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Original Research Article

Simplified modeling of gain characteristics of optically controlled GaAs MESFETs including substrate related effects

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ABSTRACT
This research presents an analytical model for investigating the gain control of optically controlled GaAs MESFET. Since changes to S-parameters under illuminated conditions, including substrate-related effects like the presence of deep level traps and backgating, are used to model the amplifier gain, this is because the gain characteristics of the MESFET amplifier as a function of frequency are a function of device S-parameters. Finally, we have investigated the impact of light on the maximum stable gain, the maximum available gain, and the unilateral power gain of MESFET amplifiers. The findings unequivocally demonstrate that an amplifier's gain may be adjusted by changing the incident light intensity in a manner similar to changing gate bias. When the device is used close to the pinch-off state, the tuning range of the MESFET amplifier is found to be as high as 7dB. To verify this model, the predicted outcomes are contrasted with the reported experimental findings made in dimly lit conditions. Specifically in photonic MMICs and OEICs, we think that this paradigm may be very helpful for building and optimising optically controlled GaAs MESFET amplifiers.

1. Introduction

A MESFET, also known as a metal-semiconductor field-effect transistor, is a semiconductor field-effect transistor device similar to a JFET that uses a Schottky (metal-semiconductor) junction for the gate rather than a p-n junction. MESFETs are quicker but more costly than silicon-based JFETs or MOSFETs because they are built using compound semiconductor technologies lacking good quality surface passivation, such as gallium arsenide, indium phosphide, or silicon carbide. Production MESFETs can run up to 45 GHz and are often employed in radar and microwave frequency communications. In 1967, the performance of the first MESFETs was shown in an extremely high frequency RF microwave regime.

A developing area of study is direct optical control of microwave semiconductor devices. Particularly in photonic MMICs and OEICs, optically controlled GaAs MESFETs (GaAs OPFETs) have filled significant niches. Many attractive applications, including optical control of amplifiers and oscillators, are made possible by using light to control the microwave properties of the GaAs MESFET [1–5]. The light sensitivity of the GaAs MESFET and its uses have been extensively studied over the past two decades [1-2]. Their findings demonstrated that a MESFET amplifier's gain increases monotonically as a function of light intensity when it is designed properly, and they successfully reported a tuning range of up to 10dB [2]. Unfortunately, the majority of the published papers are experimental and showed how well MESFET amplifiers' gain controls worked. The circuit designer is instantly aware of the importance of a good analytical model with all important effects evaluated for the optimization of various gains of MESFET amplifiers in order to have a better degree of confidence in constructing photonic MMICs utilising GaAs MESFETs.

In this research, we offer an analytical model for the optically controlled gain regulation of a GaAs MESFET amplifier. The model takes into account detrimental substrate effects including self-backgating and backgating, which are important in determining S-parameters. We modelled different power increases over a wide variety of bias values in the saturation area of operation to better assess the performance of optically controlled GaAs MESFET. The results of the simulation showed how well the MESFET amplifier's gain control worked.

2. Theoretical model

Figure 1 depicts a GaAs OPFET's schematic structure in the saturation zone (a). The transparent or semi-transparent gate metal is supposed to be illuminated by light with photon energy larger than the band gap of GaAs. Figure 1 also depicts the corresponding tiny signal GaAs OPFET device with parasitic components (b). Each photon absorbed produces an electron-hole pair when irradiated with light with photon energy larger than the bandgap of the GaAs material. In different areas of the device, these surplus carriers lead to photovoltaic and photoconductive effects that change all of the intrinsic device characteristics, including transconductance, output conductance, gate-source capacitance, gate-drain capacitance, gunn domain capacitance, and resistance. The gain of the amplifier may be accurately adjusted by adjusting

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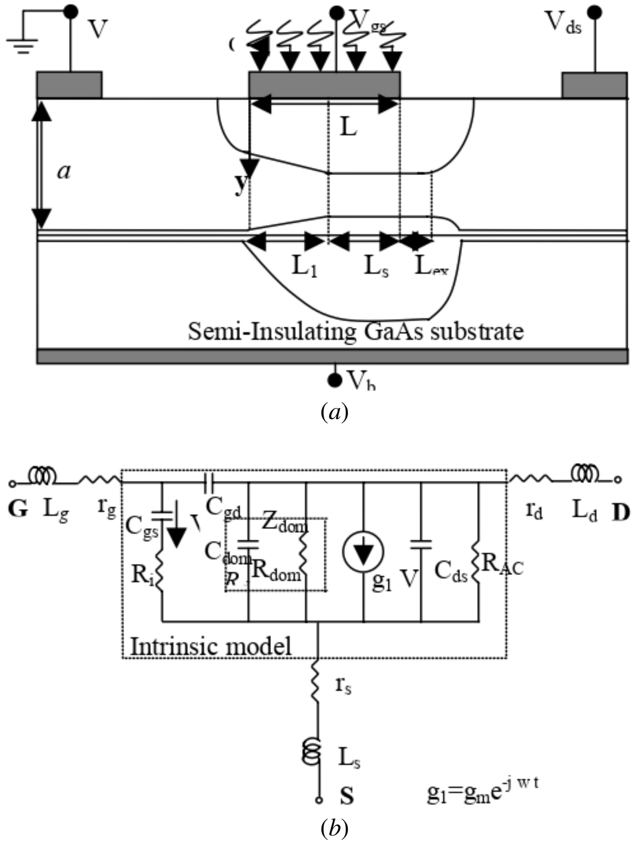
incident light level when the external circuit is created such that the GaAs MESFET is utilised as an amplifier.



(*a*)

(*b*)

Figure 1. (a) Schematic structure of GaAs MESFET in saturation region. (b) Small signal equivalent model of GaAs OPFET.

The intrinsic Y-parameters of the device shown in Figure 1(b) are [3]:

$$Y_{11} = i\omega C_{gd} + \frac{i\omega C_{gs}}{1 + i\omega C_{gs} R_i}, \tag{1a}$$

$$Y_{21} = \frac{g_m \exp(-i\omega t)}{1 + i\omega C_{gs} R_i} - i\omega C_{gd}, \tag{1b}$$

$$Y_{12} = -i\omega C_{gd}, \tag{1c}$$

$$Y_{22} = i\omega (C_{ds} + C_{gd}) + \frac{1}{R_{AC}} + \frac{1}{Z_{dom}}. \tag{1d}$$

where C_{gs}, C_{gd} are intrinsic gate-source, gate-drain capacitances of GaAs MESFET under optically controlled conditions [3]; g_m, R_{AC} are transconductance and drain-source resistance of MESFET at microwave frequencies [4, 5] and the remaining elements are parasitic resistances, inductances and capacitances in the device.

Note that the analytical models for C_{gs}, C_{gd}, g_m and R_{AC} [3 - 5] include substrate related effects like self-backgating and backgating. The microwave characteristics of the device are characterized by *S*-parameters which can be obtained as follows.

We then translate the Y-parameters of the intrinsic MESFET into ABCD form in order to derive the S-parameters of the whole small signal MESFET model. The gate and drain lead ABCD-matrix representations are multiplied by this transformed intrinsic model. The matrix equation that results is:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{MOSFET} = \begin{bmatrix} 1 & r_g + i\omega L_g \\ 0 & 1 \end{bmatrix}_{gate} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{int}\, rinsic} \begin{bmatrix} 1 & r_d + i\omega L_d \\ 0 & 1 \end{bmatrix}_{drain}. \tag{2}$$

Converting the ABCD representation of MESFET with the attached gate and drain leads into *Z*-parameter form and add the resulting matrix to the Z-matrix of source lead,

$$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}_{complete} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}_{MESFET} + \begin{bmatrix} r_s + i\omega L_s & r_s + i\omega L_s \\ r_s + i\omega L_s & r_s + i\omega L_s \end{bmatrix}_{source}. \tag{3}$$

Finally, the *S*-parameters of the complete MESFET model including all above mentioned effects can be modelled as [2]:

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}_{complete} = \begin{bmatrix} \dfrac{(Z_{11} - Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}}{(Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}} & \dfrac{2Z_{12}Z_0}{(Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}} \\ \dfrac{2Z_{21}Z_0}{(Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}} & \dfrac{(Z_{11} + Z_0)(Z_{22} - Z_0) - Z_{12}Z_{21}}{(Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{12}Z_{21}} \end{bmatrix}_{MOSFET}. \tag{4}$$

Different definitions of power gain can be applied to assess the performance of an optically controlled GaAs MESFET [6]. Here [6] is a list of well-known terms for various gains. Transducer power gain in a 50 Ω system is,

$$G_T = |S_{21}|^2. \tag{5}$$

Stability factor,

$$k = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |S_{11}S_{22} - S_{12}S_{21}|^2}{2|S_{12}||S_{21}|}. \tag{6}$$

Maximum available gain (for $k > 1$)

$$G_{ma} = \frac{|S_{21}|}{|S_{12}|}(k - (k^2 - 1)^{1/2}) . \tag{7}$$

For the amplifier to be unconditionally stable, the following conditions should be met

$$\left. \begin{array}{c} |S_{11}S_{22} - S_{12}S_{21}| < 1 \\ k > 1 \end{array} \right\} . \tag{8}$$

The incident light level causes multiple changes in all intrinsic MESFET equivalent circuit characteristics, which then modify the device's S-parameters. Equations (5)–(8) demonstrate that different MESFET amplifier power increases are, in fact, a function of incident optical power. It is therefore possible to regulate GaAs MESFET amplifiers by merely changing the input power gain.

3. Results and Discussion

In this section, we have presented some numerical results to show the effects of illumination on the various power gains of the GaAs MESFET with the following parameters:

$K_d = 0.1$, $L_g = 0.28$ nH, $L_s = 0.35$ nH, $L_d = 0.55$ nH,
$C_{ds} = 0.06$ pF, $r_g = r_s = r_d = 9\ \Omega$, $\tau_p = 5$ ps,
$C_{ds} = 0.01$ pF, $L = 1.3$ µm,
$Z = 300$ µm, $a = 0.18$ µm.

Table 1 shows the calculated transducer power gain, stability factor, and maximum achievable gain for two distinct gate bias situations near pinch-off and near zero volts in saturation zone at two distinct frequencies. As is evident, the amplifier is invariably stable for the majority of the bias settings and applied frequencies. Both power improvements decrease at higher frequencies. Both power gains are effectively increased by the incident optical power. And when the gadget is used in close proximity to pinch-off voltage, these changes are more obvious.

Table 1. Power gains of an optically controlled GaAs MESFET for different input powers, bias conditions and frequencies.

Frequency, bias condition	G_t (dB)	$\|S_{11}S_{22} - S_{12}S_{21}\|$	k	G_{mn} (dB)
$V_{gs} = -2\text{V}$, $P_{in} = 0$				
at 6 GHz	– 4.38	0.7	1.18	1.42
at 7 GHz	– 4.26	0.6	1.29	0.42
$V_{gs} = -2\text{V}$, $P_{in} = 0.3$ mV				
at 6 GHz	+0.0074	0.7	1.01	5.876
at 7 GHz	– 0.1924	0.64	1.12	3.99
$V_{gs} = -2\text{V}$, $P_{in} = 0$				
at 6 GHz	2.25	0.626	0.95	---
at 7 GHz	1.74	0.562	1.06	6.90
$V_{gs} = -2\text{V}$, $P_{in} = 0.3$ mV				
at 6 GHz	2.94	0.58	0.922	---
at 7 GHz	2.30	0.52	1.10	8.17

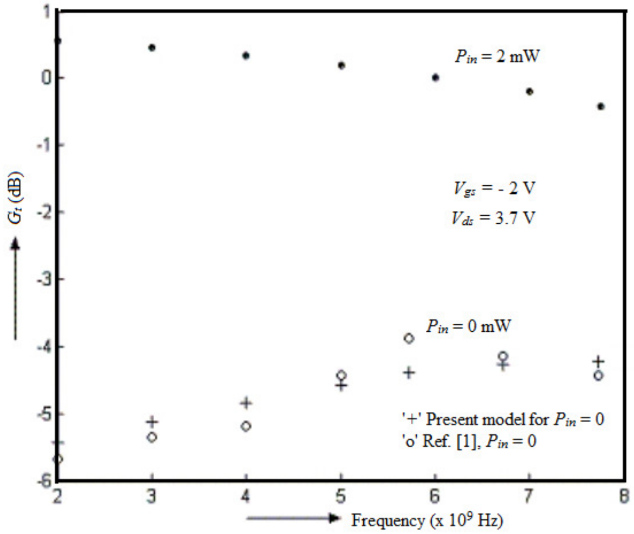


Figure 2. Variation of transducer power gain of GaAs MESFET amplifier with and with out illumination. Various parameters are taken from Gautier et al. [1].

Additionally, Figure 2 shows how the transducer power gain varies with frequency and incident optical power when the device is used close to the threshold voltage. Without any illumination, the transducer power is very low (-4.3dB), and it rises to a larger value when it is illuminated (0.007dB), with a gain control of about 4.5dB. We evaluated the estimated results for transducer power growth under the dark condition with the previously published experimental results [7-10] to validate our model. They appear to match well with one another.

4. Conclusions

For the first time in the literature, a new analytical model for different power gains of optically controlled GaAs MESFETs at microwave frequencies is described in this study. The modelled S-parameters, including substrate-related effects, are used to determine the power increases. In terms of device parameters, the numerical results unmistakably demonstrate the effectiveness of gain control of optically controlled GaAs MESFET. When the gadget is used in close proximity to the pinch-off state, these changes become more noticeable. This model, in our opinion, might be a very helpful tool for developing MESFET amplifiers in photonic MMICs.

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