# Thermal transients in microwave active devices and their influence on intermodulation distortion

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*Abstract*— **A fully physical transient thermal model is used to investigate the effects of temperature on the intermodulation distortion performance of microwave devices. A 24mm, 60 finger pHEMT is used to compare measurements with predictions from the model. Results are in very good agreement and are a strong indication of thermally induced intermodulation distortion.**

## I. Introduction

With the recent interest in mobile communication, where channel separation can be as low as 25KHz, linearity is becoming a very essential asset in amplifiers. Thermal non-linearity has received very little attention, when compared to transconductance and gate capacitance induced dispersion, and the effects of thermal transients on spectral regrowth are very often neglected. It has been previously argued that in the HBT, the second order intermodulation product, or IM2, could fall well within the range of the transient thermal response of a device [1]. This would result in an oscillating temperature within the active channel of the device, which will affect both its DC and RF performance, leading to deteriorated third order intermodulation products, IM3. This dynamic thermal response is dependent on the physical dimensions of the device, with cut-off frequencies ranging from a few KHz to 10 MHz. As the dimensions of solid-state microwave active components are further reduced, and their power dissipation remains unchanged, ever increasing peak operating temperatures and dynamic response have to be expected. There is, therefore, a need to fully understand the mechanism by which the thermal response of a device or a MMIC is going to affect the intermodulation products. This paper presents the first reported fully physical dynamic thermal model suitable for describing accurately MMIC structures. A thermal impedance matrix approach is used to couple this model very efficiently to the Leeds Physical Model (LPM), [2] [3], a fast physically based microwave transistor model. This is used to investigate the influence of temperature variation under normal operating conditions on the IMD performance of microwave devices. Experimental data as well as simulation indicate a strong interaction between the device thermal response and its intermodulation distortion characteristics.

## II. Transient thermal modelling

The transient thermal model solves the time dependent heat diffusion equation, in an isotropic solid, given in Eq. (1),

$$\nabla.\left[K(T)\nabla T\right] + \dot{q} = \frac{1}{\rho c}\frac{\partial T}{\partial t}. \tag{1}$$

Here $T$ is temperature, $t$ is time, $\dot{q}$ the heat generation term and $K(T)$ is the temperature dependent thermal conductivity. The diffusivity $\kappa$ is equal to $\frac{K(T)}{\rho c}$, where $c$ is specific heat and $\rho$ is density.

This equation is linearised by a relatively simple change of variable on $T$ as described in [4]. The transient thermal model is coupled to the LPM by thermal impedance matrix expression,

$$\Delta T_i(t) = \sum_{j=1..N} P_j Rth_{i,j}(t), \tag{2}$$

which gives the averaged temperature rise over the discretised element $i$ as a function of the power dissipated by all $N$ elements. This method is very efficient as the expression for $Rth$ is only required for the areas of interest, and as the matrix is precomputed, the temperature in a coupled electro-thermal simulation is given directly by a simple matrix multiplication. As the temperature dependence of the thermal conductivity has been removed, $Rth$ is independent of temperature and therefore independent of dissipated power. $P_j$ is however strongly dependent on temperature through the expression for the electron mobility in the physical electrical model. Eq. (2) is therefore generalised to account for time varying power dissipation, and give the following expression,

$$\Delta T_i(t) = \sum_p P_{p,j}\Big[U(t-t_{p-1})Rth_{i,j}(t-t_{p-1}) \\ -U(t-t_p)Rth_{i,j}(t-t_p)\Big], \tag{3}$$

where $P_{p,j}$ is the constant power dissipated at element $j$ over the time step $p$, and $U$ is the unit step function.

The Green's function approach is chosen here, to obtain the analytical expression for the thermal impedance matrix, as the temperature rise in the time domain at any point in the 3-dimensional solid can be obtained by multiplying three 1-dimensional solutions, as shown in [5] and [6]. The expression for $Rth$ can also be derived in the complex frequency domain, as described in [7]. The boundary conditions imposed on the volume are the same that have been used previously by other authors, and can be described as follows:

$$\frac{\partial T}{\partial x}\Big|_{x=0,L} = \frac{\partial T}{\partial z}\Big|_{y=0,D} = \frac{\partial T}{\partial y}\Big|_{z=0} = 0, \tag{4}$$

and

$$\Delta T(t) = 0|_{z=H}. \tag{5}$$

$L$,$D$ and $H$ are the dimensions of the substrate in the $x$,$y$ and $z$ direction respectively.

The Green's function solution for the thermal resistance matrix gives an expression of the form:

$$\begin{aligned} Rth_{i,j}(t) &= \tfrac{2}{KLDH} \\ &\times \textstyle\sum_{mnl=0}^{\infty} \frac{4}{(1+\delta_{m0})(1+\delta_{n0})} \frac{I^i_{mnl} I^j_{mnl}}{V_i} \\ &\times \left(1-\exp(-\kappa t(\tfrac{n^2\pi^2}{L^2}+\tfrac{m^2\pi^2}{D^2}+\tfrac{\beta_l^2}{H^2}))\right) \\ &\times \left[\tfrac{n^2\pi^2}{L^2}+\tfrac{m^2\pi^2}{D^2}+\tfrac{\beta_l^2}{H^2}\right]^{-1}. \end{aligned} \tag{6}$$

Here, $V_i$ is the volume of the $i^{th}$ heat source, $L$, $D$ and $H$ are the dimensions of the MMIC, $\delta_{mn}$ is the Kronecker delta function, $\beta_l = \pi(l+1/2)$ and $I^i_{mnl}$ is the volume integral over the heating element $V_i$

$$\int_{V_i} \cos\frac{n\pi x}{L}\cos\frac{m\pi y}{D}\cos\frac{\beta_l z}{H}dxdydz. \tag{7}$$

This is based on the large time Green's function solution.

Via holes, surface metallisation and airbridges can be described following the USE method, as indicated in [8] and [9]. This model was previously validated in part, using a balanced amplifier MMIC and duroid test structures [10].

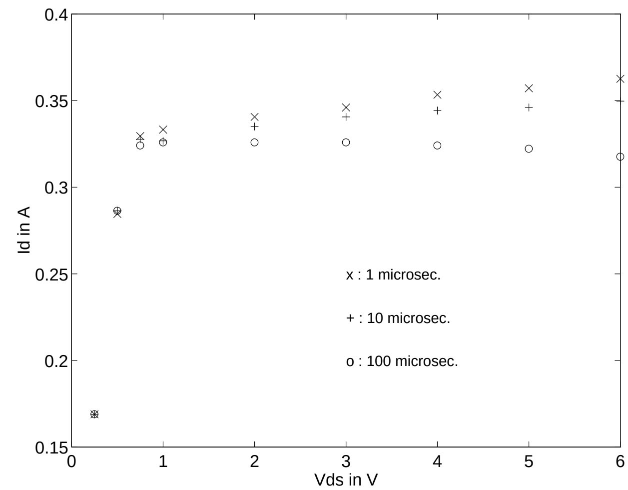


Fig. 1. Simulated results of 'pulsed' IV characteristics using different pulse duration.

## III. Electro-thermal coupling

A multi-variable Newton-Raphson scheme is used to couple the thermal impedance matrix to the electrical model. This robust method allows self-consistent solution for individual discretised gate fingers. Eq. (8) describes the vector $\bar{F}$ equal to the difference between the channel temperature $X_i$ and the temperature $T_j$ that is obtained from the power dissipation of all active elements $P_j$.

$$f_n(X_n) = X_n - T_n(P_1, P_2, ..., P_N) \tag{8}$$

$$F(x) = \begin{bmatrix} f_1(X_1) \\ f_2(X_2) \\ ... \\ f_N(X_N) \end{bmatrix}$$

Electrical and thermal models are solved self-consistently when the vector $\bar{F}(x)$ is null. This algorithm converges rapidly within a few iterations.

The coupled electro-thermal model is being validated using 'pulsed' IV characteristics for a 24mm power HEMT. Fig. (1) presents the simulated results, where different pulse durations have been used to characterise the device with the gate voltage equal to 0V. The current drop due to the increased temperature is clearly visible.

## IV. Thermal contribution to Intermodulation distortion

This model is used to investigate the effects of thermal transients on intermodulation distortion. Calculation of the time dependent thermal resistance matrix, shown in Fig. (2) for the 24mm device mentioned previously, is very suggestive of the thermal response of the device to relatively low frequency excitation. The matrix was computed for a single heating element, under one of the 60 gate fingers of the pHEMT, representing an area 2 micron wide and 400 micron long. The figure of 8000 K/W per finger is in good agreement with the experimental results. It has to be noted that using an averaged thermal impedance over the whole device surface would shift the time response by several decades and would not be representative of the physical dimensions of the heat dissipating area. The matrix was used to obtain the dynamic temperature response of the device, with different excitation frequencies, computed self-consistently with the electrical model for a similar device.

Results are shown in Fig. (3). This Bode plot shows that for different electrical frequencies, different values of thermal response are to be expected. It can be seen from this plot that the substrate behaves as a low pass thermal filter. The active region clearly shows significant temperature variations at frequencies of the order of a few hundreds of KHz. This temperature rise is however considerably reduced by the relatively large size of the simulated device, and would be significantly increased in a smaller size device, or a device structure less able to dissipate heat, such as an HBT. Fig. (4) shows the self-consistently computed channel temperature due to a 125KHz electrical excitation. The total dissipated power in the device, at the thermal frequency is just under 1W. The resulting temperature swing in the channel area spans over 22 K. Even though 1W of power at 125KHz is extreme, 2-tone simulations have shown that a figure of 60mW at the difference frequency, is possible. Depending on the frequency spacing, this could lead to temperature swings in the channel of the order of 10K or more. The effects of such a variation on the linearity of the device still has to be investigated.

Experiments were conducted to verify the validity of these results. 2-tone measurements were performed on the pHEMT. The results are shown in Fig. (5). This plot shows the amplitude of the third order intermodulation product, IM3, as a function of the frequency separation between the two tones. The response is flat below 50 KHz and above 2MHz. A sharp rise in the amplitude of IM3 is observed for frequency separation of around 400 KHz. This value falls within the computed thermal response for this particular device, as illustrated by Figs. (2) and (3), and though not conclusive, it is highly suggestive of the influence of thermal transients on the intermodulation distortion performance of the pHEMT. A low power AC sweep was also performed on the test fixture of the device, to check for any electrical feature in its low frequency response. None was found.

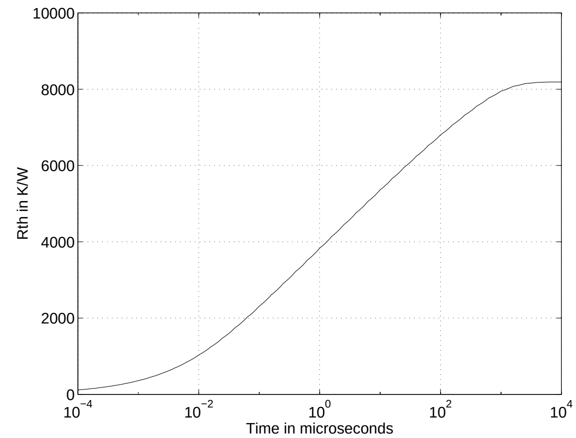


Fig. 2. Computed time dependent thermal resistance matrix, under one gate finger.

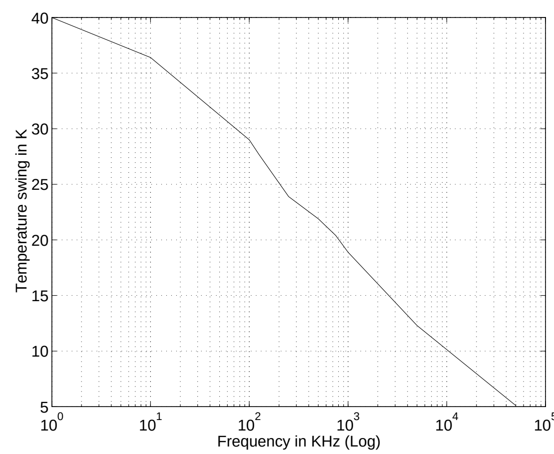


Fig. 3. Relative dynamic response of the substrate with frequency of excitation. The thermal low-pass characteristic of the substrate is clearly visible.

The power dissipated at the difference frequency is the key factor determining temperature variation. Obtaining an accurate measure of those power components is difficult in typical devices, as out of band intermodulation products are usually filtered out. However, filtering the output of amplifier to achieve high rejection of in-band intermodulation distortion products would not prevent the impact of the lower frequency component in the amplifier, leading to thermally stimulated intermodulation distortion products.

## V. Conclusion

This is the first time a fully physical electro-thermal model has been used to investigate thermally induced

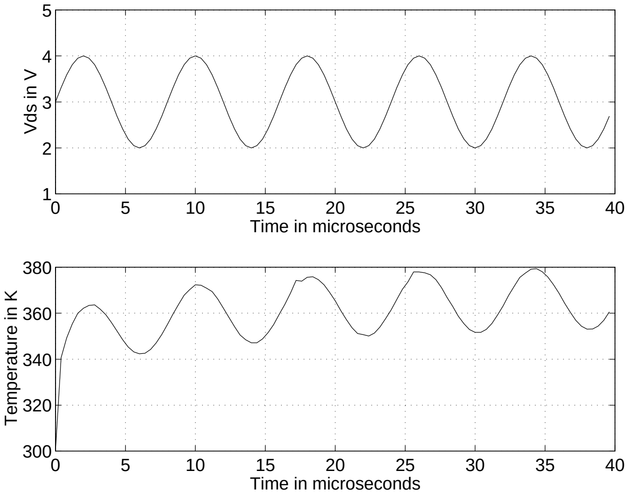


Fig. 4. Temperature time domain response, for electrical excitation at 125 KHz. The mean temperature rises slowly to a steady state value due to substrate heating.

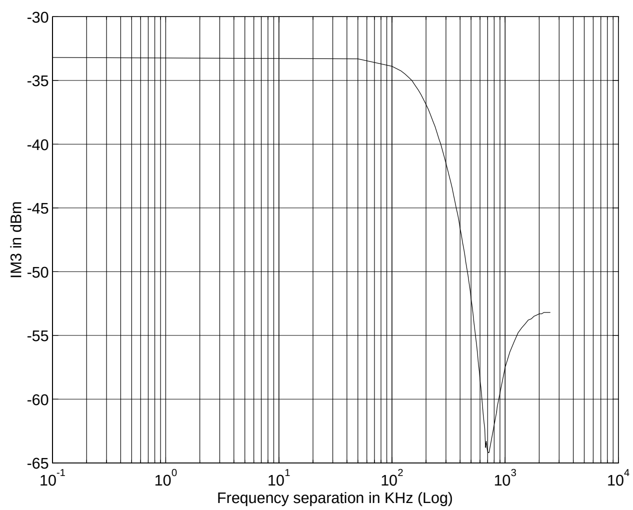


Fig. 5. Measure of IM3 as a function of the 2-tone frequency spacing. Input signal power is 7dBm for both tones.

intermodulation distortion. This model was used to characterise thermally a 24 mm, 60 gate finger pHEMT. The results are highly indicative of a strong thermal response at frequencies of the order of hundreds of KHz. Measurements of IM3 against frequency spacing between two tones were in very good agreement with results from the thermal model. The temperature variation simulated under an excitation of 1W at 125 KHz reached over 20 K. Realistic estimates from simulations have shown that thermal oscillations of the order of a few K are possible. Such an order of magnitude in temperature swing would most probably become an important source of nonlinearity in the device.

## References


[1] K. Lu, P.M. McIntosh, C.M. Snowden, and R.D. Pollard, "Low-frequency dispersion and its influence on the intermodulation performance of AlGaAs/GaAs HBT's," *IEEE Microwave Theory and Techniques Symposium Digest*, pp. 1373–1376, 1996.

[2] C.M. Snowden and R.R. Pantoja, "Quasi–two–dimensional MESFET simulations for CAD," *IEEE Transactions on Electron Devices*, vol. 36, no. 9, pp. 1564–1574, Sept. 1989.

[3] C.G. Morton, J.S. Atherton, C.M. Snowden, R.D. Pollard, and M.J. Howes, "A large-signal physical HEMT model," *IEEE Microwave Theory and Techniques Symposium Digest*, pp. 1759–1762, 1996.

[4] W.B. Joyce, "Thermal resistance of heat sinks with temperature dependent conductivity," *Solid State Electronics*, vol. 18, pp. 321–322, 1975.

[5] H.S. Carslaw and J.C. Jaeger, *Conduction of Heat in Solids*, Oxford Univeristy Press, 1962.

[6] R.C. Joy and E.S. Schlig, "Thermal properties of very fast transistors," *IEEE Transactions on Electron Devices*, vol. 17, no. 8, pp. 586–594, Aug. 1970.

[7] W. Batty, A.J. Panks, R.G. Johnson, and C.M. Snowden, "Electro-thermal modelling and measurement for spatial power combining at millimeter wavelengths," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 12, pp. 2574–2585, Dec. 1999.

[8] J.V. Beck, K.D. Cole, A. Haji-Sheikh, and B. Litkouhi, *Heat conduction using Green's functions*, Hemisphere publishing corp., 1992.

[9] S. David, W. Batty, A.J. Panks, R.G. Johnson, and C.M. Snowden, "Fully physical coupled electro-thermal modelling of transient and steady-state behaviour in microwave semiconductor devices," in *Eighth Gallium Arsenide Application Symposium (GAAS2000), Paris*, 2000.

[10] S. David, W. Batty, A.J. Panks, R.G. Johnson, and C.M. Snowden, "Electro-thermal modelling of microwave transistors and MMICs for optimised transient and steady-state performance," in *Eighth IEEE International Symposium on high performance Electron Devices for Microwave and Optoelectronic Applications, (EDMO 2000), Glasgow, 2000*, 2000, pp. 206–211.


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