Correspondence

Comments on "Ill Conditioning in Self-Heating FET Models"

Anthony E. Parker

***Abstract*—A recent letter[1] reported ill conditioning in nonlinear circuit simulators caused by the introduction of self-heating effects into FET models. This is true for circumstances outlined in that work but is a consequence of using an incomplete thermal model. This letter points out that an account for both thermal potential and mobility variation with temperature will eliminate the problem.**

***Index Terms*—Circuit simulation, microwave FETs.**

I. Introduction

In the above letter, the circumstances and mechanisms reported cause a class of FET models to be ill conditioned. Consideration of temperature-dependent threshold potential alone can produce instability or nonconvergence. The latter may be thermal runaway. If the real devices were unstable, then the simulator model would be doing its job correctly. However, FETs are thermally stable by nature, so it can only be concluded that there is a deficiency in the model or the model parameters.

The problem is that many models consider certain aspects of device behavior and ignore others. In the case of thermal modeling, it is necessary to consider both the effect of quantum thermal potential (q/kT), which affects the threshold potential, and the temperature dependence of carrier mobility. The inclusion of both of these effects adds the extra degree of complexity that guarantees at least one solution. That is, there will be no thermal runaway. Moreover, the extra parameter introduced gives adequate control to ensure that there will be only one solution. That is, there is no thermal instability.

II. Theory

A simple model of drain current, which is presented for illustration rather than as a valid model, is given by the expression

$$I_d = \beta(1 - \lambda\Delta T)(V_{\rm gs} - V_{\rm TO}(1 + \alpha\Delta T))^2 \quad (1)$$

where β is a constant, $V_{\rm gs}$ is the gate–source potential, α is the temperature coefficient of threshold potential, λ is the temperature coefficient of mobility [1], $V_{\rm TO}$ is the threshold potential at the base temperature, and ΔT is the change in temperature relative to the base temperature given by

$$\Delta T = V_{\rm dd} I_d R_{\rm th} \quad (2)$$

where $V_{\rm dd}$ is the drain-source potential and $R_{\rm th}$ is the thermal resistance.

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[1]S. A. Maas, *IEEE Microwave Wireless Componen. Lett.*, vol. 12, pp. 88–89, Mar. 2002.

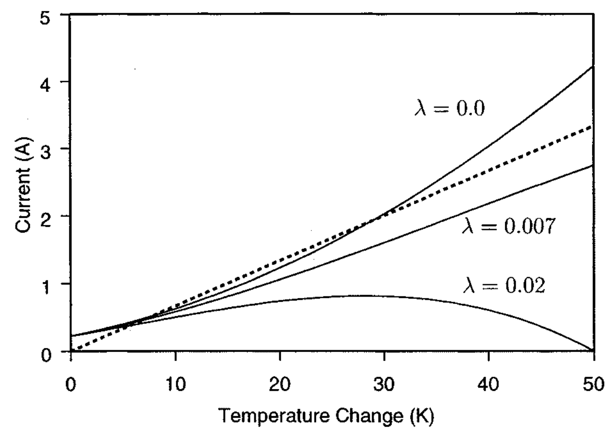

Fig 1. Plots of I_d from (1) (-) and (2) (- - -) for the case $\alpha = 0.1$, $R_{\rm th} = 5.0$, $\beta = 0.1$, $V_{TO} = -1.0$, $V_{\rm gs} = 0.5$, $V_{\rm dd} = 3.0$, and three values for λ as indicated. Two solutions exist with $\lambda = 0$, whereas only one exists otherwise.

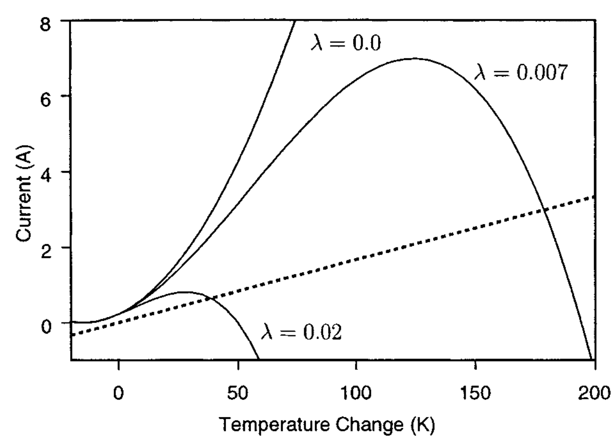

Fig 2. Plots of I_d from (1) (-) and (2) (- - -) for the same parameters in Fig. 1, except that $R_{\rm th} = 20.0$. The solution with $\lambda = 0.2$ is more realistic.

Equations (1) and (2) are the same as the illustrative model used by Maas, except for the introduction of λ. Setting $\lambda = 0$ restores the original model.

The model has a solution when both (1) and (2) are satisfied. With $\lambda = 0$, the system is quadratic with respect to ΔT and there will be two roots, which should be the same and real. However, the solutions may be imaginary, corresponding to thermal runaway, or not the same, corresponding to thermal instability. With $\lambda > 0$, the system becomes cubic and there will be at least one real root. For sufficiently large λ, it is possible to ensure that the remaining roots are imaginary and that there will be only one solution to the simulation. That is, the system is thermally stable.

Fig. 1 shows the effect of including λ. For $\lambda = 0.0$, the case is the same as used by Maas, which has two solutions corresponding to the intersection of (1) and (2). For $\lambda > 0.052$, there is only one real solution. It is more likely that λ is larger for a real device. Fig. 2 shows the effect of increasing $R_{\rm th}$. There is a solution only if $\lambda > 0.0$. It is necessary to use a sensible value for λ to obtain a solution at the correct temperature change.

III. Conclusion

Self-heating effects in FET models must be complete. Otherwise, as pointed out by Maas, the simulation can become ill conditioned. It is important to model all aspects of temperature variation. Then, if, and only if, the parameters and model have been chosen correctly, any ill conditioning would correctly indicate a thermal runaway or instability in the real circuit. In general, if temperature dependence of mobility is included, then there will always be a solution.

References

[1] A. E. Parker and J. G. Rathmell, "Measurement and characterization of HEMT dynamics," *IEEE Trans. Microwave Theory Tech.*, vol. 49, pp. 2105–2111, Nov. 2001.

Author's Reply

Stephen Maas

In his comments, Prof. Parker makes the point that a properly designed model should not predict thermal instability or have multiple solutions in a device that is thermally stable, and, if it does, the model is not doing its job. I certainly cannot disagree with that point.

The issue addressed in the letter[1] goes a bit beyond this, however. Since self-heating models are inherently nonlinear, and many model designers seem unable to avoid equating complexity with accuracy, it is almost inevitable that multiple solutions can occur, under some conditions. A harmonic-balance analysis searches over a wide range of its independent variables (usually voltage components) to find a solution, so multiple solutions, even at unrealistic temperatures, are likely to be discovered. Models are frequently formulated to work in the expected range of temperatures, and often are not robust outside of that range. Another concern is the existence of indistinct solutions, which can lead to convergence failure in harmonic-balance analysis. These conditions can be maddeningly difficult to avoid and puzzling to the user when they occur.

Indeed, the above example can be modified to make it ill conditioned. If $R_{\rm th}$ is approximately 5.5, the $\lambda = 0.007$ case shows multiple solutions; even the $\lambda = 0.02$ case may be sufficiently indistinct to slow convergence at certain values of $R_{\rm th}$. Of course, as suggested in the comment, increasing λ removes the ill conditioning, but what if the user decides that $\lambda = 0.007$ describes his device most accurately within the expected range of operation? Or, what if he decides that a quadratic model, or other simple model, is not adequate, and therefore increases the complexity? I think it is important to know the consequences.

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[1]S. A. Maas, *IEEE Microwave Wireless Compon. Lett.*, vol. 12, pp. 88–89, Mar. 2002.

Comments on "Improvement of Broadband Feedforward Amplifier Using Photonic Bandgap"

Thomas J. Ellis

***Abstract*—A number of technical facts were either claimed or implied in the above letter, which appeared in the November 2001 issue of IEEE Microwave and Wireless Components Letters. Without clarification or supporting data, the claims presented could mislead the reader into drawing inaccurate conclusions regarding the performance increase of feed forward amplifiers due to the so-called photonic bandgap structure.**

***Index Terms*—Feedforward amplifier, photonic band gap.**

I. Introduction

In the above letter,[1] some general claims are made that a photonic band gap (PBG) enhanced feed-forward amplifier shows a 4% increase in power added efficiency (PAE), a 15 dB reduction in intermodulation distortion, and a doubling of the bandwidth, as compared to a "conventional feed-forward" amplifier. The data and explanations presented in the paper do not appear to support the claims, and the data that was presented does not appear to be consistent with the explanations in the accompanying text.

It is important to note that the popular PBG structure used for the claimed improvement is essentially a large, distributed, stepped impedance filter whose response can be completely predicted using cascaded transmission line analysis. This type of structure was initially investigated at The University of Michigan in 1996 and 1997 [1], and was not pursued for publication.

The headings of this letter will follow those of the original paper, with questions and inconsistencies being contained in the corresponding sections.

II. Main Amplifier Design and Measurement

It was reported that the "main amplifier" was based on an "NE650 FET," which is assumed to be the NE6 500 496 GaAs FET. The authors report a "theoretical" gain of 11 dB, which is consistent with the manufacturers data sheet, but an "actually manufactured" gain of 8 dB with a class A bias point of 8 V, 500 mA. Having the fabricated amplifier to perform significantly worse than the manufacturers data sheet would imply a nonoptimal design. This could seriously skew any conclusions drawn from the "improvements" gained by using the distributed filter structure (i.e., PBG), which will be explained in more detail later.

The authors report that the amplifier was used at an output power level of +28 to +30 dBm. With the bias point listed (which may be more class AB bias), the resulting efficiency should be 25% and not the 8%–12% listed.

The authors claim that adding the PBG provides a 3-dB improvement in intermodulation distortion (IMD). The linearity of a power amplifier is sensitive to the load impedance presented to the output of the transistor. If the PBG effect truly caused the decrease in distortion, it would have presented a purely 50-Ω load to the output of the amplifier

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[1]J. Yoon and C. Seo, *IEEE Microwave Wireless Compon. Lett.*, vol. 11, pp. 450–452, Nov. 2001.