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DISTRIBUTED GaAs FET CIRCUIT MODEL FOR BROADBAND AND MILLIMETER WAVE APPLICATIONS

R. LaRue, C. Yuen, G. Zdasiuk

Varian Associates, Inc., Solid State Laboratory
Palo Alto, California 94303

ABSTRACT

In this paper, the Z-parameters of a fully distributed, equivalent circuit MESFET model are presented as simple, closed-form expressions. The benefit of this new model is to extend the frequency range of accurate, predicted device performance beyond that of a simple lumped element model. Comparison with the simpler circuit model shows differences at frequencies beyond 18 GHz for a 285-micron x 0.5-micron GaAs MESFET.

INTRODUCTION

Circuit models of GaAs MESFET devices are extensively used for computer-aided design (CAD) of hybrid and monolithic microwave integrated circuits. Accurate device models are needed, especially above 18 GHz, where accurate measurement of chip device S-parameters is difficult. An attractive alternative approach to S-parameter measurements is to predict S-parameters based on lower frequency measurements using a circuit model.

While previous work has considered transmission-like aspects of MESFET electrodes (1-3), we believe that this work is the first explicit, exact description of the two-port parameters of a fully distributed MESFET circuit model. For wide devices or high frequencies, voltage variations along the gate stripe exist which affect performance. To analyze this effect, the MESFET is represented as a two-port, composed of two coupled transmission lines -- a gate and drain line, terminated at the end with an open. This new model has been incorporated into an optimization program which adjusts equivalent circuit elements to fit measured S-parameter data. The results of this optimization will be shown for a wide, 285-micron x 0.5-micron, MESFET.

The distributed MESFET model extends the ability to predict modeled device parameters to high frequencies for any gate width. Normally gate widths are kept to a minimum to avoid loss and standing waves on the gate line. This new model allows prediction of this maximum gate width.

THEORY

To study the effect of a MESFET's width on its performance, the distributed nature of the device must be taken into account. A typical MESFET may be viewed as two coupled transmission lines, as shown in the upper portion of Fig. 1. The distributed gate and drain electrodes are coupled by incremental sections of the active device, designated by the two-port Y shown in the lower half of the figure. All element values are distributed values. Simple transmission line theory (4) yields two coupled second-order differential equations for the gate and drain voltages, V_g and V_d,

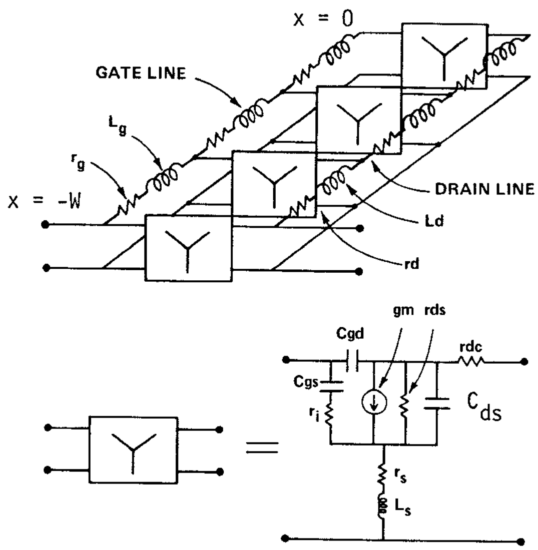

Fig. 1 Distributed model of a MESFET.

$$d^2V_g/dx^2 = \alpha^2 V_g + \beta^2 V_d$$

$$d^2V_d/dx^2 = \gamma^2 V_d + \delta^2 V_g ,$$

where α, β, γ and δ are the propagation constants,

$$\alpha^2 = (r_g+j\omega L_g)\, Y_{11} , \quad \beta^2 = (r_g+j\omega L_g)\, Y_{12}$$

$$\gamma^2 = (r_d+j\omega L_d)\, Y_{22} , \quad \delta^2 = (r_d+j\omega L_d)\, Y_{21} .$$

β and δ determine the amount of coupling between gate and drain lines. Y_{11}, Y_{12}, Y_{22}, and Y_{21} are the Y-parameters of the two-port Y and are easily computed in terms of element value. The general solutions, V_g and V_d, are exponential with distance and by applying the appropriate boundary conditions, each Z-parameter may be computed in a convenient, closed analytic form. The results are presented below.

$$Z_{11} = \frac{(r_g+j\omega L_g)}{(\varepsilon^4+\delta^2\beta^2)} \left[\frac{\varepsilon^4}{\rho_-} + \frac{\delta^2\beta^2}{\rho_-} \right]$$

$$Z_{22} = \frac{(r_d+j\omega L_d)}{(\varepsilon^4+\delta^2\beta^2)} \left[\frac{\varepsilon^4}{\rho_-} + \frac{\delta^2\beta^2}{\rho_+} \right]$$

$$Z_{12} = \frac{(r_d+j\omega L_d)\ \beta^2\varepsilon^2}{(\varepsilon^4 + \delta^2\beta^2)} \left[\frac{1}{\rho_+} - \frac{1}{\rho_-} \right]$$

$$Z_{21} = \frac{(r_g+j\omega L_g)\ \delta^2\varepsilon^2}{(\varepsilon^4 + \delta^2\beta^2)} \left[\frac{1}{\rho_+} \quad \frac{1}{\rho_-} \right]$$

where

$$\rho_\pm = r_\pm \tanh(r_\pm W)$$

$$\varepsilon^4 = (r_+^2 - \gamma^2)^2$$

$$r_\pm^2 = (\alpha^2+\gamma^2)/2 \pm \left((\alpha^2-\gamma^2)^2 + 4\delta^2\beta^2\right)^{1/2}/2$$

When parasitic lumped bondwire inductances and pad capacitances are accounted for, the result is a high-frequency model useful for calculating scattering parameters, maximum available gain, and other useful performance parameters.

An optimization program, run on a desktop computer, was written to fit the calculated S-parameters of the distributed model to experimental S-parameters of a wide, 285-micron x 0.5-micron, device. Optimization is complete when the equivalent circuit elements are adjusted, using a direct-search method, so that the least-squares error between experimental and calculated results is a minimum. As can be seen in Fig. 2, the fit up to 18 GHz is quite good. Once the optimized model is obtained, extrapolation of device parameters to higher frequencies for any width is readily computed.

Figures 3 and 4 show the predicted voltage magnitude and phase along the gate stripe at 18 GHz and above. As can be seen in Fig. 2, a large standing wave exists along the gate stripe above 18 GHz and attenuation starts reducing the voltage magnitude. At 60 GHz, the standing wave is severely damped. As seen in Fig. 4, phase variations along the gate stripe increase with frequency. These variations along the gate mean that different portions of the gate produce varying out-of-phase voltage contributions at the drain and yield a lower overall gain.

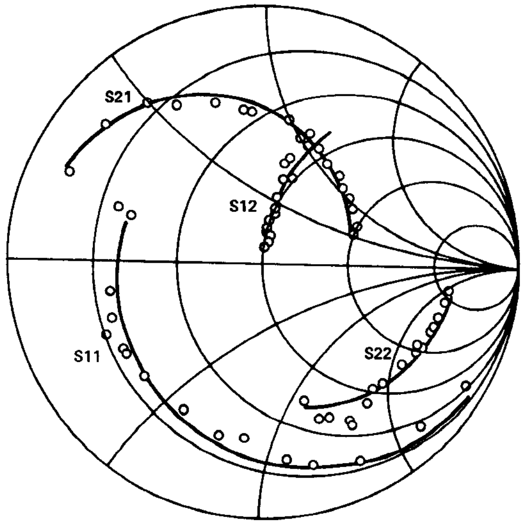

Fig. 2 Optimized theoretical and experimental S-parameters from 2 GHz to 18 GHz for a 285-micron x 0.5-micron MESFET. Radius is 0.2 for S12 and 4 for S21.

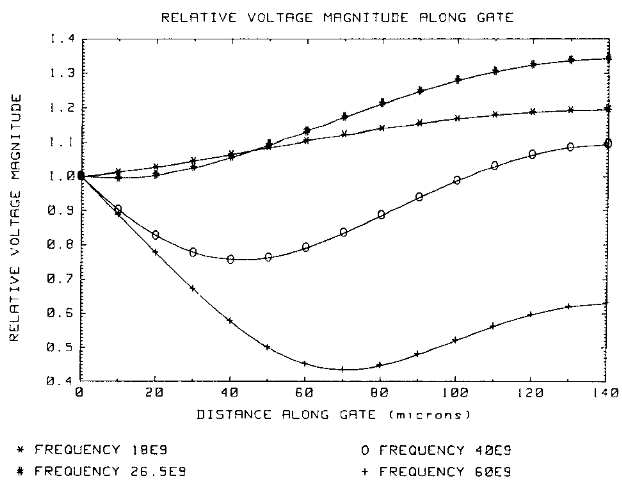

Fig. 3 Calculated voltage magnitude along gate stripe of 285-micron x 0.5-micron MESFET.

COMPARISON WITH LUMPED ELEMENT MODEL

A lumped element model, composed of a single section of the distributed model in Fig. 1, has also been incorporated into an optimization program. Optimization of the same device was carried out and Fig. 5 shows the distributed and lumped model results extrapolated up to 40 GHz. As can

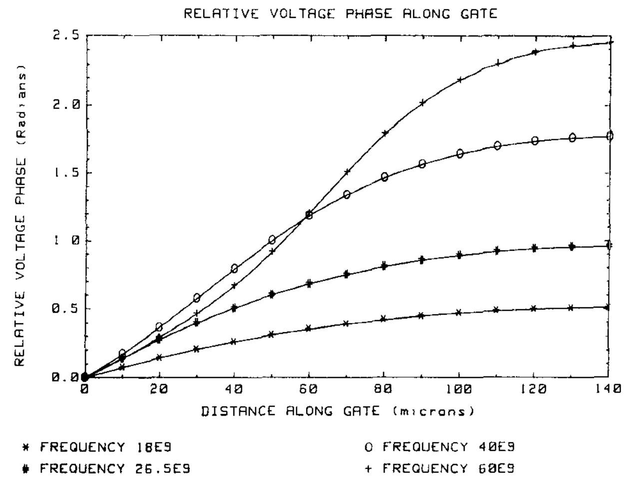

Fig. 4 Calculated voltage phase along gate stripe of 285-micron x 0.5-micron MESFET.

be seen, the results are identical well past 18 GHz. Discrepancies occur only at much higher frequencies. This is not surprising, since it was shown in Fig. 3 that the voltage along the gate is nearly constant up to 18 GHz, suggesting that distributed effects are small. In fact, using $\lambda \cong 1/f\sqrt{L_g C_{gs}}$ with L_g and C_{gs} obtained from the optimized distributed model, the gate wavelength at 18 GHz is 1.04 mm. This is seven times longer than the width of the device. For frequencies at which the gate wavelength is long compared to device width, the lumped element model is adequate.

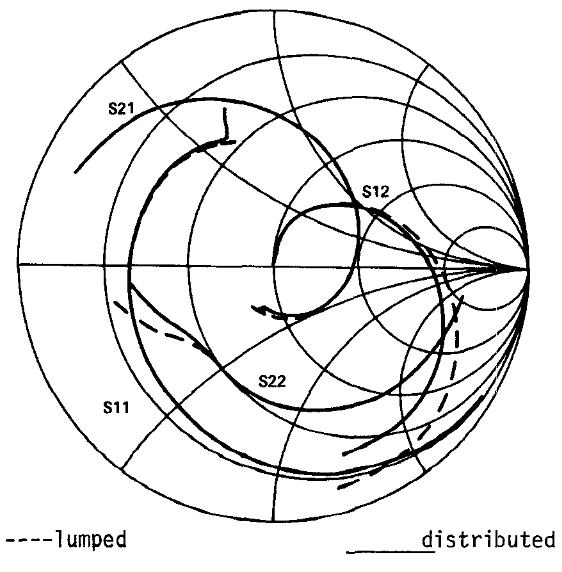

Fig. 5 Comparison of simple lumped and distributed MESFET models from 2 GHz to 40 GHz for 285-micron x 0.5-micron MESFET. Radius is 0.5 for S12 and 4 for S21.

For an accurate comparison of both models, S-parameters must be obtained above 18 GHz. However, maximum available gain measurements up to 40 GHz were carried out on a 150-micron x 0.25-micron device. The lumped model predicted gain 1-dB higher than measured at 40 GHz, whereas the distributed model predicted the gain accurately.

CONCLUSION

The Z matrix of a fully distributed MESFET equivalent circuit model has been presented which extends the ability to predict device performance up to any frequency. Comparison with experiment shows that the simple lumped model fits the data well, but that the distributed model above 18 GHz should be a more accurate representation of the device, since gain up to 40 GHz has been accurately predicted. S-parameters beyond 18 GHz must be obtained to determine this conclusively.

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