IMPLEMENTATION OF HEMT MODELS AND COMPARISON WITH THE MEASURED DATA FROM MOTOROLA

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I. INTRODUCTION

Four HEMT models have been implemented in HarPE [1] and OSA90/hope [2]. They include the Curtice HEMT model (HEMTC) [3], the advanced Curtice HEMT model (HEMTAC) [3], the high order beta degradation HEMT model (HEMTG1) [4] and the double parabolic HEMT model (HEMTG2) [4].

In this report we describe the details of the implementation of each HEMT model. HEMTG1 and HEMTG2 were compared with the same models from Motorola [4,5] against the measured DC and *S* parameters at several bias points [5]. Reasonable DC agreement and *S*-parameter match between the model responses and the measurements are observed by using the model parameter values provided in [4] and [5].

In order to improve the models we performed optimization by taking the parameter values given in [4] and [5] as the starting point. The match between the model responses and the measurements was significantly improved after optimization.

Parameter extraction was carried out for HEMTAC and HEMTC by fitting the model responses including DC and *S* parameters at several bias points to the measurements. A good agreement between the model responses and measurements was obtained.

II. MODEL EQUATIONS

The HEMT models are implemented according to the model equations given in [3] and [4]. The intrinsic circuit of the models consists of two nonlinear capacitors, two diodes and one nonlinear current source as shown in Fig. 1.

The following HEMT capacitance equations proposed by Golio in [3] are used to compute the nonlinear capacitances for all four models.

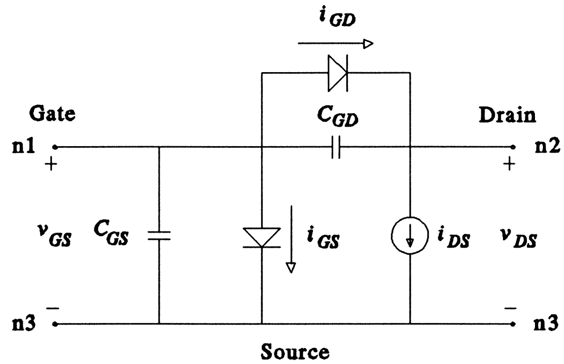


Fig. 1 The intrinsic equivalent circuit of the HEMT models.

$$C_{GS} = \begin{cases} \frac{2}{3}\left[1 - \frac{(V_{DSS} - v_{DS})^2}{(2V_{DSS} - v_{DS})^2}\right]C_G + C_{GS0} & \text{for } v_{DS} < V_{DSS} \\ \frac{2}{3}C_G + C_{GS0} & \text{for } v_{DS} \geq V_{DSS} \end{cases} \tag{1}$$

$$C_{GD} = \begin{cases} \frac{2}{3}\left[1 - \frac{V_{DSS}^2}{(2V_{DSS} - v_{DS})^2}\right]C_G + C_{GD0} & \text{for } v_{DS} < V_{DSS} \\ C_{GD0} & \text{for } v_{DS} \geq V_{DSS} \end{cases} \tag{2}$$

where

$$C_G = \begin{cases} C_{M0}(v_{GS} - V_{T0})^{1/\chi} & \text{for } v_{GS} > V_{T0} \\ 0 & \text{for } v_{GS} \leq V_{T0} \end{cases} \tag{3}$$

$$V_{DSS} = \begin{cases} V_{DS0}\left[1 - \frac{v_{GS}}{V_{T0}}\right] & \text{for } v_{GS} > V_{T0} \\ 0 & \text{for } v_{GS} \leq V_{T0} \end{cases} \tag{4}$$

C_{GS0}, C_{GD0}, C_{M0}, χ, V_{DS0} and V_{T0} are model parameters.

The following diode equations are used to compute the nonlinear currents of the two diodes in the intrinsic circuit for all four models.

$$i_{GS} = \begin{cases} I_S \left[\exp\left(\dfrac{v_{GS}}{NV_{TH}} \right) - 1 \right] + G_{MIN} v_{GS} & \text{for } v_{GS} \geq -5NV_{TH} \\ -I_S + G_{MIN} v_{GS} & \text{for } -V_{BR} + 50V_{TH} < v_{GS} < -5NV_{TH} \\ -I_S \left[\exp\left(-\dfrac{v_{GS} + V_{BR}}{V_{TH}} \right) + 1 \right] + G_{MIN} v_{GS} & \text{for } v_{GS} \leq -V_{BR} + 50V_{TH} \end{cases} \tag{5}$$

where

$$V_{TH} = \frac{kT}{q} \tag{6}$$

is the thermal voltage. G_{MIN}, I_S, N, T (temperature) and V_{BR} are model parameters.

The equations for calculating the nonlinear currents of each model are as follows [3,4].

A. The Curtice HEMT Model (HEMTC)

$$i_{DS} = \begin{cases} i_{DSFET} & \text{for } v_{GS} \leq V_{PF} \\ i_{DSFET} - \dfrac{\xi}{\psi + 1}(v_{GS} - V_{PF})^{\psi + 1} f(v_{DS}) & \text{for } v_{GS} > V_{PF} \end{cases} \tag{7}$$

where

$$i_{DSFET} = \begin{cases} 0 & \text{for } v_{GS} \leq V_{T0} \\ \beta(v_{GS} - V_{T0})^2 f(v_{DS}) & \text{for } v_{GS} > V_{T0} \end{cases} \tag{8}$$

$$f(v_{DS}) = \tanh(\alpha v_{DS})(1 + \lambda v_{DS}) \tag{9}$$

α, β, λ, ξ, ψ, V_{PF} and V_{T0} are model parameters.

B. The Advanced Curtice HEMT Model (HEMTAC)

$$i_{DS} = \begin{cases} i_{DSFET} & \text{for } v_{GS} \le V_{PF} \\ i_{DSFET} - \beta_{eff}\xi(v_{GS} - V_{PF})^{\psi} f(v_{DS}) & \text{for } v_{GS} > V_{PF} \end{cases} \tag{10}$$

where

$$i_{DSFET} = \begin{cases} 0 & \text{for } v_{GS} \le V_T \\ \beta_{eff}(V_{GST})^{V_{GEXP}} f(v_{DS}) & \text{for } v_{GS} > V_T \end{cases} \tag{11}$$

$$\beta_{eff} = \frac{\beta}{1 + \mu_{CRIT} V_{GST}} \tag{12}$$

$$V_{GST} = v_{GS} - V_T \tag{13}$$

$$V_T = V_{T0} + \gamma v_{DS} \tag{14}$$

$$f(v_{DS}) = \tanh(\alpha v_{DS})(1 + \lambda v_{DS}) \tag{15}$$

α, β, γ, λ, μ_{CRIT}, ξ, ψ, V_{GEXP}, V_{PF} and V_{T0} are model parameters.

C. The High Order Beta Degradation HEMT Model (HEMTG1)

$$i_{DS} = \begin{cases} 0 & \text{for } v_{GS} \le V_T \\ \beta_{eff}(V_{GST})^{V_{GEXP}} f(v_{DS}) & \text{for } v_{GS} > V_T \end{cases} \tag{16}$$

where

$$\beta_{eff} = \frac{\beta}{1 + \mu_{CRIT}(V_{GST})^{G_{MEXP}}} \tag{17}$$

$$V_{GST} = v_{GS} - V_T \tag{18}$$

$$V_T = V_{T0} + \gamma v_{DS} \tag{19}$$

$$f(v_{DS}) = \tanh(\alpha v_{DS})(1 + \lambda v_{DS}) \tag{20}$$

α, β, γ, G_{MEXP}, λ, μ_{CRIT}, V_{GEXP} and V_{T0} are model parameters.

D. The Double Parabolic HEMT Model (HEMTG2)

$$i_{DS} = \begin{cases} 0 & \text{for } v_{GS} < V_T \\ \frac{\beta}{3}(v_{GS} - \gamma v_{DS} - V_{T0})^3 f(v_{DS}) & \text{for } V_T \le v_{GS} < V_{PF} \\ \beta\left[\frac{(V_C - V_{T0})^2(v_{GS} - V_{PF})}{2} - \frac{(v_{GS} - \gamma v_{DS} - V_C)^3}{3}\right] f(v_{DS}) & \text{for } v_{GS} \ge V_{PF} \end{cases} \tag{21}$$

where

$$V_{PF} = \frac{V_{T0} + V_C}{2} + \gamma v_{DS} \tag{22}$$

$$V_T = V_{T0} + \gamma v_{DS} \tag{23}$$

$$f(v_{DS}) = \tanh(\alpha v_{DS})(1 + \lambda v_{DS}) \tag{24}$$

α, β, γ, λ, V_C and V_{T0} are model parameters.

III. MODEL VERIFICATION

The HEMT models implemented are verified by comparing the model responses with the measured data. Two HEMT models: HEMTG1 and HEMTG2 are tested using the parameter values given in [4] and [5]. The measured data from Motorola [5] including DC I-V characteristics at 21 points and *S* parameters under 6 bias points (gate bias: -1.25 V, -1.0 V, -0.75 V, -0.5 V, -0.25 V and 0 V, drain bias: 1 V) are used for the test.

The built-in linear subcircuit EXTRINSIC1 shown in Fig. 2 is used for modeling the parasitic elements in the extrinsic circuits of the models for verification.

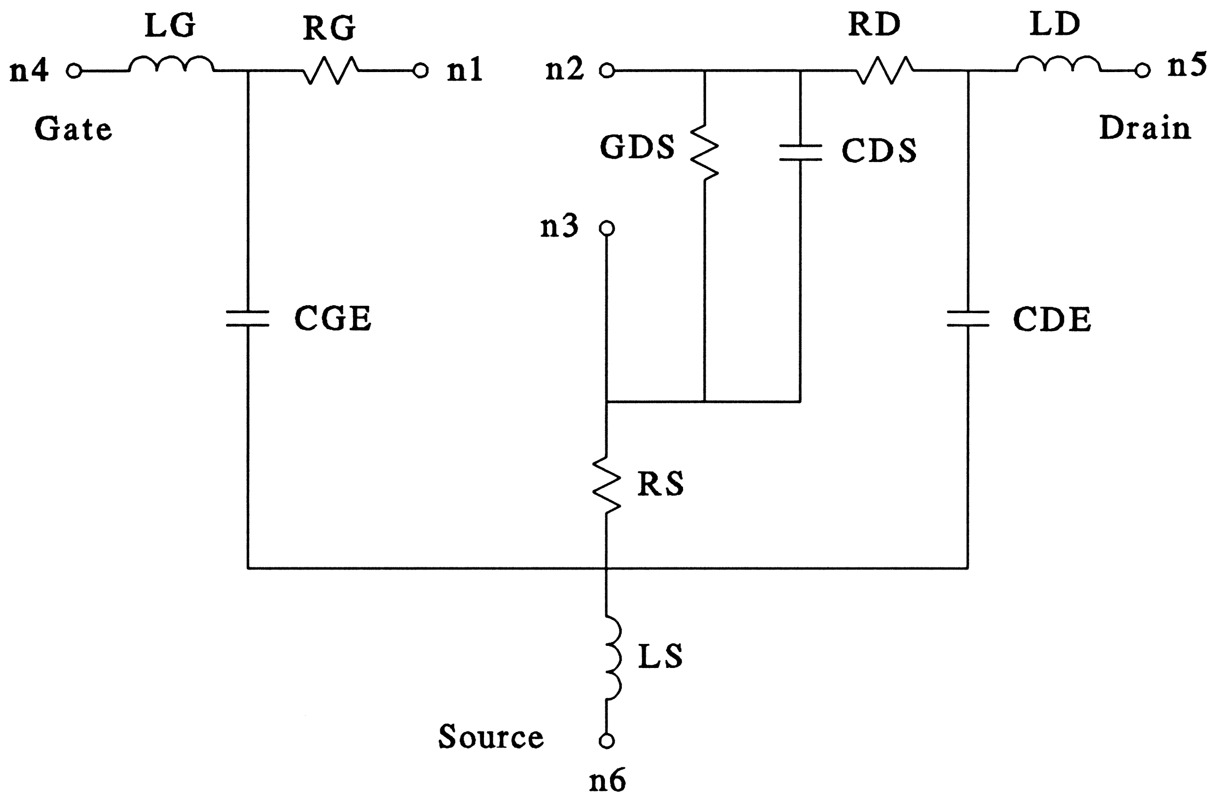


Fig. 2 The extrinsic circuit used for HEMT model verification.

A. Verification of HEMTG1

The parameter values of the model are listed in Table I.

TABLE I
PARAMETER VALUES FOR HEMTG1

Intrinsic		Extrinsic	
α	4.046	LG(nH)	0.134
β	0.018	LD(nH)	0.066
γ	-0.082	LS(nH)	0.0
G_{MEXP}	4.582	RG(Ω)	27.1
λ	0.054	RD(Ω)	9.6
μ_{CRIT}	0.457	RS(Ω)	8.1
V_{GEXP}	4.236	CDS(pF)	0.02868
V_{T0}(V)	-1.533	CGE(pF)	0.0
C_{GD0}(pF)	0.0034*	CDE(pF)	0.0
C_{GS0}(pF)	0.064*	GDS(1/Ω)	0.0
C_{M0}(pF)	1.81E-6*		
χ	0.042*		
V_{DS0}(V)	0.575*		
G_{MIN}(1/Ω)	1.0E-12*		
I_S(A)	1.0E-14*		
N	1.0*		
V_{BR}(V)	30*		

* parameter values, not given in [4] or [5], are extracted by DC and *S*-parameter matching.

Temperature *T* is set to room temperature: 298°K

The DC match between the HEMTG1 and the measured data is shown in Fig. 3. The S-parameter match between the HEMTG1 and measurements at two bias points are plotted in Figs. 4 and 5.

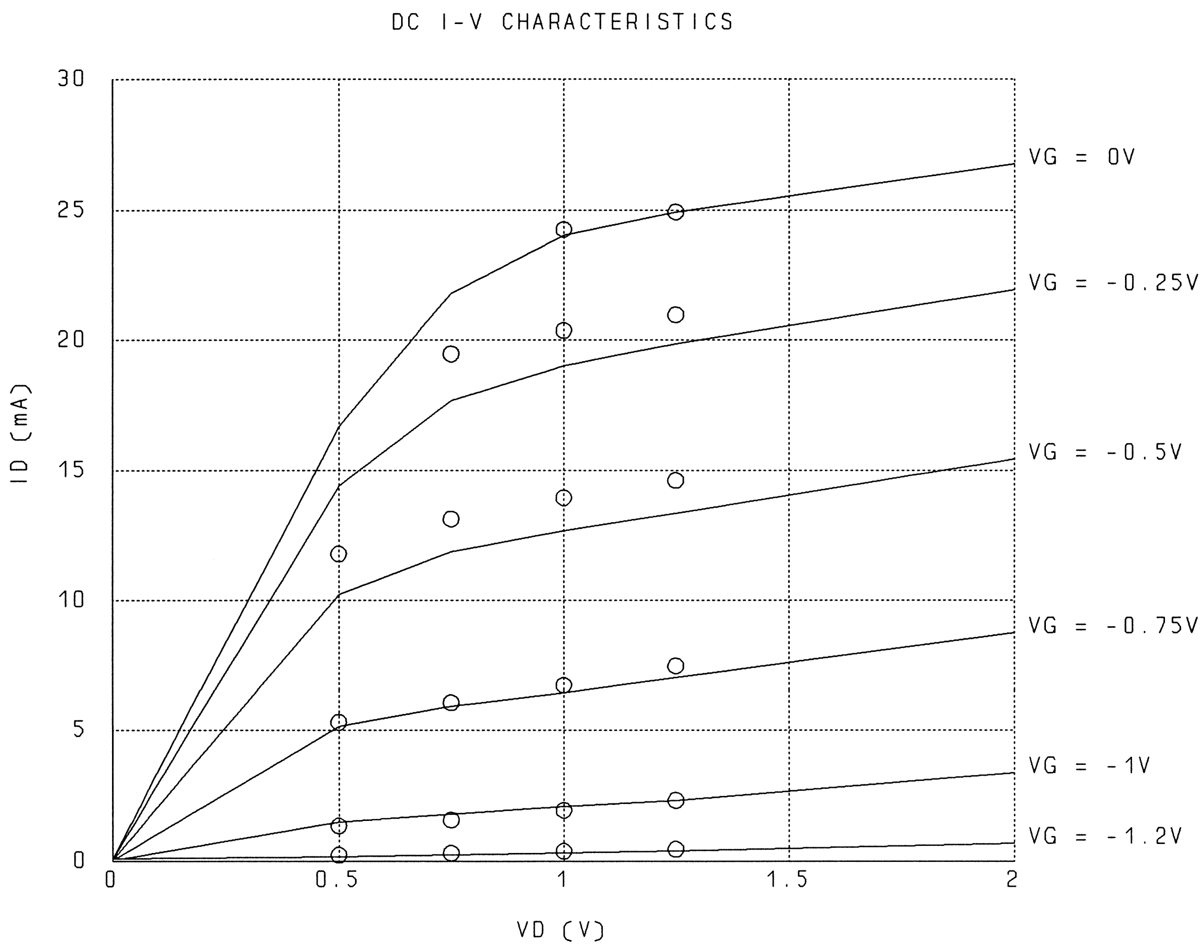
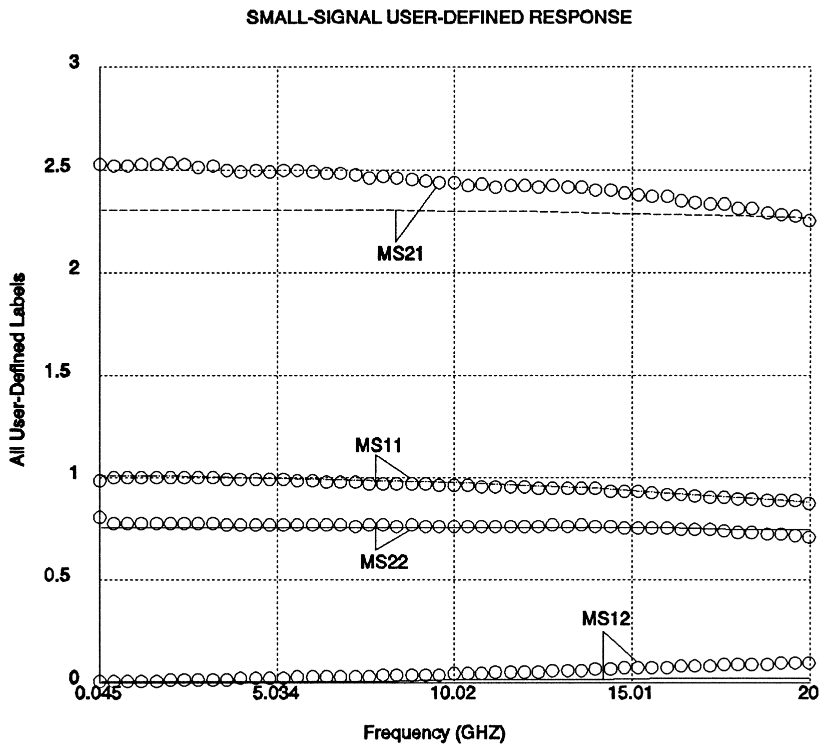
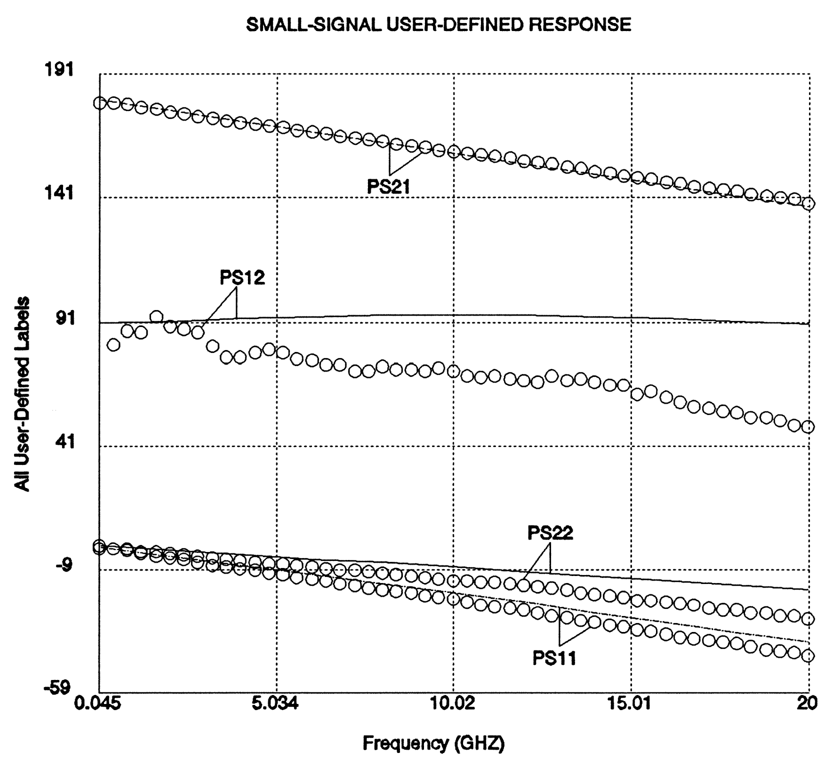


Fig. 3 DC I-V characteristics from HEMTG1 (solid line) and measurements (circles).

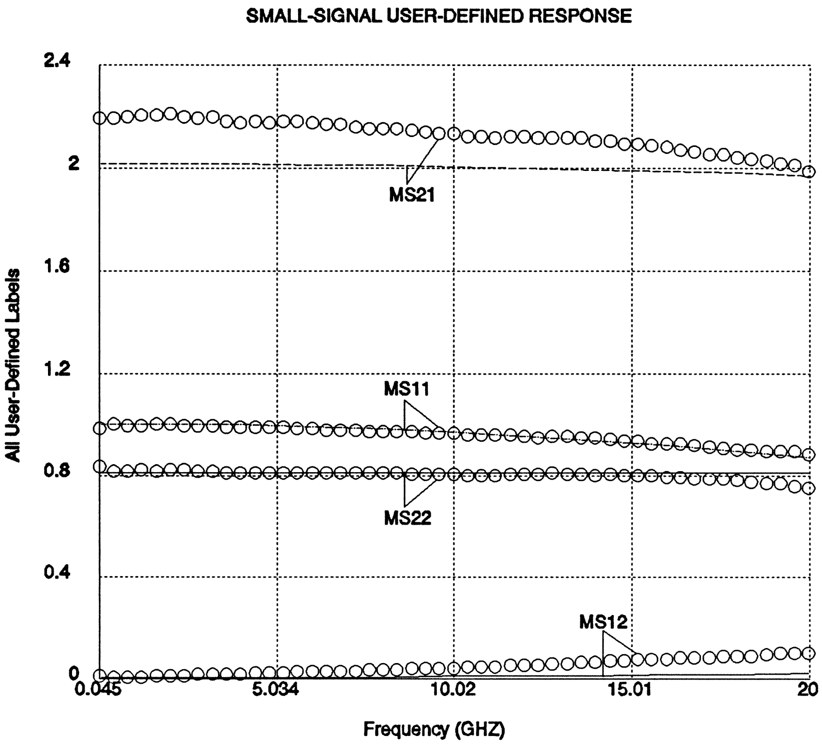


(a)

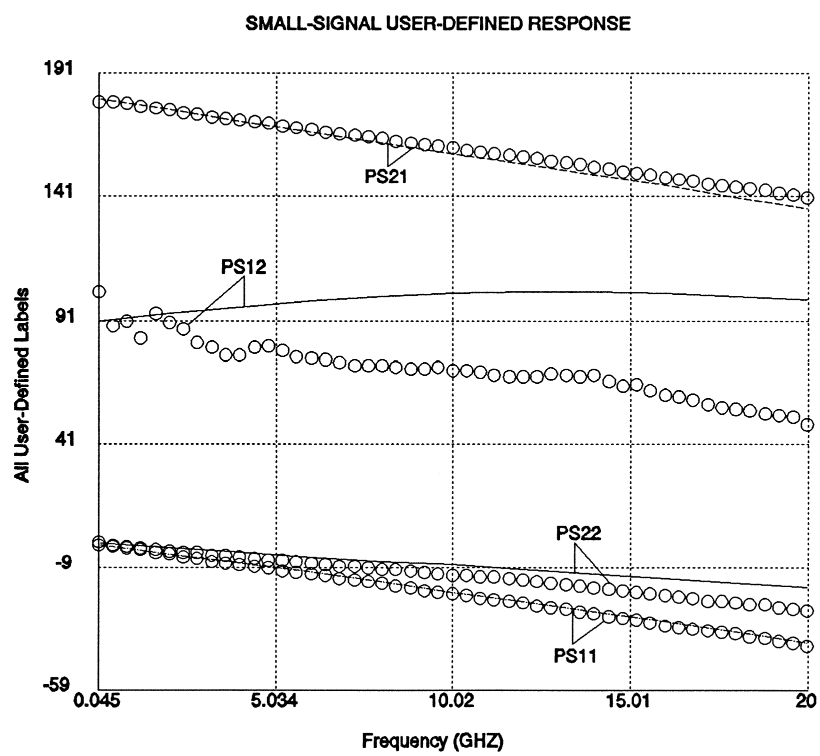


(b)

Fig. 4 *S*-parameter match between HEMTG1 and the measured data at gate bias: -0.5 V and drain bias: 1 V, (a) magnitudes and (b) phases.



(a)



(b)

Fig. 5 S-parameter match between HEMTG1 and the measured data at gate bias: -0.75 V and drain bias: 1 V, (a) magnitudes and (b) phases.

B. Verification of HEMTG2

The parameter values of the model are listed in Table II.

TABLE II
PARAMETER VALUES FOR HEMTG2

Intrinsic		Extrinsic	
α	4.294	LG(nH)	0.134
β	0.090	LD(nH)	0.066
γ	-0.117	LS(nH)	0.0
λ	-0.016	RG(Ω)	27.1
V_C	-0.525	RD(Ω)	9.6
V_{T0}(V)	-1.338	RS(Ω)	8.1
C_{GD0}(pF)	0.0042*	CDS(pF)	0.02868
C_{GS0}(pF)	0.063*	CGE(pF)	0.0
C_{M0}(pF)	1.28E-6*	CDE(pF)	0.0
χ	0.026*	GDS(1/Ω)	0.0
V_{DS0}(V)	0.499*		
G_{MIN}(1/Ω)	1.0E-12*		
I_S(A)	1.0E-14*		
N	1.0*		
V_{BR}(V)	30*		

* parameter values, not given in [4] or [5], are extracted by DC and *S*-parameter matching.

Temperature T is set to room temperature: 298°K

The DC match between the HEMTG2 and the measured data is shown in Fig. 6. The *S*-parameter match between the HEMTG2 and measurements at two bias points are plotted in Figs. 7 and 8.

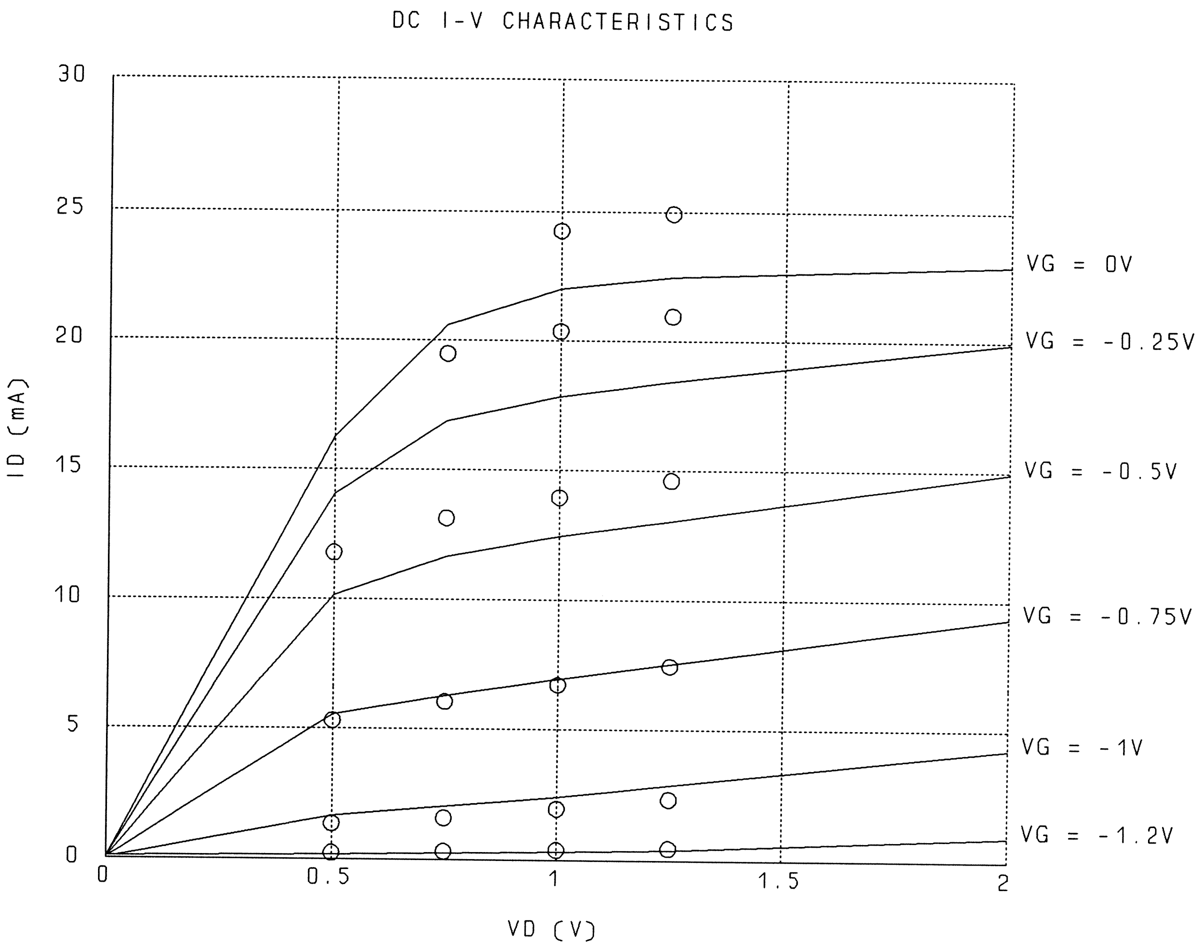
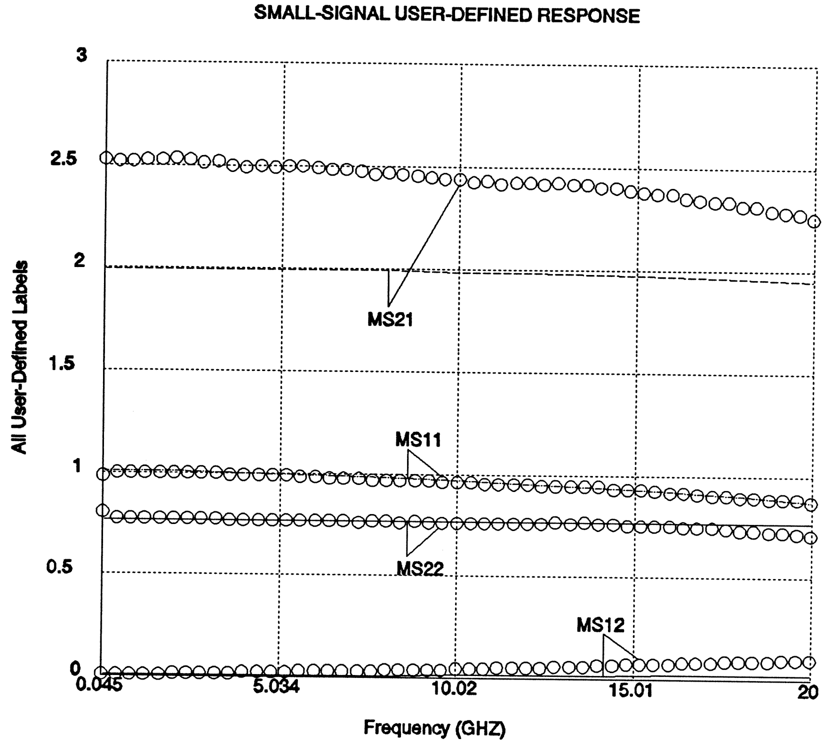
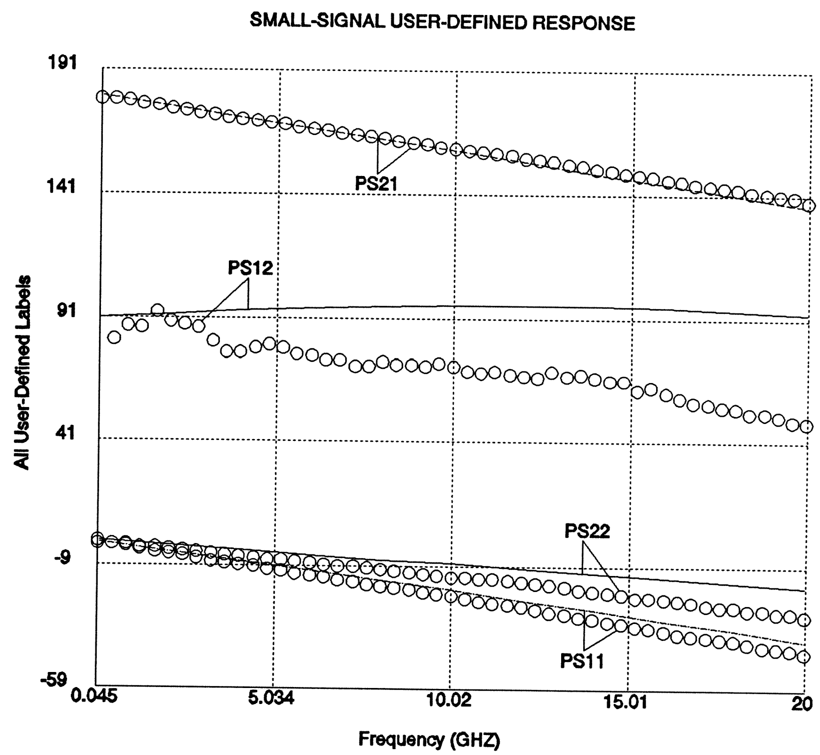


Fig. 6 DC I-V characteristics from HEMTG2 (solid line) and measurements (circles).

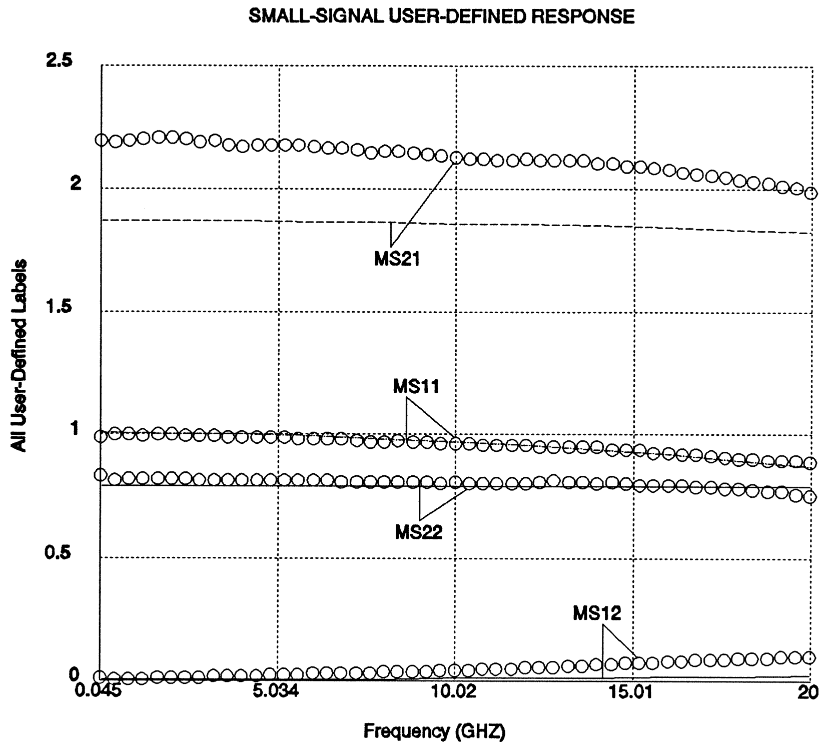


(a)

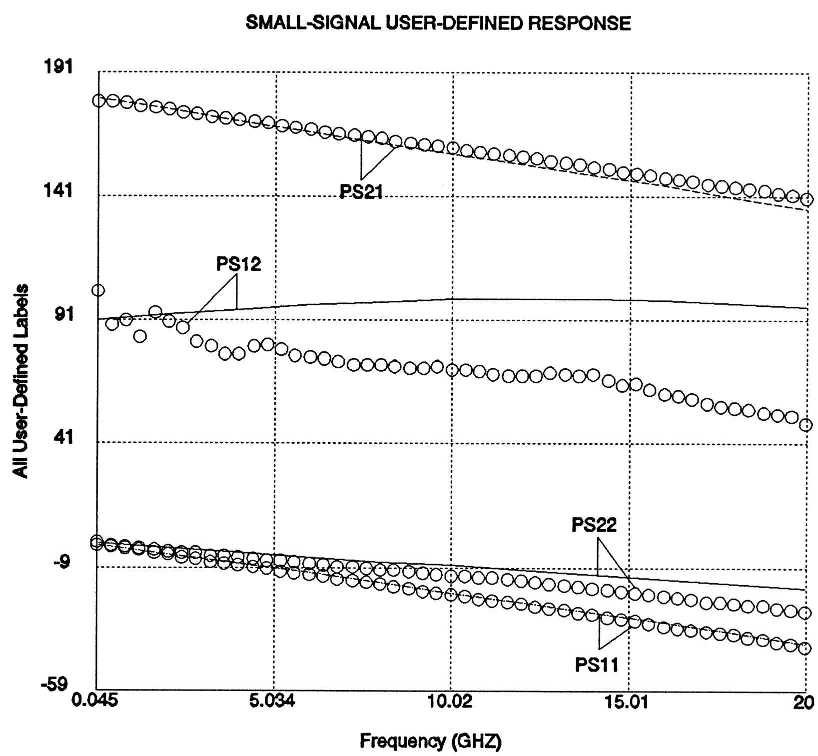


(b)

Fig. 7 S-parameter match between HEMTG2 and the measured data at gate bias: -0.5 V and drain bias: 1 V, (a) magnitudes and (b) phases.



(a)



(b)

Fig. 8 *S*-parameter match between HEMTG2 and the measured data at gate bias: -0.75 V and drain bias: 1 V, (a) magnitudes and (b) phases.

IV. MODEL OPTIMIZATION

From the comparison between the model responses and measurements in Section III we observed that with the parameter values given in [4] and [5] there are some discrepancies between the simulated and measured responses. In order to improve the match we performed optimization starting from the values provided in [4] and [5]. All parameters including intrinsic and extrinsic elements are defined as variables. The match is significantly improved after optimization. The results are shown as follows.

A. Optimization of HEMTG1

The model parameter values after optimization are listed in Table III.

TABLE III
PARAMETER VALUES FOR HEMTG1 AFTER OPTIMIZATION

Intrinsic		Extrinsic	
α	3.385	LG(nH)	0.0077
β	0.0004	LD(nH)	0.0850
γ	-0.079	LS(nH)	1.69E-4
G_{MEXP}	10.594	RG(Ω)	8.597
λ	0.0026	RD(Ω)	0.764
μ_{CRIT}	0.014	RS(Ω)	15.542
V_{GEXP}	10.583	CDS(pF)	2.05E-4
V_{T0}(V)	-2.118	CGE(pF)	1.44E-4
C_{GD0}(pF)	0.0026	CDE(pF)	0.0309
C_{GS0}(pF)	0.088	GDS(1/Ω)	8.94E-5
C_{M0}(pF)	1.90E-6		
χ	0.109		
V_{DS0}(V)	0.525		
G_{MIN}(1/Ω)	1.321E-12		
I_S(A)	3.186E-14		
N	0.319		
V_{BR}(V)	79.83		
Temperature T is set to room temperature: 298°K			

The DC match between the HEMTG1 after optimization and the measured data is shown in Fig. 9. The S-parameter match between the HEMTG1 after optimization and measurements at two bias points are plotted in Figs. 10 and 11.

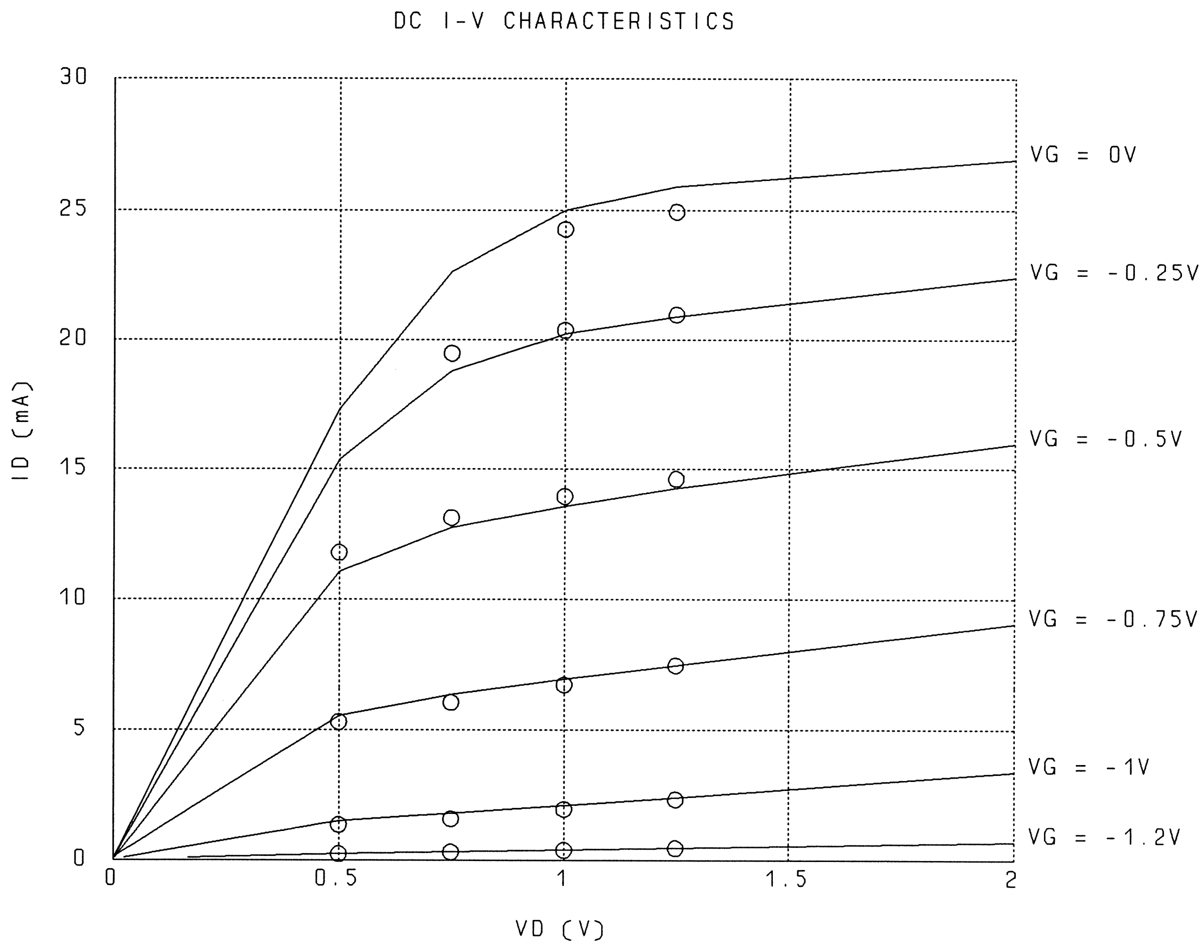
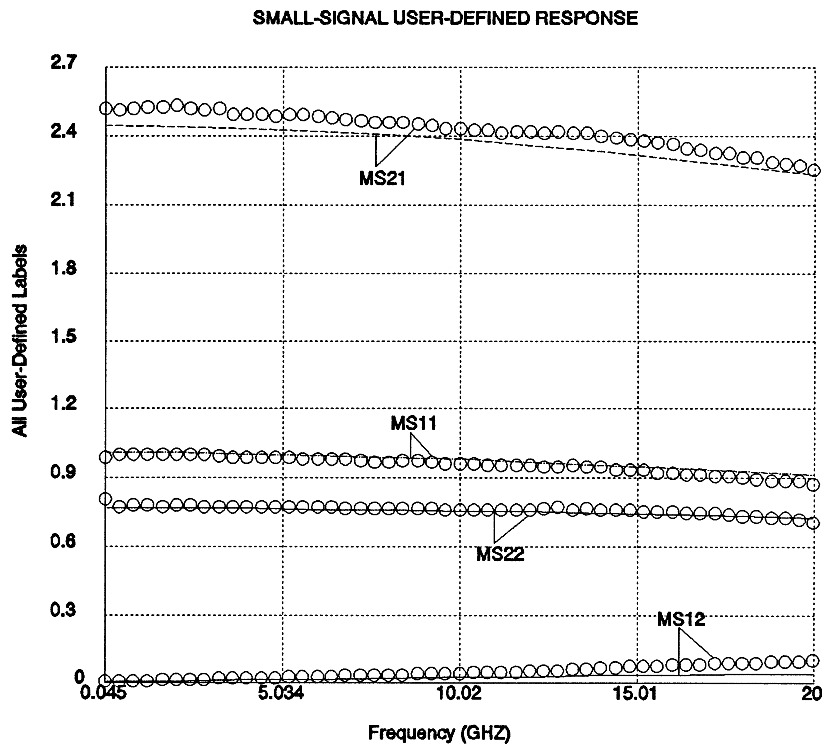
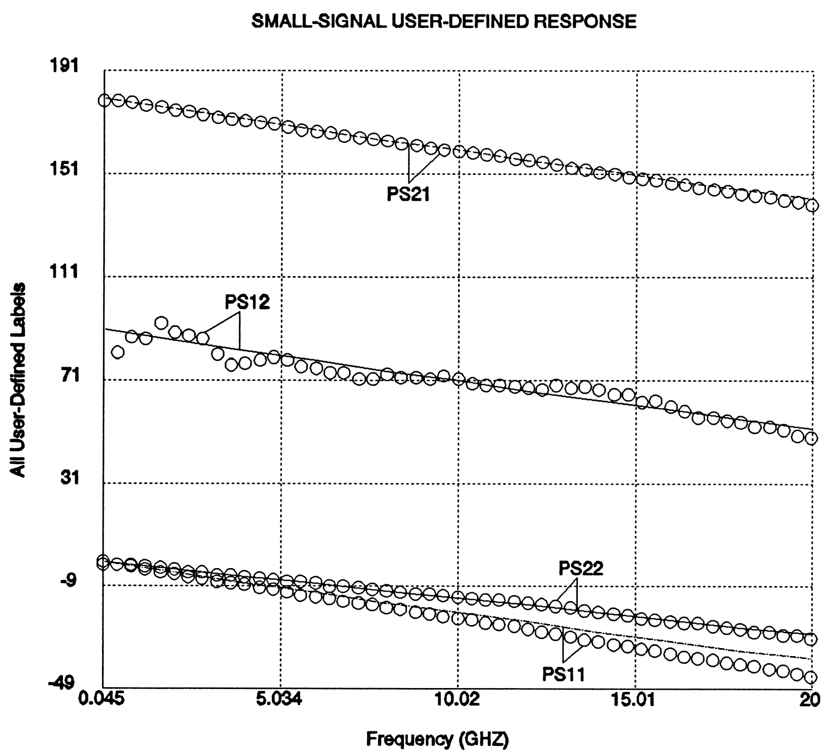


Fig. 9 DC I-V characteristics from HEMTG1 after optimization (solid line) and measurements (circles).

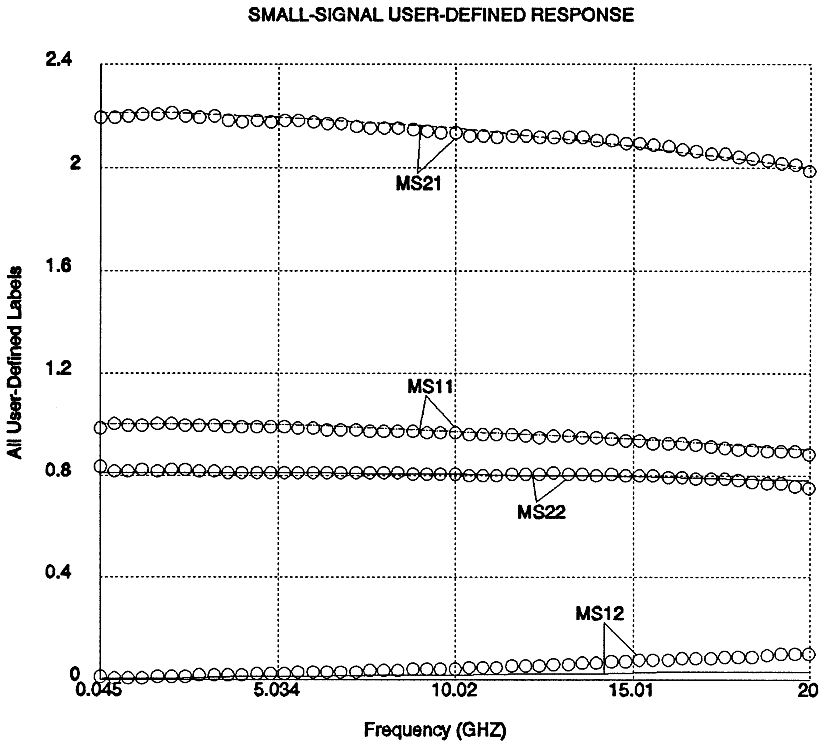


(a)

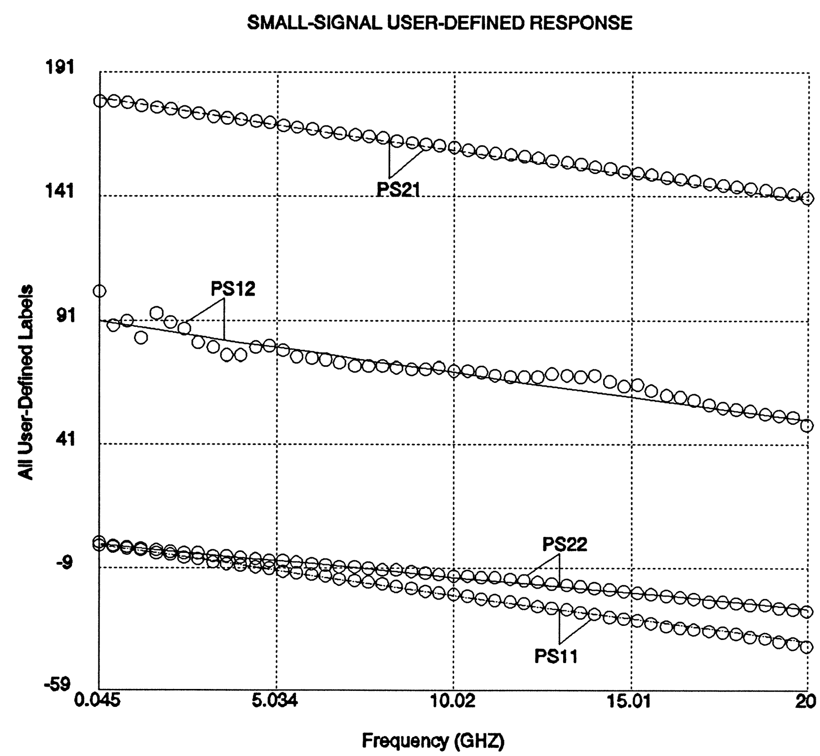


(b)

Fig. 10 S-parameter match between HEMTG1 after optimization and the measured data at gate bias: -0.5 V and drain bias: 1 V, (a) magnitudes and (b) phases.



(a)



(b)

Fig. 11 *S*-parameter match between HEMTG1 after optimization and the measured data at gate bias: -0.75 V and drain bias: 1 V, (a) magnitudes and (b) phases.

B. Optimization of HEMTG2

The model parameter values after optimization are listed in Table IV.

TABLE IV
PARAMETER VALUES FOR HEMTG2 AFTER OPTIMIZATION

Intrinsic		Extrinsic	
α	3.688	LG(nH)	0.0040
β	0.080	LD(nH)	0.0667
γ	-0.085	LS(nH)	2.98E-4
λ	-0.030	RG(Ω)	19.66
V_C	-0.436	RD(Ω)	15.31
V_{T0}(V)	-1.334	RS(Ω)	1.746
C_{GD0}(pF)	0.0058	CDS(pF)	8.55E-4
C_{GS0}(pF)	0.0590	CGE(pF)	5.96E-4
C_{M0}(pF)	4.8E-7	CDE(pF)	0.0352
χ	0.0307	GDS(1/Ω)	1.31E-4
V_{DS0}(V)	3.885		
G_{MIN}(1/Ω)	0.8E-12		
I_S(A)	0.3E-14		
N	3.752		
V_{BR}(V)	26.15		

Temperature T is set to room temperature: 298°K

The DC match between the HEMTG2 after optimization and the measured data is shown in Fig. 12. The S-parameter match between the HEMTG2 after optimization and measurements at two bias points are plotted in Figs. 13 and 14.

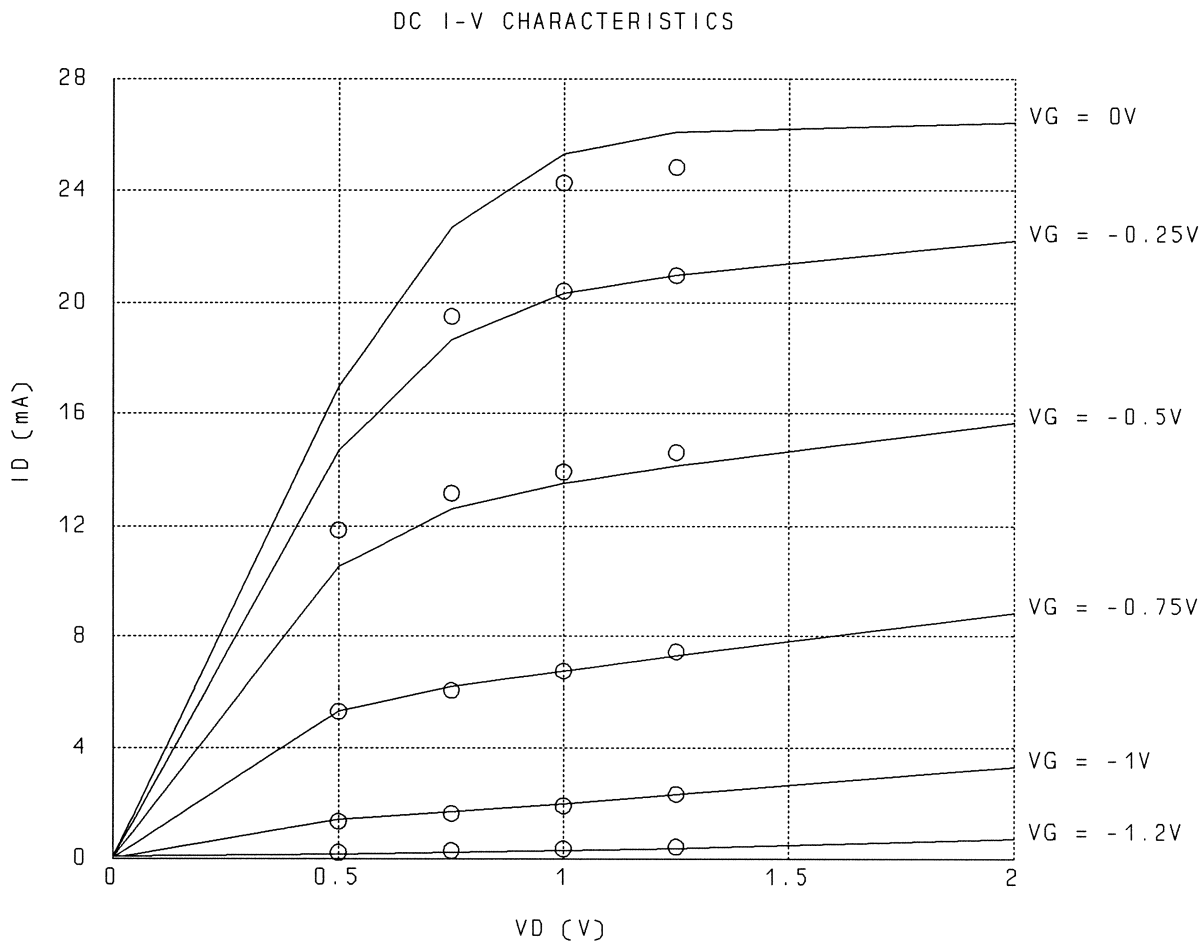
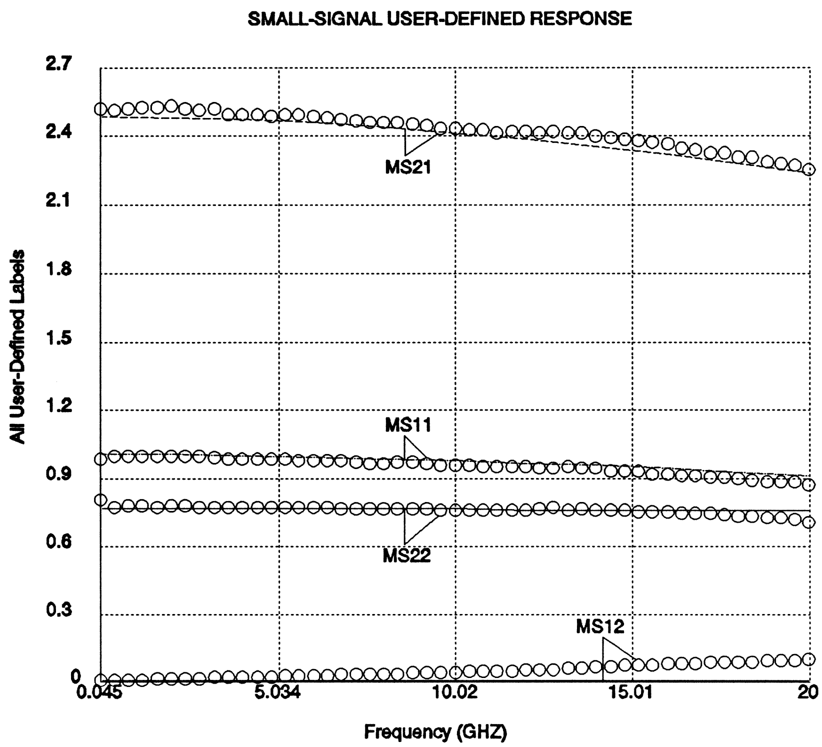
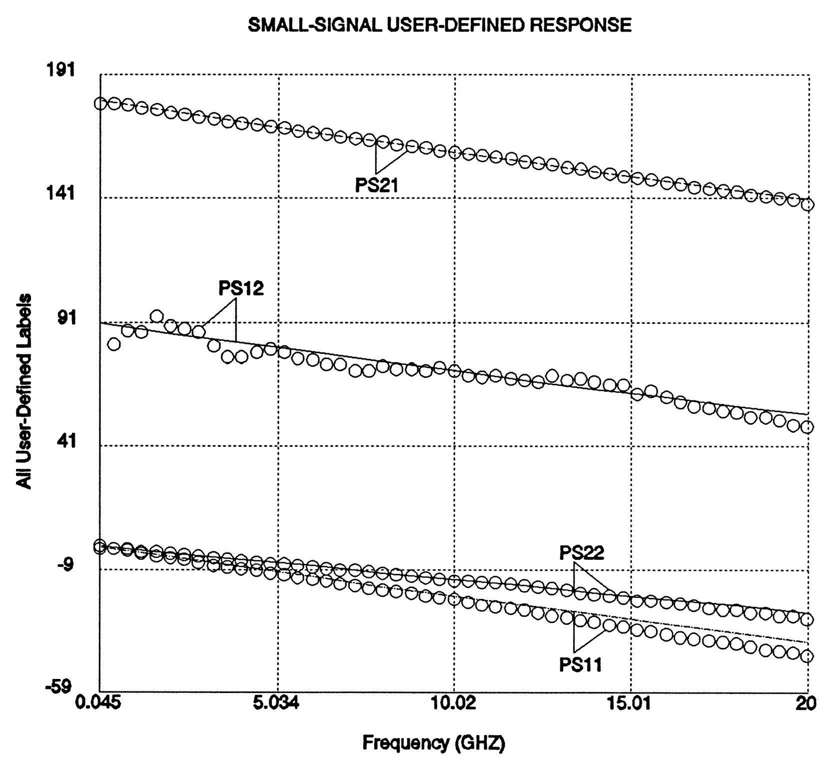


Fig. 12 DC I-V characteristics from HEMTG2 after optimization (solid line) and measurements (circles).

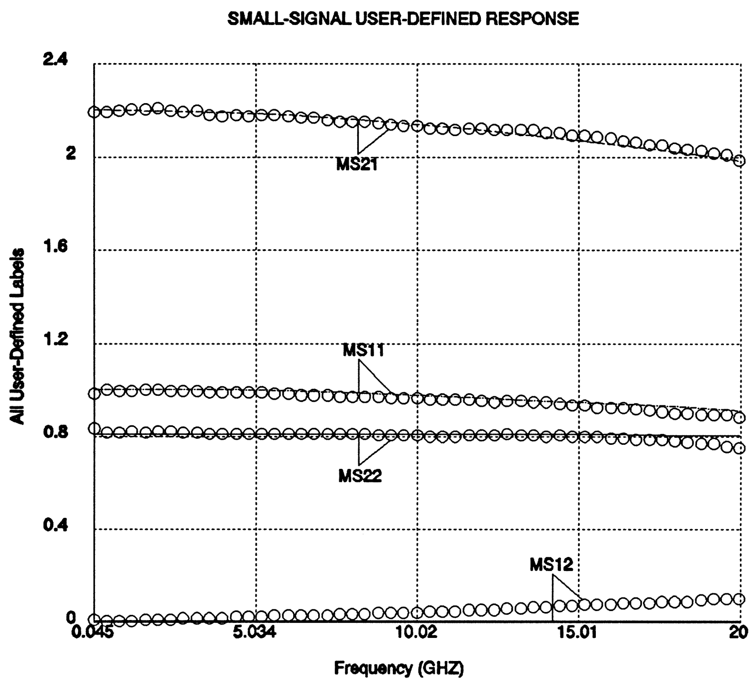


(a)

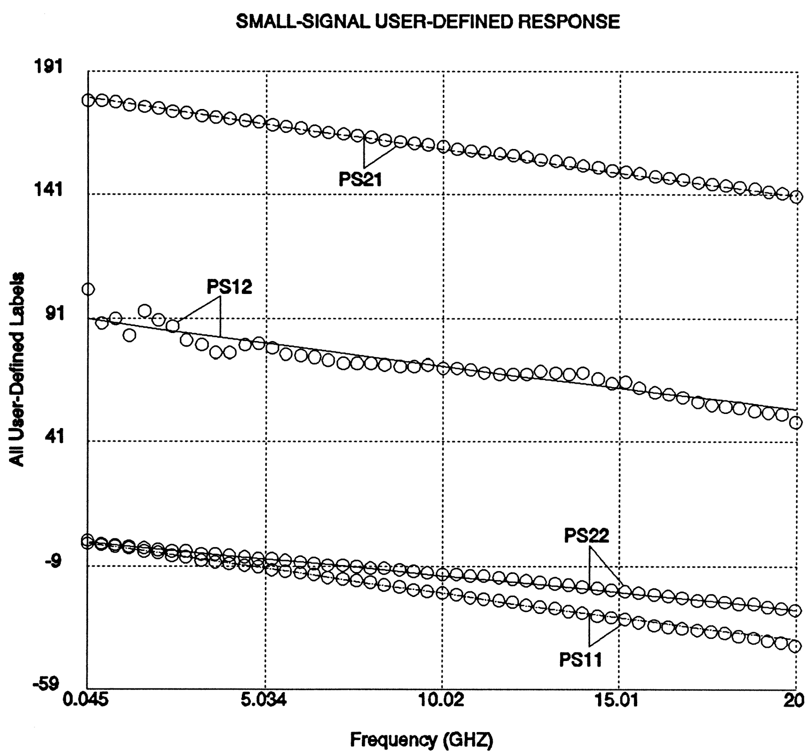


(b)

Fig. 13 S-parameter match between HEMTG2 after optimization and the measured data at gate bias: -0.5 V and drain bias: 1 V, (a) magnitudes and (b) phases.



(a)



(b)

Fig. 14 S-parameter match between HEMTG2 after optimization and the measured data at gate bias: -0.75 V and drain bias: 1 V, (a) magnitudes and (b) phases.

V. PARAMETER EXTRACTION FOR HEMTAC AND HEMTC

There are no comparisons between HEMTAC, HEMTC and the measurements given in [4] or [5]. In order to test these two models we perform parameter extraction by fitting the DC and *S* parameters from models to the corresponding measurements. The same measurement data used in Section III and IV are applied here. A good match between the model responses and the measurements is observed.

A. Parameter Extraction for HEMTAC

The model parameter values extracted are listed in Table V.

TABLE V
THE EXTRACTED PARAMETER VALUES FOR HEMTAC

Intrinsic		Extrinsic	
α	11.26	LG(nH)	0.005
β	0.032	LD(nH)	0.003
γ	-0.050	LS(nH)	8.18E-4
λ	0.205	RG(Ω)	32.73
μ_{CRIT}	0.827	RD(Ω)	24.23
ξ	-0.397	RS(Ω)	10.05
ψ	0.918	CDS(pF)	0.0012
V_{GEXP}	2.169	CGE(pF)	7.17E-4
V_{PF}(V)	-0.878	CDE(pF)	0.032
V_{T0}(V)	-1.263	GDS(1/Ω)	7.60E-4
C_{GD0}(pF)	0.016		
C_{GS0}(pF)	0.054		
C_{M0}(pF)	5.7E-4		
χ	0.016		
V_{DS0}(V)	0.188		
G_{MIN}(1/Ω)	0.823E-12		
I_S(A)	0.995E-14		
N	1.067		
V_{BR}(V)	27.42		

Temperature *T* is set to room temperature: 298°K

The DC match between the extracted HEMTAC and the measured data is shown in Fig. 15. The S-parameter match between the extracted HEMTAC and measurements at two bias points are plotted in Figs. 16 and 17.

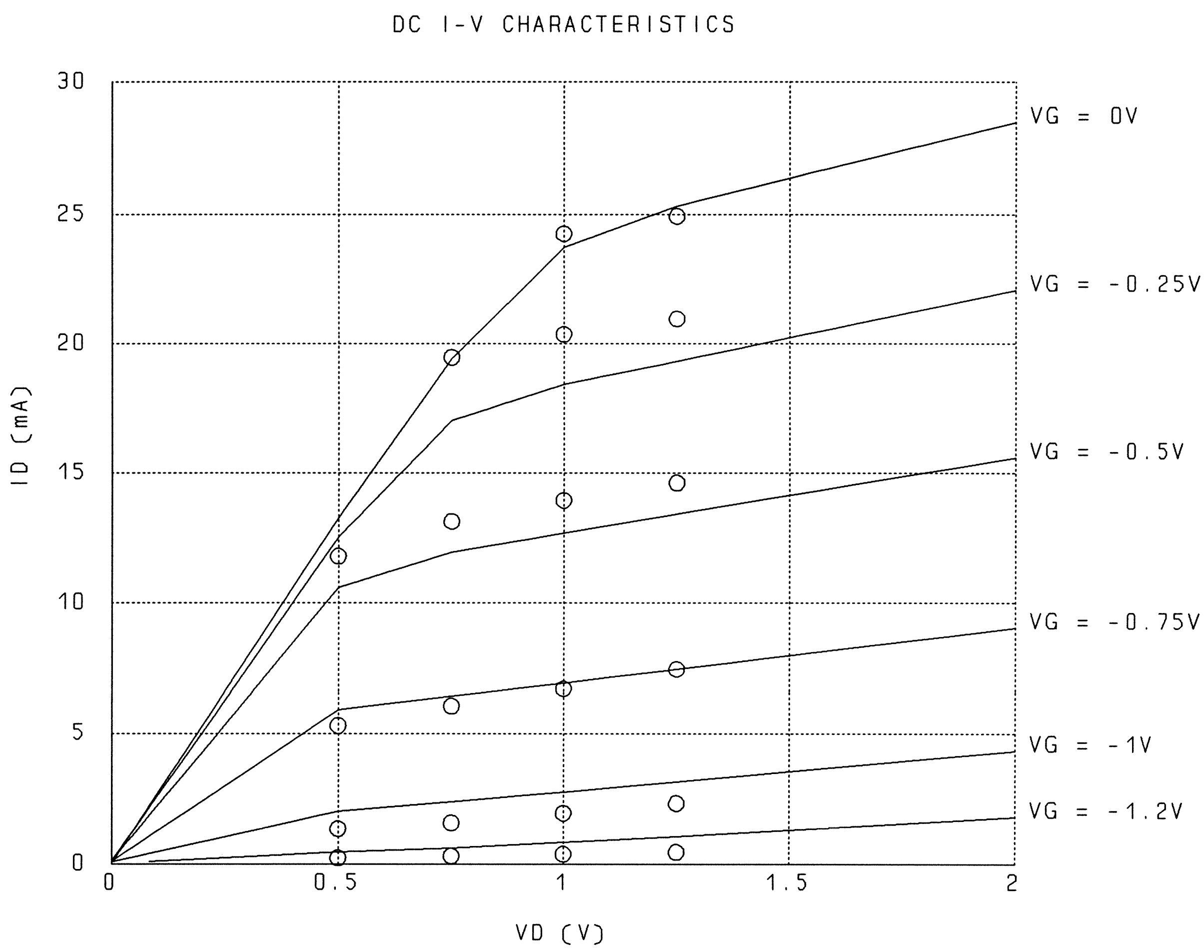
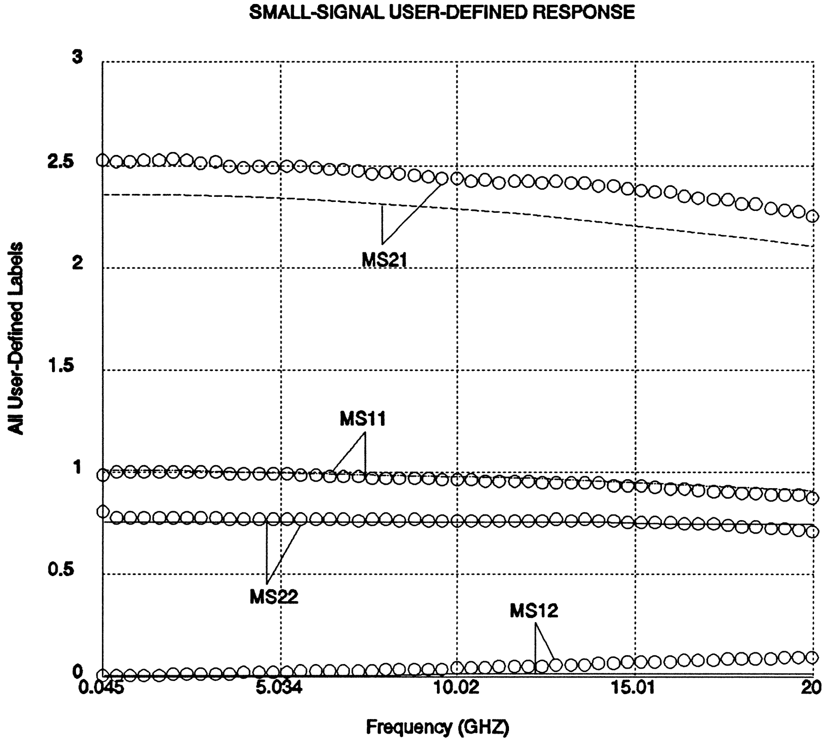
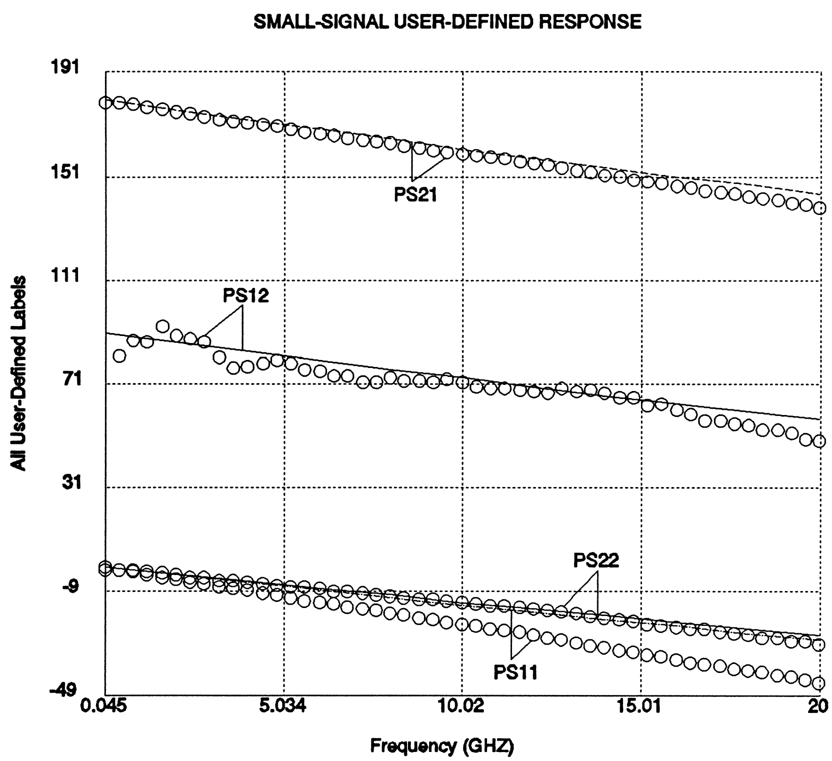


Fig. 15 DC I-V characteristics from the extracted HEMTAC (solid line) and measurements (circles).

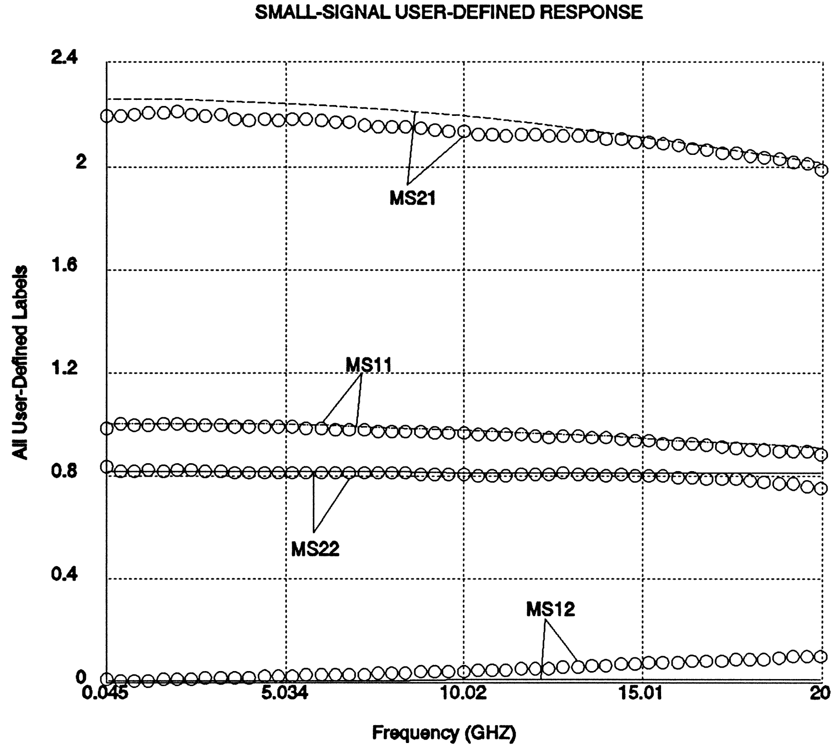


(a)

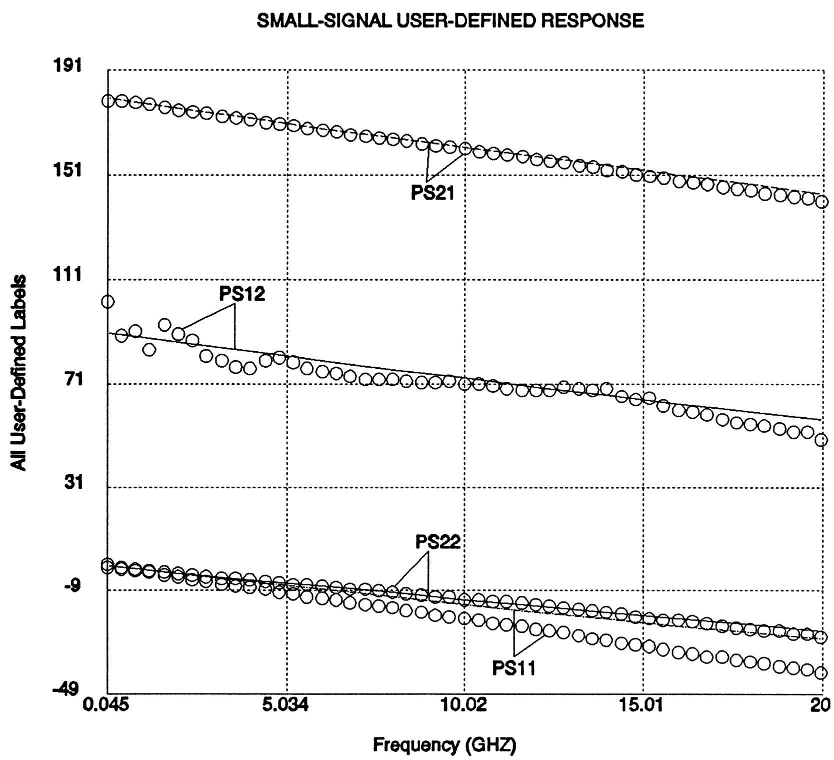


(b)

Fig. 16 S-parameter match between the extracted HEMTAC and the measured data at gate bias: -0.5 V and drain bias: 1 V, (a) magnitudes and (b) phases.



(a)



(b)

Fig. 17 S-parameter match between the extracted HEMTAC and the measured data at gate bias: -0.75 V and drain bias: 1 V, (a) magnitudes and (b) phases.

B. Parameter Extraction for HEMTC

The model parameter values extracted are listed in Table VI.

TABLE VI
EXTRACTED PARAMETER VALUES FOR HEMTC

Intrinsic		Extrinsic	
α	8.054	LG(nH)	0.0044
β	0.037	LD(nH)	0.114
λ	0.653	LS(nH)	1.54E-4
ξ	-0.396	RG(Ω)	2.523
ψ	4.172	RD(Ω)	3.827
V_{PF}(V)	-0.145	RS(Ω)	22.826
V_{T0}(V)	-1.281	CDS(pF)	1.8E-4
C_{GD0}(pF)	0.074	CGE(pF)	5.2E-4
C_{GS0}(pF)	0.101	CDE(pF)	0.0282
C_{M0}(pF)	3.6E-4	GDS(1/Ω)	3.4E-4
χ	0.0834		
V_{DS0}(V)	2.646		
G_{MIN}(1/Ω)	0.812E-12		
I_S(A)	0.987E-14		
N	1.054		
V_{BR}(V)	27.74		

Temperature T is set to room temperature: 298°K

The DC match between the extracted HEMTC and the measured data is shown in Fig. 18. The *S*-parameter match between the extracted HEMTC and measurements at two bias points are plotted in Figs. 19 and 20.

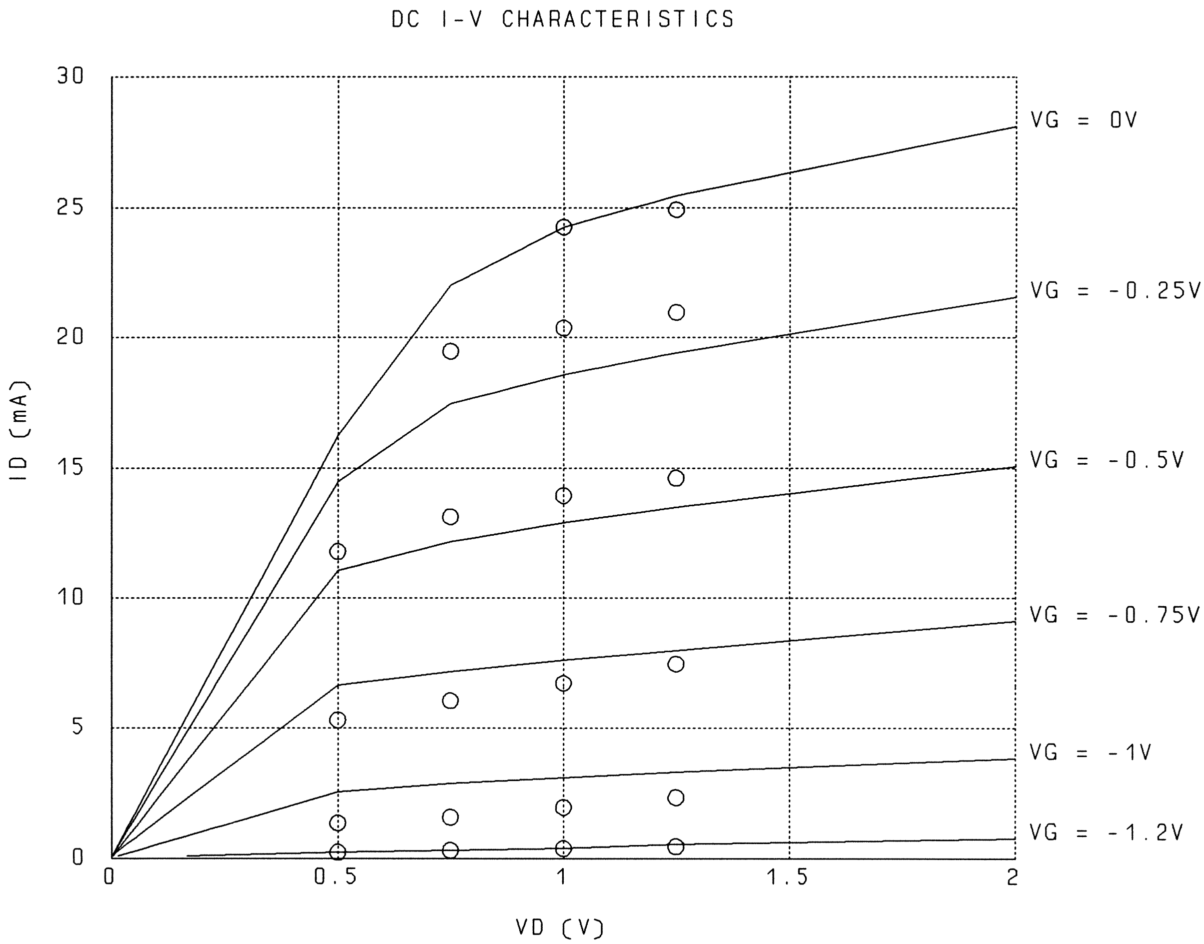
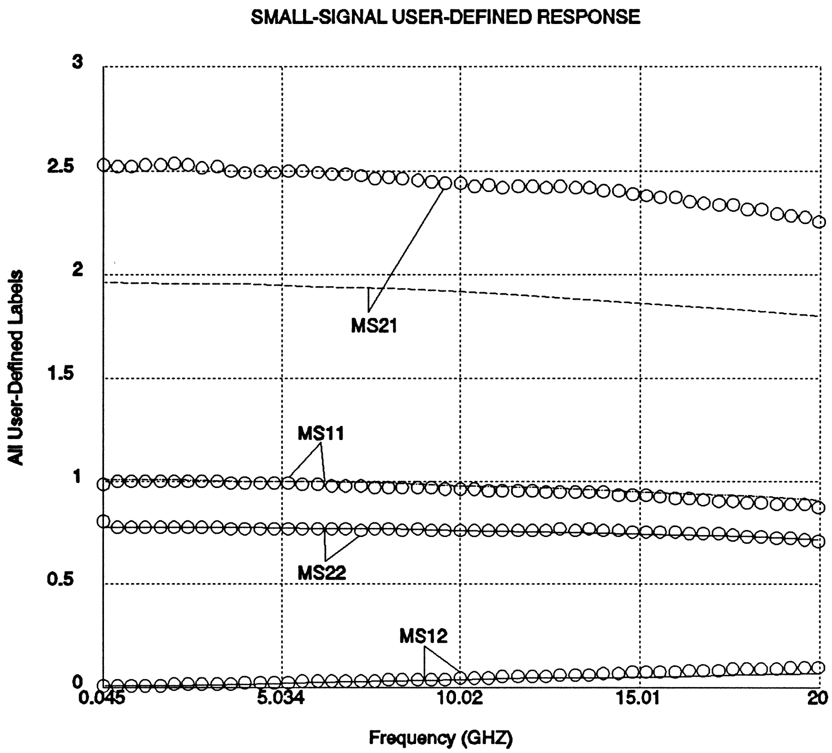
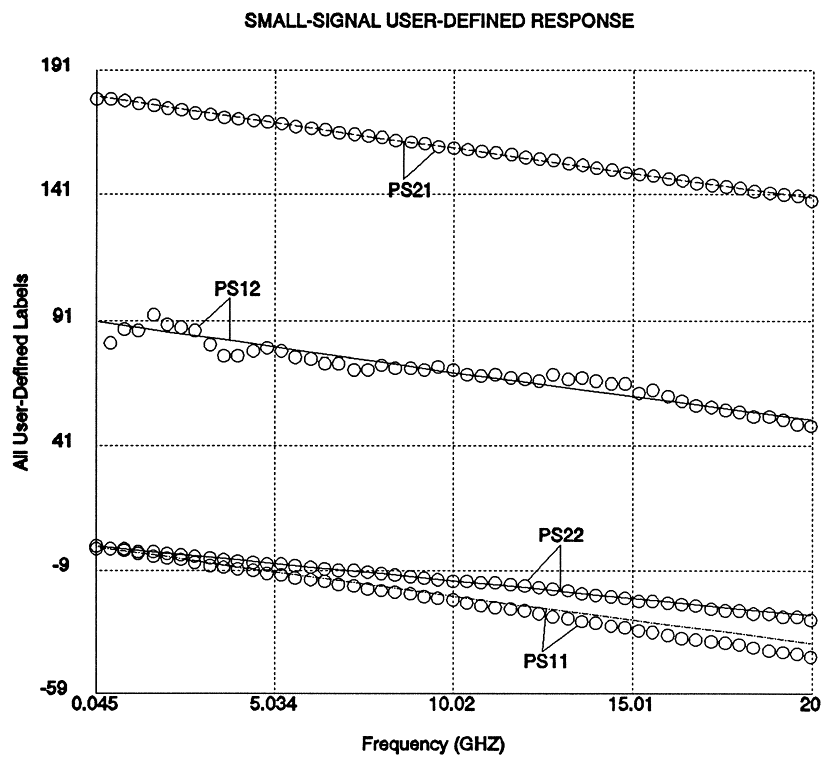


Fig. 18 DC I-V characteristics from the extracted HEMTC (solid line) and measurements (circles).

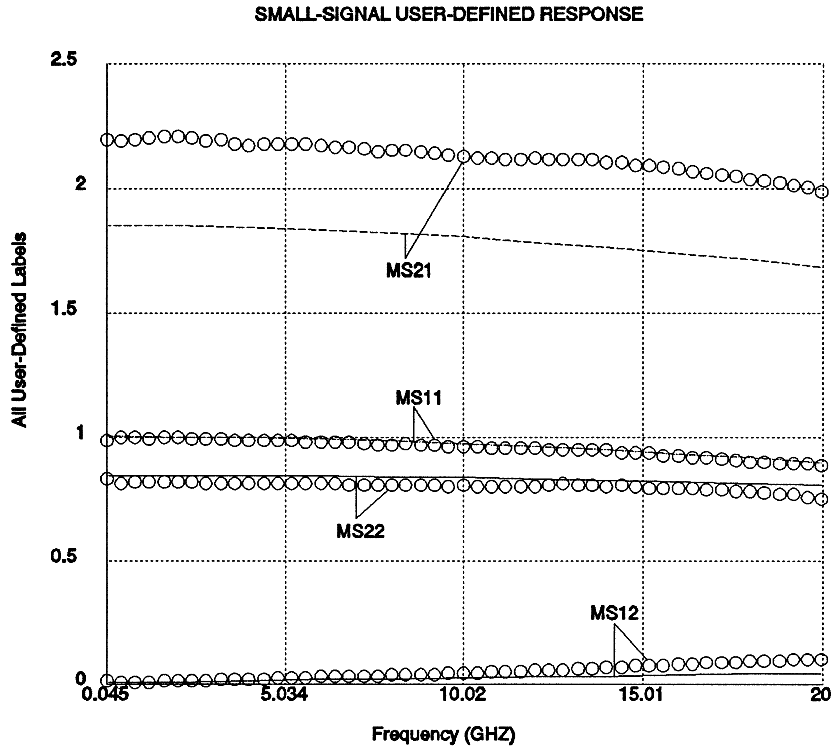


(a)

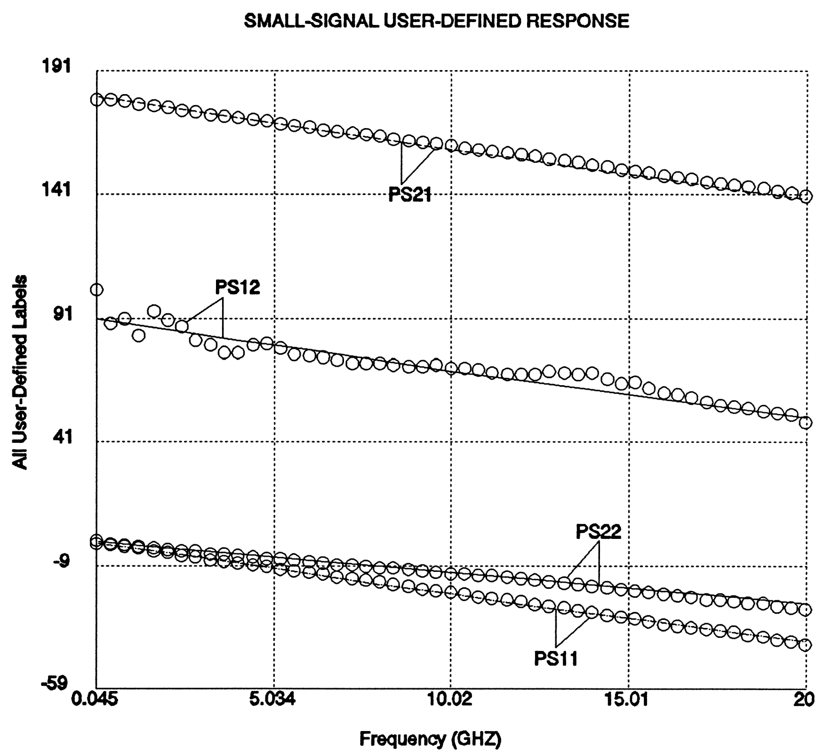


(b)

Fig. 19 *S*-parameter match between the extracted HEMTC and the measured data at gate bias: -0.5 V and drain bias: 1 V, (a) magnitudes and (b) phases.



(a)



(b)

Fig. 20 S-parameter match between the extracted HEMTC and the measured data at gate bias: -0.75 V and drain bias: 1 V, (a) magnitudes and (b) phases.

VI. CONCLUSIONS

We have described the details of implementation of HEMT models in HarPE and OSA90/hope. The models, including HEMTG1 and HEMTG2, have been verified by comparing the model responses with the measured data containing DC I-V characteristics and *S* parameters taken at several bias points.

There are some discrepancies between the model responses and the measured data with the parameter values provided in [4] and [5]. These discrepancies may due to the following two reasons. First, the models for the intrinsic nonlinear capacitors used by Motorola may be different from those used in our models since there is no description given in [4]. Secondly, the extrinsic circuit for the model may also be different.

We have performed optimizations starting from the parameter values given in [4] and [5]. The match between the model responses and the measured data is significantly improved after optimization.

We have also carried out parameter extraction for HEMTAC and HEMTC. The extracted models give good DC and *S*-parameter match to the measurements.

From our experiments we noticed that, for this particular case, HEMTG1 and HEMTG2 can provide better fit to the measurements than HEMTAC and HEMTC.

VII. REFERENCES

[1] *HarPE*™, Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1994.

[2] *OSA90/hope*™, Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1994.

[3] J.M. Golio, *Microwave MESFETs and HEMTs*, Norwood, MA: Artech House, 1991.

[4] D. Halchin, M. Miller, M. Golio and S. Tehrani, "HEMT models for large signal circuit simulation," *IEEE MTT-S Int. Microwave Symp. Digest* (San Diego, CA), 1994, pp. 985-988.

[5] Measurement data provided by Dave Halchin, Motorola, 2100 E. Elliot Road, Tempe, AZ 85284, 1994.