A New Analytical Small-Signal Model of Dual-Gate GaAs MESFET

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Abstract **— The development of an analytical small-signal model for the intrinsic elements of a dual gate GaAs MESFET (DGMESFET) is described. The model is based on splitting the Z-parameters of each FET part analytically without any simplifications or assumptions. The model is extracted directly from the measured three-port S-parameters. No extra measurements are required, thus reducing the lengthy procedures needed to characterize the DGMESFET. Experimental verification of the new model is presented.**

I. INTRODUCTION

THE dual-gate GaAs MESFET is involved in a wide range of applications. Several small-signal models of a DGMESFET have been reported [1]-[5]. The basic model of a DGMESFET is a cascode connection of two single-gate MESFET's, FET_1 and FET_2 [2]. To extract the intrinsic elements of DGMESFET, very lengthy procedures are required. Tsironis and Meierer [3] needed a dc bi-directional transfer characteristics [6], two-sets of two-port S-parameters measured at two different bias conditions, three-port S-parameters, and four levels of optimization, to extract the equivalent circuit elements of DGMESFET. The same procedures were carried out by Deng and Chu [7] but with only one level of optimization.

Scott and Minasian [4] derived relationships between the three-port Z-parameters of the DGMESFET (Z) and the individual two-port Z-parameters of the two single-gate FET's (Z^{I} and Z^{II}). Except for Z^{I}_{22}, the two-port Z-parameters of FET_1 were given explicitly from the three-port Z-parameters of the DGMESFET. To separate Z^{I}_{22}, Scott and Minasian [4] assumed that up to moderate frequencies, $Z^{I}_{22} \approx Z_{23}$. Extracting the elements of FET_1 from its two-port Z-matrix, Scott and Minasian [4] found that the elements of FET_2 can be evaluated analytically from the three-port Y-parameters of DGMESFET provided that the transconductance of FET_2 (g_{m2}) is available. Measuring g_{m2} by using the model presented by Minasian [8], Scott and Minasian [4] derived expressions for extracting the elements of FET_2 under the assumptions that:

$1 + j\omega C_{gs_1} R_{i_1} \approx 1$; and $1 + j\omega C_{gs_2} R_{i_2} \approx 1$.

In this paper we derive an analytical expression of Z^{I}_{22} that can be evaluated from the measured three-port Z-parameters of the DGMESFET. Once Z^{I}_{22} is evaluated, the Z-matrix of each individual FET part is separated and the intrinsic elements of each FET can be evaluated analytically.

In the following, Section II describes the derivation of the Z^{I}_{22} analytical expression. In Section III, the experimental results using the analytical model are presented. Finally, the conclusion is presented in Section IV.

II. DERIVATION OF Z^{I}_{22} EXPRESSION

The typical intrinsic small-signal model of DGMESFET is shown in Fig. 1. For simplicity, Fig. 2. will be used, where the current sources and the admittances of each branch of the small-signal model are shown, and given by the following equations:

$$Y_1 = \frac{\omega^2 R_{i_1} C^2_{gs_1}}{E_1} + j\frac{\omega C_{gs_1}}{E_1} \quad (1)$$

$$Y_2 = j\omega C_{gd_1} \quad (2)$$

$$Y_3 = g_{d_1} + j\omega C_{ds_1} \quad (3)$$

$$Y_4 = \frac{1}{R_{12}} \tag{4}$$

$$Y_5 = g_{d_2} + j\omega C_{ds2} \tag{5}$$

$$Y_6 = j\omega C_{gd_2} \tag{6}$$

$$Y_7 = \frac{\omega^2 R_{i_2} C^2{}_{gs_2}}{E_2} + j\frac{\omega C_{gs2}}{E_2} \tag{7}$$

$$G_1 = G_{1r} + jG_{1i} \tag{8}$$

$$G_2 = G_{2r} + jG_{2i} \tag{9}$$

where

$$E_1 = 1 + \omega^2 R_{i_1}^2 C_{gs_1}^2$$

$$E_2 = 1 + \omega^2 R_{i_2}^2 C_{gs_2}^2$$

$$G_{1r} = \frac{g_{m_1}}{E_1}\left(\cos(\omega\tau_1) - \omega R_{i_1} C_{gs_1} \sin(\omega\tau_1)\right)$$

$$G_{1i} = \frac{-g_{m_1}}{E_1}\left(\omega R_{i_1} C_{gs_1} \cos(\omega\tau_1) + \sin(\omega\tau_1)\right)$$

$$G_{2r} = \frac{g_{m_2}}{E_2}\left(\cos(\omega\tau_2) - \omega R_{i_2} C_{gs_2} \sin(\omega\tau_2)\right)$$

$$G_{2i} = \frac{-g_{m_2}}{E_2}\left(\omega R_{i_2} C_{gs_2} \cos(\omega\tau_2) + \sin(\omega\tau_2)\right)$$

When the inter-gate resistance R_{12} is taken into consideration, the three-port Z-parameters derived by Scott and Minasian [4] are modified as follows:

$$Z_{11} = Z_{11}^{I}$$

$$Z_{12} = Z_{12}^{I}$$

$$Z_{21} = Z_{21}^{I}$$

$$Z_{13} = Z_{12}^{I}$$

$$Z_{22} = Z_{22}^{I} + Z_{11}^{II} + R_{12}$$

$$Z_{23} = Z_{22}^{I} + Z_{12}^{II} + R_{12}$$

$$Z_{31} = Z_{21}^{I}$$

$$Z_{32} = Z_{22}^{I} + Z_{21}^{II} + R_{12}$$

$$Z_{33} = Z_{22}^{I} + Z_{22}^{II} + R_{12} \tag{10}$$

The two-port Y and Z-matrices of FET_1 are given by:

$$Y^{I} = \begin{bmatrix} Y_1 + Y_2 & -Y_2 \\ G_1 - Y_2 & Y_2 + Y_3 \end{bmatrix} \tag{11}$$

$$Z^{I} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22}^{I} \end{bmatrix} \tag{12}$$

Since $Y = Z^{-1}$, the following relationship results:

$$Y_2 = \frac{Z_{12}}{\det(Z^{I})} \tag{13}$$

where

$$\det(Z^{I}) = Z_{11}Z_{22}^{I} - Z_{12}Z_{21}.$$

Similarly the two-port Y and Z-matrices of FET_2 are:

$$Y^{II} = \begin{bmatrix} Y_6 + Y_7 & -Y_6 \\ G_2 - Y_6 & Y_5 + Y_6 \end{bmatrix} \tag{14}$$

$$Z^{II} = \begin{bmatrix} Z_{22} - R_{12} - Z_{22}^{I} & Z_{23} - R_{12} - Z_{22}^{I} \\ Z_{32} - R_{12} - Z_{22}^{I} & Z_{33} - R_{12} - Z_{22}^{I} \end{bmatrix} \tag{15}$$

It can be shown that:

$$Y_6 = \frac{Z_{23} - R_{12} - Z_{22}^{I}}{\det(Z^{II})} \tag{16}$$

where

$$\det(Z^{II}) = \alpha_1 - \alpha_2 Z_{22}^{I}$$

$$\alpha_1 = (Z_{22} - R_{12})(Z_{33} - R_{12}) - (Z_{23} - R_{12})(Z_{32} - R_{12})$$

$$\alpha_2 = Z_{22} + Z_{33} - Z_{23} - Z_{32}$$

It is clear from (2) and (6) that the real parts of both Y_2 and Y_6 are zeros. Solving $\mathrm{Re}(Y_2) = 0$ gives:

$$k_1 \mathrm{Re}(Z_{22}^{I}) - k_2 \mathrm{Im}(Z_{22}^{I}) = k_3 \tag{17}$$

where

$$k_1 = \mathrm{Re}(Z_{11})\,\mathrm{Re}(Z_{12}) + \mathrm{Im}(Z_{11})\,\mathrm{Im}(Z_{12})$$

$$k_2 = \mathrm{Im}(Z_{11})\,\mathrm{Re}(Z_{12}) - \mathrm{Re}(Z_{11})\,\mathrm{Im}(Z_{12})$$

$$k_3 = \mathrm{Re}(Z_{12})\,\mathrm{Re}(Z_{12}Z_{21}) + \mathrm{Im}(Z_{12})\,\mathrm{Im}(Z_{12}Z_{21})$$

Solving $\mathrm{Re}(Y_6) = 0$ gives:

$$\beta_1\left(\mathrm{Re}^2(Z^I_{22}) + \mathrm{Im}^2(Z^I_{22})\right) - \beta_2\mathrm{Re}(Z^I_{22}) + \beta_3\mathrm{Im}(Z^I_{22}) + \beta_4 = 0 \quad (18)$$

where

$$\beta_1 = \mathrm{Re}(\alpha_2)$$

$$\beta_2 = \mathrm{Re}(\alpha_2)\,\mathrm{Re}(Z_{23} - R_{12}) + \mathrm{Re}(\alpha_1) + \mathrm{Im}(\alpha_2)\,\mathrm{Im}(Z_{23})$$

$$\beta_3 = \mathrm{Im}(\alpha_2)\,\mathrm{Re}(Z_{23} - R_{12}) - \mathrm{Re}(\alpha_2)\,\mathrm{Im}(Z_{23}) - \mathrm{Im}(\alpha_1)$$

$$\beta_4 = \mathrm{Re}(\alpha_1)\,\mathrm{Re}(Z_{23} - R_{12}) + \mathrm{Im}(\alpha_1)\,\mathrm{Im}(Z_{23})$$

Solving (17) and (18) results in:

$$\mathrm{Re}(Z^I_{22}) = \frac{-B - \sqrt{B^2 - 4AC}}{2A} \quad (19)$$

$$\mathrm{Im}(Z^I_{22}) = \frac{k_1\mathrm{Re}(Z^I_{22}) - k_3}{k_2} \quad (20)$$

where

$$A = \beta_1\left(1 + (\frac{k_1}{k_2})^2\right)$$

$$B = \beta_3(\frac{k_1}{k_2}) - \beta_2 - 2\beta_1\frac{k_1k_3}{k_2^2}$$

$$C = \beta_1(\frac{k_3}{k_2})^2 - \beta_3(\frac{k_3}{k_2}) + \beta_4$$

Once Z^I_{22} is evaluated from (19) and (20), the two-port Z-matrix of each individual single-gate FET is separated using (10). Converting the Z-matrix into a Y-matrix, the intrinsic elements of each FET part are evaluated using the well-established analytical model of single-gate FET [9].

III. EXPERIMENTAL RESULTS

The model described in section II has been coded into a MATLAB program and is used to determine the intrinsic elements of the DGMESFET using the measurements published in [7]. Table I summarizes the extracted element values, with our model and compares these results with those obtained in [7]. It is clear that the extracted values are very close to those extracted by Deng and Chu [7], which verifies the validity of the new model.

TABLE I

AVERAGE VALUES OF THE EXTRACTED INTRINSIC ELEMENTS OF DGMESFET

Elements	Average values using the new model		Average values using the model described in [7]	
	FET_1	FET_2	FET_1	FET_2
C_{gs}(pF)	0.2194	0.2414	0.22	0.24
R_i(Ω)	6.431	8.96	6.44	9
C_{gd}(fF)	64.583	59.78	64.3	60
g_m(A/V)	0.0614	0.0251	0.0618	0.025
τ(ps)	7.21	7.71	7.2	7.7
g_d(mS)	9.5	6.7	9.6	6.67
C_{ds}(fF)	50.2	29.94	51	30

IV. CONCLUSION

An analytical small-signal model of a dual-gate MESFET has been described. The two-port Z-matrix of each individual single-gate MESFET is separated analytically without any simplifications. The model is extracted entirely from the measured three-port S-parameters, with no need for extra measurements. The model gives unique solution to the intrinsic elements of the DGMESFET without lengthy procedures to extract those elements.

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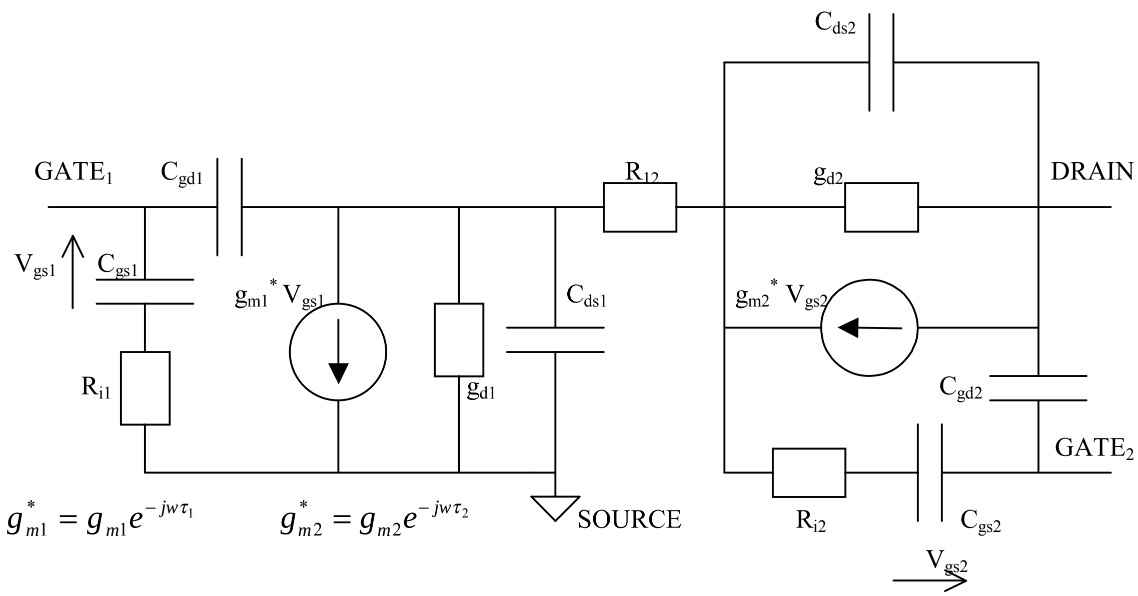

Fig. 1. The small-signal equivalent circuit of intrinsic DGMESFET.

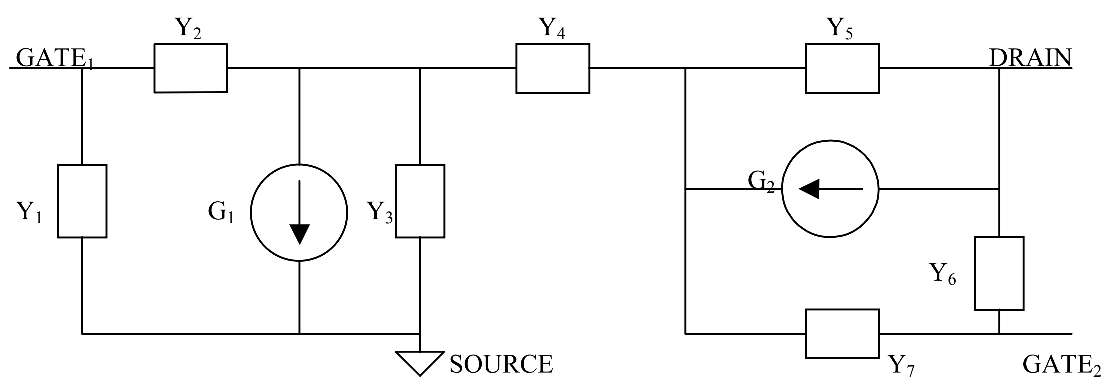

Fig. 2. The simplified equivalent circuit used for analysis.