Distributed and Transient Electro-thermal Modeling and Its Impact on RF Predistortion

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Outline

• Introduction
• Electrical modeling
• Part I: Image method thermal modeling and distributed thermal model
• Part II: Transient thermal response and memory effects in RF predistorter
• Part III: Experimental results on memory effects
Introduction

• High power devices suffer from self-heat during operation, which affects its electrical performances.

• Most of the power device models use simple low pass RC circuit to model the self-heating. The non-uniformly distributed temperature across the power device requires a model to capture the temperature distribution.

• Dynamic self-heating due to the low frequency modulation envelop causes thermal memory effects.

• Memory effects are categorized into thermal and electrical memory effects. Via simulation we can identify their separate contributions.

• Temperature rise in a multilayer material involves fast and slow time constants. A multiple RC time-constant model is required to capture the complete device electro-thermal dynamic.
Thermal Rth Measurement

20 fingers
6.34C/W

144 fingers
1.44 C/W

Rth is obtained through steady state temperature measurement
- calculated using an average device temperature
- exhibits a nonlinear scaling with the device size
Thermal Time Constant Measurement

Thermal time constant can be obtained through pulse IV measurement: the Drain current decrease/increase due to the heating

- Measured rise time may be affected by $C_{gs}$, $L_s$, and the power supply.

- Two competing temperature dependences ($V_{th}$, mobility) may cancel each other, resulting in a reduced thermal dependence.

$$I_{ds}(t) = I_{ds,dc} + A_1 \exp\left(-\frac{t}{\tau_1}\right) + A_2 \exp\left(-\frac{t}{\tau_2}\right)$$
Large Signal Electro-Thermal Model

- Nonlinear large signal electrical model
- IV characterization from both iso-thermal and pulse measurement
- S-parameter characterization from iso-thermal measurement
- Parasitics from cold FET measurement
- Simple RC circuit to model the temperature response
Electro-Thermal IV for LDMOSFET

Vgs from 4 to 6.5 in steps of 0.25 V

Temperature in °C

Extrinsic Vds in Volts

Drain Current in Amps

MISES Non-Linear RF Lab
Model Verification Using Scattering Parameters

OSUFET B-spline model (2 bias points)  AET analytic model
Model Verification Through Loapull

Loadpull test bench

P1dB Contour

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Model Verification using the Harmonic Response of an Amplifier

1 W amplifier
Part I: Lateral Thermal Model

- 3D steady state temperature calculation
- Experimental Results
- ADS implementation
- Results
Image Method for Steady State Temperature Field

Green function:  \[ dT(r, r') = \frac{q_s}{4\pi k\Delta r} dx' dy' \]

B.C.:  \[ T(Z = Z^-) = T(Z = Z^+) \]

Image sources are formed so that B.C be satisfied

Non-Linear Scaling of Average Rth

<table>
<thead>
<tr>
<th>Gate Width</th>
<th># of cells</th>
<th>Rth °C/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 μm</td>
<td>1</td>
<td>6.17</td>
</tr>
<tr>
<td>12 μm</td>
<td>4</td>
<td>2.79</td>
</tr>
<tr>
<td>48 μm</td>
<td>16</td>
<td>1.07</td>
</tr>
</tbody>
</table>

2.8 °C/W measured in our testbed for 12 μm devices.

The device models cannot rely on linear scaling rule for Rth because of the lateral heat flow.
Distributed Thermal Model

Mutual heat flow is modeled by mutual thermal resistance

Extraction from $R_{th}$ matrix calculation through image method

$P = 1W$
8 fingers
Heat Area = 1.45mm x 1.27mm
$R_{th} = 1.67$ C/W
Distributed Electro-Thermal Model Reduction

Fingers are symmetrical to the center
Number of fingers is reduced by half
Each finger has its size doubled
Rth matrix folded, each Cth is doubled

$$\begin{bmatrix}
\frac{R_{1,1} + R_{1,n}}{2} & \cdots & \frac{R_{1,n/2} + R_{1,n/2+1}}{2} \\
\vdots & \ddots & \vdots \\
\frac{R_{n/2,1} + R_{n/2,n}}{2} & \cdots & \frac{R_{n/2,n/2} + R_{n/2,n/2+1}}{2}
\end{bmatrix}$$

Thermal Y matrix implemented in ADS
Transient Simulation with Distributed Model

3 models: non-distributed, distributed, distributed half

Red (line) – one-finger approximation
Magenta (o) – distributed 16 fingers
Blue (x) – distributed 8 fingers

• Temperature distribution is seen in distributed model

• Non-distributed model reports the averages temperature across the fingers

• Overall electrical behavior is consistent, indicating the non-distributed model has enough accuracy
Results for Part I: Lateral Distributed Thermal model

- A recently reported image method can facilitate the thermal modeling of multilayer devices to account for lateral distributed thermal effects in large multifinger devices.
- Model was implemented in a circuit simulator using a distributed lateral thermal model using a single RC time constant for each finger.
- Temperature distribution can be reproduced. This is useful in applications where accurate temperature information is required.
- However the overall electrical behavior can be modeled with enough accuracy by a non-distributed model reproducing the average temperature.
- An important application of distributed model is however to predict the non-linear scaling of $R_{th}$ with device area.
Part II: Transient Thermal Modeling and Memory effects

- Approximate transient response with image method
- Multistage RC model for ADS implementation
- Impact of transient thermal model on a RF amplifier with a predistorter
- Results for multisine excitation on 1W and 60W PAs
- Results for IS95 CDMA excitation
Image Method for Approximated Transient Temperature Rise in Multilayer Structure

Time dependent Green function of a rectangular heat source:

\[ T(x, y, z, t) = \frac{q_s}{4k\sqrt{\pi}} \int_0^{2L} e^{-\frac{z^2}{u^2}} \left[ f\left(\frac{X_2-x}{u}\right) - f\left(\frac{X_1-x}{u}\right) \right] \left[ f\left(\frac{Y_2-y}{u}\right) - f\left(\frac{Y_1-y}{u}\right) \right] du \]

\[ f(x) = \text{erf}(x) \]

\[ L = \sqrt{Dt} \]

Boundary conditions:

\[ T(Z = Z_1^-) = T(Z = Z_1^+) \quad \text{For all } t \]

Approximation 1: when \( D1 = D2 \), boundary condition is independent of time, so that image method can be used

Approximation 2: thermal conductivity of layer 2 is large enough
Transient Temperature Rise

FEM provides ‘true’ temperature response, long computation time
Image method provides approximated solution
Multi-time-constant Thermal Model

Slow and fast transient temperature rise can be modeled

Rth includes junction, Si chip, flange, and copper block

Extraction from transient temperature measurement/calculation
Thermal Parameter Extraction

Extracts Rth and Cth by curve fitting in log scale
Constraint total Rth constant
Amplifier

Transistor model

Input matching

Output matching

Thermal network

MISES Non-Linear RF Lab
Two-tone Simulation

- Low modulation frequency generates bigger temperature variation
- Temperature variations are too small to affect the electrical behavior (IMD3)
- Class A amplifier less sensitive

MISES Non-Linear RF Lab
Thermal Step Response for Devices of Various Sizes

The thermal RC time constant increases with the device area or with thinner Silicon layer.
Impact of Thermal Memory Effects on RF-Predistortion

9-tone signal

\[ f_0 = 880 \text{MHz} \]

RF predistorter is expected to be more sensitive to low frequency temperature variation
Background and Motivation

From recent studies:

- Memory effects (frequency dependence of non-linearities) in RF PAs (power amplifier) degrade the performance of a PA linearization [1]

- The linearization degradation for signals with bandwidth above 1MHz is linked to fast electrical memory effects rather than slow thermal memory effects [2]


FPGA Digital Testbed for RF Predistortion

DUT: Power Amplifier

Before linearization

After linearization

Digital Testbed
RF-Predistorter in ADS

9-tone source signal
Newman’s Phase (1965)
f₀ = 880 MHz
PAR = 2.6
ACPR versus Multisine Bandwidth

P_{out} = P_{1dB} - 6 = 22\, \text{dBm}

Above 1\, \text{MHz}, electrical memory effects dominates

Strong memory effects at low frequencies

Distributed model gives the same ACPR as RC1 does

RC3 and RC5 converges RC1 deviates
Spectral Regrowth for a 1MHz Bandwidth Multisine

Center freq: 880MHz
9 tones
Tone-spacing: 0.1MHz

<table>
<thead>
<tr>
<th></th>
<th>Pout</th>
<th>Lacpr</th>
<th>Uacpr</th>
</tr>
</thead>
<tbody>
<tr>
<td>no pred</td>
<td>24.08</td>
<td>-31.14</td>
<td>-31.12</td>
</tr>
<tr>
<td>with pred</td>
<td>21.88</td>
<td>-66.59</td>
<td>-66.47</td>
</tr>
</tbody>
</table>

Small differences between thermal models

\[ ACPR = \frac{\text{total power of inband 9 tones}}{\text{total power of adj band 9 tones}} \]
Spectral Regrowth for a 1KHz Bandwidth Multisine

Center freq: 880MHz
9 tones
Tone-spacing: 0.1KHz

Noticeable differences up to 3dB between thermal models

\[
ACPR = \frac{\text{total power of inband 9 tones}}{\text{total power of adjband 9 tones}}
\]
** IS95 CDMA simulation **

Power level: P1dB-4dB=24dBm

<table>
<thead>
<tr>
<th></th>
<th>Direct</th>
<th>RC0</th>
<th>RC1</th>
<th>RC3</th>
<th>RC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>LACPR (dBc)</td>
<td>-44.2</td>
<td>-61.3</td>
<td>-61.6</td>
<td>-61.6</td>
<td>-61.6</td>
</tr>
<tr>
<td>HACPR (dBc)</td>
<td>-40.2</td>
<td>-58.9</td>
<td>-59.4</td>
<td>-59.4</td>
<td>-59.4</td>
</tr>
<tr>
<td>Pout (dBm)</td>
<td>28.1</td>
<td>24.1</td>
<td>24.0</td>
<td>24.0</td>
<td>24.0</td>
</tr>
</tbody>
</table>

** ACPR defined as power ratio of 30KHz adjband to 1.2288MHz inband **

Env simulation of IS95 CDMA signal
Bandwidth: 1.2288MHz
Time: 0 – 0.833ms
Freq resolution: 2.4KHz
Frequency span: 5MHz
Input PAR: 7.39

Improved thermal model has a negligible effect for a class A with IS95
Conditions for Strong Thermal Memory Effects

• ACPR needs to be strongly sensitive to fluctuations of the temperature

*Note: ACPR is more sensitive to Delta T when using a predistorter (by a factor 10)*

*Note: sensitivity is 0.43dB/C (small)*

• Amplifier needs to exhibit a large fluctuation (variance) of the temperature

*Note: temperature fluctuation increases with input RF power and Rth*
Temperature Variation

RC5 and RC3 have converged, But RC1 is not accurate.

Temperature variations are small for CDMA source in the class A amp considered here.
Sensitivity of ACPR to Temperature with Predistorter

Measure ACPR vs. Tsub in RC0 model

Sensitivity is non-negligible

Predistorter optimized at this temperature

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Class AB 60W Amplifier

4-port S-parameters are used to control the IF termination which affects the electrical memory effects are reduced.
ACPR Degradation for 60W PA

Up to 17 dB degradation of ACPR at low and high bandwidth

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Results for Part II: Transient Thermal Modeling and Memory Effects in LDMOSFETs

- Transient thermal response can be obtained from FEM simulation or using an approximate image method extended to predict the 3D transient thermal response of a multi-layer LDMOSFET device.

- The comparison of 1, 3 and 5 stage RC thermal time constant models in circuit simulations shows that the 3 and 5 stage RC models have essentially converged, and provide better accuracy in reporting both fast and slow temperature fluctuations. Larger devices exhibit larger thermal delay.

- Thermal memory effects are found to be dominant over electrical memory effects with bandwidth below 100 and 10 kHz in 1W and 60W devices respectively. These thermal fluctuations can be easily handled using adaptive techniques.

- Electrical memory effects were found to dominate over thermal memory effects with bandwidth over 1 MHz.

- Dynamic thermal memory effects were demonstrated to have a negligible impact on the linearization of a class A and AB amplifiers for wide bandwidth sources.

- Fast electrical memory effects are the primary mechanism degrading the linearization performance at wide bandwidth.
Part III: Experimental Results on Memory Effects

Setup used for the PA Characterization

The vectorial source generator used (ESG 4438C) is synchronized with the LSNA 10 MHz reference clock

Large signal network analyser

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Amplifier Under Test

- Class AB LD-MOSFET PA operating at 895 MHz

Gain: 13 dB, P1dB: 27.5dBm, PAE = 34%,
Extraction of $Y_{m3-}$ & $Y_{m3+}$ using a 2-tone Signal

- The $a_1$ & $b_2$ waves are measured with the LSNA

- Generalized Volterra coefficients $Y_{m3-}$ and $Y_{m3+}$ for IMD3:

$$Y_{m3-} = \frac{b_2(\omega - \omega_m)}{a_1^2(\omega) a_1^*(\omega + \omega_m)}$$

$$Y_{m3+} = \frac{b_2(\omega + 2\omega_m)}{a_1^*(\omega) a_1^2(\omega + \omega_m)}$$
Comparison of Amplitude of $Y_{m3^-}$ and $Y_{m3^+}$ versus the modulation frequency $\omega_m$ for different power levels (-4 ~ 6 dBm).

The amplitude difference at 3 MHz tone spacing is up to 40%.
Comparison of the Phase of $Y_{m3^-}$ and $Y_{m3^+}$

- Comparison of phase of $Y_{m3^-}$ and $Y_{m3^+}$ versus the modulation frequency $\omega_m$ for different power levels (-4 ~ 6 dBm).
- 60° angle difference at 3MHz tone spacing: memory effects

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Difference of $Y_{m3-}$ and $Y_{m3+}$

$|Y_{m3+} - Y_{m3-}|$

$\angle(Y_{m3+} - Y_{m3-})$

-4 dBm 6 dBm 4 dBm 6 dBm

0

0

Modulation Frequency $\omega_m$

Modulation Frequency $\omega_m$

• The difference in amplitude and phase between $Y_{m3-}$ and $Y_{m3+}$ is mostly significant above 0.3 MHz

• Referred to as a differential memory effect
Results from Part III on Non-Linear Measurements

- Below 0.3 MHz the difference in phase and amplitude of $Y_{m3-}$ and $Y_{m3+}$ is small in the PA under test.

- Above 0.3 MHz the difference in phase and amplitude increases rapidly with tone spacing.

- This indicates the presence of a strong differential memory effect between the LSB & USB for wide bandwidth signals.

- There is however no experimental evidence for a strong differential memory effect induced by self-heating.