High-Frequency Limits of Millimeter-Wave Transistors

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***Abstract*—Estimates of transistor performance at millimeter-wave frequencies are generally based on extrapolation of microwave gain measurements at a gain roll-off of 6 dB per frequency octave. In this paper we show that a complex-conjugate pole pair leads to a 12-dB/octave gain roll-off in the millimeter-wave region. As a result the actual f_{max} of millimeter-wave transistors can be considerably less than that determined using extrapolation of gain measurements.**

I. Introduction

OPERATION of microwave transistors as oscillators has been demonstrated at frequencies up to 110 GHz [1]. Furthermore, predictions based on extrapolation (at a gain roll-off of 6 dB/octave) of microwave-frequency gain measurements suggest that reasonable gain can be obtained at frequencies well above 100 GHz [2]–[5]. These extrapolations do not consider the limiting effects of parasitic elements upon device high-frequency performance. For example, it has been shown [6] that parasitic resistance and capacitance cause the unilateral gain G_U of JFET's and MESFET's to roll off at a 12-dB/octave rate at high frequencies.

The major purpose of this paper is to demonstrate that the charge dipole domain that is known to form in the channel of FET-type devices dominates the high-frequency performance of these devices and results in a fundamental limitation to obtaining high-frequency operation. In particular, G_U is forced to roll off at a 12-dB/octave rate above the frequency of a complex pole pair, thereby limiting f_{max}. The dipole domain is known to exist in modern microwave GaAs MESFET's [7] and has also been shown to exist in submicrometer gate-length HEMT's [8]. The detailed physics of the domain and how it is affected by device design and operating conditions are, at this time, not well understood.

The gain and frequency performances of microwave and millimeter-wave transistors are generally specified in terms of G_U and f_{max}. G_U is Mason's gain and is the highest possible gain that an amplifier using the active device and reactive tuning [9] could ever achieve. It is given by [10]

$$G_U=\frac{|y_{21}-y_{12}|^2}{4(g_{11}g_{22}-g_{12}g_{21})} \tag{1}$$

where y_{11}, y_{12}, y_{21}, and y_{22} are the y parameters of the active device and g_{ij} = Re (y_{ij}).

II. Transistor Amplifier Analysis

The circuit model of a common source MESFET is shown in Fig. 1 where the intrinsic transistor describes the active region of the device and is embedded in a parasitic network of ohmic resistances and fringing capacitors. The best possible gain and frequency performance of the transistor will be obtained when the parasitics are negligible, so we consider the performance of the intrinsic transistor alone. The y parameters of the intrinsic transistor are

$$y_{11}=\Delta\{sC_{GS}[G_I^2-sG_IC_{GS}-s^2C_{DC}(C_{DC}+C_{GS})]\}+sC_{GD}$$

$$y_{12}=\frac{-s^2C_{DC}C_{GS}}{G_I+s(C_{DC}+C_{GS})}-sC_{GD}$$

$$y_{21}=\frac{G_M(G_I+sC_{DC})-s^2C_{DC}C_{GS}}{G_I+s(C_{DC}+C_{GS})}-sC_{GD}$$

$$\begin{aligned}y_{22}=\Delta\{&G_I^2/R_{DS}+s[G_I^2C_{DC}-G_MC_{DC}G_I]\\&+s^2[G_MC_{DC}(C_{DC}+C_{GS})-(C_{GS}^2+C_{DC}^2)/R_{DS}\\&-2C_{DC}C_{GS}/R_{DS}-G_IC_{DC}^2]\\&-s^3[C_{GS}C_{DC}(C_{DC}+C_{GS})]\}+sC_{GD}\end{aligned}$$

where $s = j\omega$, $G_I = 1/R_I$, and $\Delta = [G_I^2 + |s|^2(C_{GS} + C_{DC})^2]^{-1}$. Making the approximation $G_M = g_{m0}e^{-s\tau} \approx g_{m0}(1 - s\tau + (s\tau)^2/2)$ and for frequencies much less than $[2\pi R_I(C_{GS} + C_{DC})]^{-1}$, $\tau \gg R_IC_{DC}$ and $\tau \gg R_IC_{GS}$, we have $\Delta \approx R_I^2$

$$|y_{21}-y_{12}|\approx g_{m0}\left|\frac{G_I+sC_{DC}}{G_I+s(C_{DC}+C_{GS})}\right| \tag{2}$$

and

$$\begin{aligned}g_{11}g_{22}-g_{12}g_{21}\approx\frac{s^2C_{GS}R_I^3}{R_{DS}}&\{G_I^2(C_{DC}g_{m0}R_{DS}-C_{GS})\\&+s^2[C_{GS}(C_{DC}+C_{GS})^2+C_{DC}g_{m0}R_{DS}G_I^2\tau^2/2]\}.\end{aligned} \tag{3}$$

Substituting (2) and (3) in (1) and replacing s by $j\omega$ we have

$$G_U=\left[\frac{g_{m0}^2R_{DS}}{4C_{GS}R_I(C_{GS}-C_{DC}g_{m0}R_{DS})}\right]\left[\frac{1}{\omega^2(1-p^2\omega^2)}\right] \tag{4}$$

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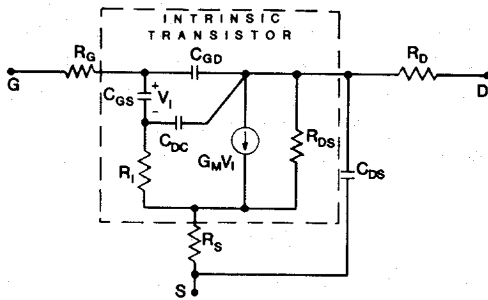

Fig. 1. Circuit model of a MESFET. R_G, R_D, and R_S are parasitic resistances resulting largely from bulk semiconductor resistance and metallization resistance. R_I is the resistance of the semiconductor channel; C_{GD} and C_{DS} are essentially parasitic fringing capacitors; C_{DC} is the domain capacitance; C_{GS} is the gate-to-source capacitance; R_{DS} is the inverse of the output conductance; $G_M = g_{m0}e^{-j\omega\tau}$ [7]; g_{m0} is the low-frequency transconductance; and τ is essentially the carrier transit time.

where

$$p^2 = \frac{(R_I^2 C_{GS})(C_{DC} + C_{GS})^2 + C_{DC} g_{m0} R_{DS} \tau^2/2}{(C_{DC} g_{m0} R_{DS} - C_{GS})}. \quad (5)$$

At frequencies much less than $(2\pi R_I C_{GS})^{-1}$ and ignoring C_{DC}, G_U reduces to [10], [11]

$$G_U = \frac{g_{m0}^2 R_{DS}}{4\omega^2 C_{GS}^2 R_I}. \quad (6)$$

III. Discussion

The commonly used expression for G_U, (6), rolls off at 6 dB/octave because of the $1/\omega^2$ term. However, with C_{DC} in the expression for G_U, (4), there is an additional 6-dB/octave roll-off at higher frequencies due to the complex pole pair contained in the $1/(1 - p^2\omega^2)$ term. The complex-conjugate poles are at frequency

$$f_p = \frac{1}{2\pi |p|}. \quad (7)$$

For millimeter-wave transistors this pole frequency is typically below f_{max} so that the pole has a limiting effect on frequency performance [12].

As an example we consider the MESFET of Maki *et al.* [13]. Maki's transistor was modeled by fitting dc and 2–18-GHz S-parameter measurements to the circuit of Fig. 1 yielding $R_S = 4.55\ \Omega$, $R_G = 1.46\ \Omega$, $R_D = 6.7\ \Omega$, $R_I = 2.69\ \Omega$, $R_{DS} = 556\ \Omega$, $C_{GS} = 0.071$ pF, $C_{GD} = 0.001$ pF, $C_{DS} = 0.025$ pF, $C_{DC} = 0.011$ pF, $g_{m0} = 15.2$ mS, and $\tau = 1.25$ ps. Comparison of G_U calculated using the model of the intrinsic transistor with that calculated using the multiple-pole formula for G_U, (4), is given in Fig. 2. Correlation is excellent with the pole frequency calculated using the model 89 GHz compared to 86 GHz obtained from (7). In Fig. 3 G_U of the intrinsic transistor and of the complete transistor are compared with and without C_{DC}. With C_{DC} in the model, the addition of parasitics (R_D, R_S, R_G, and C_{DS}) to the intrinsic transistor has little effect on low-frequency gain but dramatically lowers the frequency of the complex-conjugate pole pair. The net result is that f_{max} is considerably reduced by the presence of parasitics. Also at low frequencies G_U is higher with C_{DC} included in the

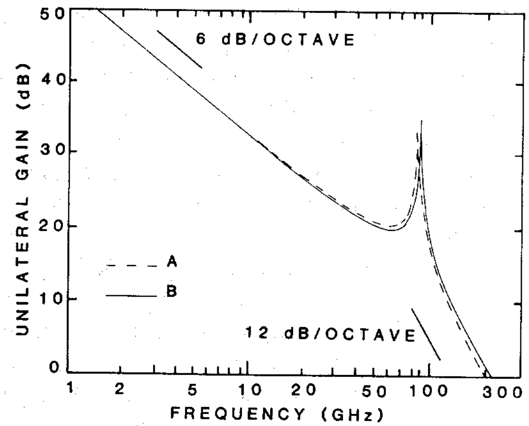

Fig. 2. Calculated G_U for the intrinsic transistor of the MESFET of Maki *et al.* [13]. (A) G_U calculated using the formula (4) developed here. (B) G_U calculated using the intrinsic transistor circuit model.

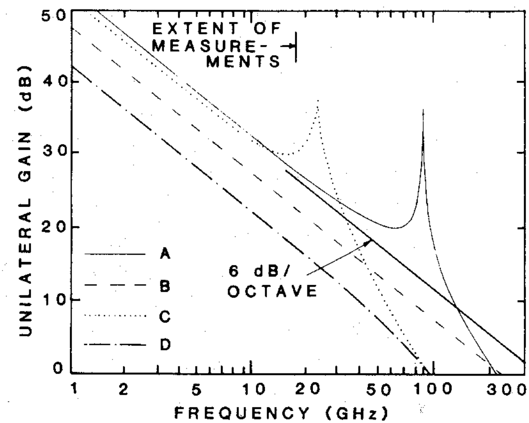

Fig. 3. Calculated G_U response of the MESFET of Maki *et al.* G_U of the intrinsic transistor model (A) with C_{DC} and (B) without C_{DC}. G_U of the full transistor model of Fig. 1 (C) with C_{DC} and (D) without C_{DC}. Also shown is the 6-dB/octave extrapolation of the low-frequency gain calculations for the full transistor model with C_{DC}.

transistor model but the effect on f_{max} is only slight. However, the calculated f_{max} of the actual transistor (with C_{DC}) is 97 GHz compared to an f_{max} of 400 GHz obtained by extrapolating low-frequency G_U calculations at 6 dB/octave.

Phenomenologically the origin of the low-frequency dependence of gain on C_{DC} and of the resonant peak at f_p and subsequent 12-dB/octave gain roll-off can be attributed to internal positive feedback by way of C_{DC}. At low frequencies the effect of this positive feedback on G_U is seen in the denominator term $C_{GS} - C_{DC} g_{m0} R_{DS}$ of (4) and, as observed in Fig. 3, C_{DC} increases low-frequency gain. Although the internal feedback is positive, the gain at frequencies below f_p is finite because the loop transmission is complex and G_U rolls off at 6 dB/octave as it is dominated by the double pole at zero.[1] At f_p the loop transmission becomes predominantly real and G_U becomes very large. Above f_p the loop transmission beomes complex and G_U again falls off but now at 12 dB/octave since G_U is dominated by four poles.

[1] At zero frequency G_U of the intrinsic transistor is infinite as the transistor is then unilateral. However, the actual transistor is never unilateral because of R_S. Consequently the dominant pole of the actual transistor is not at zero and G_U is finite at dc.

The effect of C_{DC} is magnified by the Miller effect since the internal voltage gain of a transistor, approximately $g_{m0}R_{DS}$, appears across C_{DC}. Thus when C_{DC} is referred to the gate and source terminals it appears as a much larger capacitance $C_{DC}g_{m0}R_{DS}$ as seen in (4) and (5). Therefore even very small values of C_{DC} can affect device performance at low frequencies. Unfortunately, C_{DC} can be a difficult quantity to determine from S-parameter measurements up to 18 GHz. Numerical studies [12] we have done on a variety of transistors have shown that C_{DC} has very little effect on the $f_{\max}$ of a transistor. This is not surprising as $f_{\max}$ denotes the boundary between an active device and a passive circuit. At this boundary the Miller effect and therefore the effect of C_{DC} is small. However, with all other parameters being equal, transistors with larger C_{DC} would erroneously indicate higher $f_{\max}$ if $f_{\max}$ is estimated from 6-dB/octave extrapolation of measurements, or calculations, of G_U at microwave frequencies. This can also be expected for permeable base transistors and HEMT's as they are compound semiconductor devices and will also have domain capacitance.

The millimeter-wave performance of actual transistors will be modified by the frequency dependence of the transistor model parameters. As the operating frequency increases the parasitic parts of the capacitances C_{GS}, C_{GD}, and C_{DS} will increase due to enhanced electric field fringing, and the skin effect will increase the resistances R_G, R_D, and R_S. Both effects will degrade high-frequency performance. However, the frequency behavior, and therefore the effect on performance, of R_I, g_{m0}, and R_{DS} is not clear at this time. C_{DC} is the capacitance associated with the domain that forms in the high field region under the gate of the transistor. It is well known that the negative differential mobility of a compound semiconductor such as GaAs decreases with frequency and so the dipole domain, and thus C_{DC}, become insignificant at sufficiently high frequencies. For a GaAs transistor with a peak field of 30 kV/cm the negative differential mobility will vanish in the 100–200-GHz range [14] and so C_{DC} will remain appreciable up to at least 100 GHz. However, as noted previously, $f_{\max}$ is relatively independent of C_{DC}. The major effect of C_{DC} is to increase the unilateral gain at low frequencies and this is sufficient to ensure the existence of the resonant pole pair.

While our results are an extrapolation of low microwave frequency S-parameter measurements, the extrapolation is based on a circuit model developed from physical insight as well as measurements. Our millimeter-wave performance predictions are therefore far more reliable than estimates based on 6-dB/octave extrapolation of gain measurements. Only indirect experimental evidence is available to support our performance predictions. Present state-of-the-art transistors [3], [13], [15], [16] have predicted $f_{\max}$'s of several hundred gigahertz when detemined from 6-dB/octave extrapolation of gain measurements. However, the highest measured $f_{\max}$ is only 110 GHz [1]. Our predictions are dependent on the topology of the transistor circuit model used. However, the appropriateness of our topology at high frequencies is not clear. There is therefore a pressing need to make S-parameter and gain measurements above 18 GHz and up to 100 GHz in order to better understand the behavior of millimeter-wave transistors.

IV. Conclusion

The major contribution of this work is showing that the commonly used 6-dB/octave gain roll-off assumption cannot be used to predict the performance of millimeter-wave transistors. We have shown that resonances at millimeter-wave frequencies can lead to gain roll-off at 12 dB/octave.

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