones on smith chart, using the proposed model.

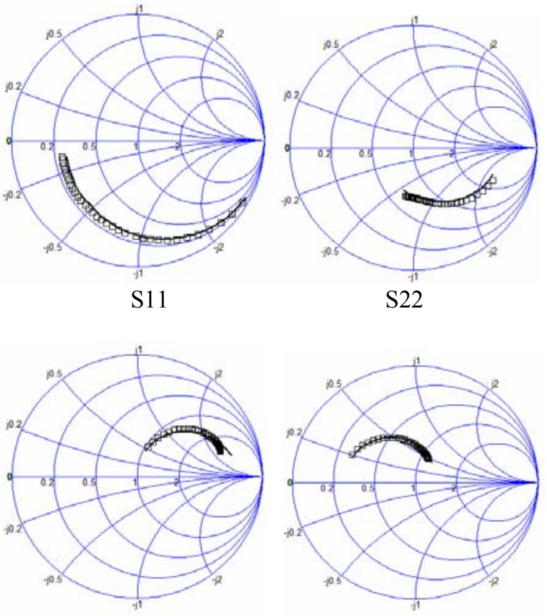
The correlation coefficient relation is used to measure the quality of the introduced model generated by the GA and is given by:

$$r=\frac{\left(\Sigma\left(S_{ij}^{m}-\overline{S_{ij}^{\mathrm{mod}}}\right)\left(S_{ij}^{\mathrm{mod}}-\overline{S_{ij}^{\mathrm{mod}}}\right)\right)}{\sqrt{\left[\Sigma\left(S_{ij}^{m}-\overline{S_{ij}^{m}}\right)^{2}\Sigma\left(S_{ij}^{\mathrm{mod}}-\overline{S_{ij}^{\mathrm{mod}}}\right)^{2}\right]}} \qquad (9)$$

where S_{ij}^{m} is the measured value of S-parameters, S_{ij}^{mod} is the optimized value , $\overline{S_{ij}^{m}}$ is the measured value mean and $S_{ij}^{\overline{\mathrm{mod}}}$ is the optimized value mean. The results of table (3) show that the values of correlation coefficients are close to one, which indicates good prediction ability for the proposed model.

TABLE III
RMS ERROR FOR THE MODELED S-PARAMETERS

S-parameters	**rms error %**	**Correlation Coefficients**
S11	2.4164	0.9663
S21	1.5480	0.9969
S12	2.9322	0.9681
S22	2.0586	0.9892



S11 S22

c- 4* *S12* *d - 0 .1* S21*

Figure 3. Typical modeled vs. measured S-parameters. Comparison is given on smith chart for lp7512 PHEMT, Frequency: 0.5 : 18GHz. Bias setting: at v_{ds}= 2 V and v_{gs}= -0.34 V. Solid line: measuring values , squares: modeling data.

VI. CONCLUSION

A proposed model is introduced to extract the parameters of small-signal equivalent circuit for microwave power AlGaAs/InGaAs PHEMT including the transit time effect, using genetic algorithms procedures as an optimization tool. The application results show that the values of relative error at the same biasing are within 2%. The quality of optimization process was validated using the correlation coefficient relation. It was observed that the values of correlation coefficients are close to unity. Simulations were conducted on a conventional 1.7 GHz PC, in the MATLAB 7 (Release 14) environment.

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