Ice Packs for Red Hot CMOS Power Amplifiers

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11 March, 2016
Motivation

- Power amplifiers are the last component in a RF transmitter chain for radar and telecommunication equipments.
- High efficiency and gain are highly commercially important parameters.
- Applications such as wireless communication devices have limited battery. Keeping the efficiency high would provide a better battery life.
- For military application scenarios it is important to maintain the same performance for electrical circuits across wide temperature ranges.
Problem description

- Power Amplifiers (PA) are high power devices which lead to significant rise in temperature due to high power dissipation.
- Temperature rise affects the MOS transistor drain current and transconductance which in turn degrades PA characteristics like gain, linearity and efficiency.

Block diagram of temperature compensation method

- A temperature compensation unit makes the PA characteristics independent of heating.
- Compensation unit can either be feedback based or non-feedback based. A temperature sensor can be used for feedback based control.
Effect of temperature on MOSFET drain current

- Drain current in saturation

\[ I_D = \frac{\mu C_{ox}}{2} \frac{W}{L} (V_{GS} - V_{TH})^2 \]

- Mobility dependence on temperature

\[ \mu = \mu_0 \left( \frac{T}{T_0} \right)^{-m} \quad \text{where} \ m \approx 1.5. \]

- Threshold voltage dependence on temperature

\[ V_{TH} = V_{TH0} + \chi (T - T_0) \quad \text{where} \ \chi \approx -1 \text{mV/°C}. \]
Drain current dependence on temperature

For very small values of \((V_{GS} - V_{TH})\), \(I_D\) increases with increase in temperature and for high values of \((V_{GS} - V_{TH})\), \(I_D\) decreases with increase in temperature.

There exists a point where \(\frac{\partial I_D}{\partial T} = 0\) (Drain current is independent of temperature variations).

\[ V_{GS} = V_{TH} - \frac{\chi T}{0.75} \]
Small signal transconductance ($G_m$) dependence on temperature

$G_m$ versus $V_{GS}$ with temperature varying from 0 to 100°C

- A similar trend is seen in ac transconductance. For small values of ($V_{GS} - V_{TH}$), $G_m$ increases with increase in temperature and for high values of ($V_{GS} - V_{TH}$), $G_m$ decreases with increase in temperature.
- In order to stabilize PA gain within a temperature range $G_m$ must be constant.
- Consider a constant $G_m$ of 1mA/V. $V_{GS}$ must vary from 0.8126V at 0°C to 1.035V at 100°C.
It is now clear that the temperature compensation unit can stabilize the PA gain by changing gate bias voltage from 0.8126 V at 0°C to 1.035 V at 100°C.

So how can one design a circuit that changes its output voltage as a function of temperature?

**Case 1:** *(No Feedback)* Use some temperature sensitive devices like diodes, BJTs, MOSFETs.

**Case 2:** *(Feedback from Temperature Sensor)* Temperature sensor output is a voltage/current indicating the temperature. This signal can be used to generate the desired variation in bias voltage either by using an external microcontroller or some on chip circuit.
Method 1: Gate bias control using diodes and resistors

- $V_{GATE}$ versus temperature varying from 0 to 100°C

- As the temperature rises, voltage drop across diode reduces and $V_{GATE}$ increases almost linearly with temperature.

- To maintain constant $G_m = 1mA/V$, $V_{GATE}$ varies from 0.8127V to 1.036V.

Method 1: Gate bias control using diodes and resistors

The variation in $G_m$ is reduced from 27.5\% (without compensation) to 1.88\% (with compensation) within temperature range 0 to 100°C.
Can we reduce it even further?? (Constant Gm contours)

$I_D$ versus $V_{GS}$ with temperature varying from 0 to 100°C
Constant $G_m$ contours using 45 nm CMOS Predictive Technology Model

For very high values of $G_m$ it may not be possible to maintain a constant $G_m$ for any $V_{GS}$ over entire temperature range.

For $G_m = 185 \mu A/V$ the following quadratic equation gives an optimal solution.

$$V_{GS} = 3.45 \times 10^{-6} \times T^2 + 4.545 \times 10^{-4} \times T + 0.3927$$
Method 2: Temperature sensor based feedback control of gate bias voltage

A temperature sensor senses the on chip temperature in vicinity of PA.

Microcontroller generates a corresponding bias control voltage depending on output of temperature sensor to stabilize $G_m$ using the optimal quadratic function.

One drawback is that there is a need for a microcontroller to perform the compensation. Can it been done using some circuit technique??

Summary of Methods 1 and 2

$V_{GATE1}$ versus temperature with compensation of Method 1

- Method 1 implements a linear bias control voltage which is not an optimal solution.
- Method 2 implements a quadratic bias voltage control but requires microcontroller for the same.
Summary of Methods 1 and 2

$G_m$ versus temperature varying from 0 to $100^\circ\text{C}$ (with compensation of Method 1)

- In method 1 bias voltage varies linearly with temperature.
- $V_{GATE1}$ increases faster than it should from 0 to $44^\circ\text{C}$ causing $G_m$ to increase with temperature.
- $V_{GATE1}$ increases slower for the remaining temperature range causing $G_m$ to decrease with temperature.
Proposed temperature compensation method using MOS diode and resistor

In this technique MOS as a diode is used to implement an on chip quadratic bias voltage. Simulations are done in UMC 180nm CMOS technology.

In saturation MOS current does not show quadratic relation with temperature and can not be used for implementing bias voltage.

\[
\frac{\partial I_D}{\partial T} = -I_D \frac{1.5}{T} - \frac{2I_D \chi}{V_{GS} - V_{TH}}
\]

Drain current equation in subthreshold is given as

\[
I_D = I_0 \exp\left(\frac{V_{GS} - V_{TH}}{nV_T}\right)[1 - \exp\left(-\frac{V_{DS}}{V_T}\right)]
\]

where \( I_0 \propto T^2 \) and \( V_T = kT/q \).
$V_{DS}$ is small and the second term is neglected. Using Taylor series expansion for exponential term and neglecting higher order terms,

$$I_D = I_0 \left(1 + \frac{V_{GS} - V_{TH}}{nV_T} + \frac{1}{2} \left(\frac{V_{GS} - V_{TH}}{nV_T}\right)^2\right)$$

The first term shows a square law relationship with temperature. So it is possible to get square law relation from MOS diode in subthreshold region.
Proposed temperature compensation method using MOS diode and resistor

Proposed circuit

DC Response

Gate bias control using diodes and resistors

Gate bias control using MOS diode and resistors
Proposed temperature compensation method using MOS diode and resistor

$G_m$ variation versus temperature is only 0.29% over the entire temperature range.

As compared to method 1 (1.88% variation), variation in $G_m$ has reduced by 6.5 times.

It shows a promising nearly optimal solution for on chip temperature compensation.
The circuit technique discussed previously is a good biasing circuit but it will be difficult to control the gain after fabrication.

We wish to explore feedback based approach using the temperature sensor.

Advantages of using a temperature sensor -
- Measures the on chip temperature.
- Estimates the PA power dissipation non invasively.
- May be used to predict characteristics like efficiency and 1-dB compression point.
Differential temperature sensor

- This sensor has been widely implemented in the past for the purpose of on chip temperature sensing of PAs due to its high sensitivity.
- How do you perform simulations for this circuit??

Measuring power dissipation in **ANSYS Icepak**

QFN package (top view)

QFN package (side view)
The two sources represent two separate power amplifiers.
Separate points to measure temperature are chosen to see the effect of temperature sensitivity versus distance from source.
The power in each of the sources is changed from 10mW to 0.5W.
Measuring power dissipation in ANSYS Icepak

Table: Temperature at monitor points for different source powers

<table>
<thead>
<tr>
<th>Power (Watt)</th>
<th>TS1</th>
<th>TS2</th>
<th>TP1</th>
<th>TP2</th>
<th>TP3</th>
<th>TP4</th>
<th>TP5</th>
<th>TP6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00E-01</td>
<td>48.862</td>
<td>48.6969</td>
<td>47.8434</td>
<td>47.9743</td>
<td>48.1554</td>
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<td>2.00E-01</td>
<td>70.724</td>
<td>70.3937</td>
<td>68.6868</td>
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<td>69.3109</td>
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</tr>
<tr>
<td>4.00E-01</td>
<td>114.448</td>
<td>113.787</td>
<td>110.374</td>
<td>110.897</td>
<td>111.622</td>
<td>110.285</td>
<td>110.779</td>
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</tr>
<tr>
<td>6.00E-01</td>
<td>158.172</td>
<td>157.181</td>
<td>152.06</td>
<td>152.843</td>
<td>153.993</td>
<td>151.927</td>
<td>152.668</td>
<td>153.599</td>
</tr>
<tr>
<td>8.00E-01</td>
<td>201.896</td>
<td>200.575</td>
<td>193.747</td>
<td>194.794</td>
<td>196.243</td>
<td>193.57</td>
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<td>195.799</td>
</tr>
<tr>
<td>1.00E+00</td>
<td>245.62</td>
<td>243.97</td>
<td>235.43</td>
<td>236.74</td>
<td>238.55</td>
<td>235.212</td>
<td>236.447</td>
<td>237.999</td>
</tr>
</tbody>
</table>

Temperature difference from source 1 versus power

Monitor Point Sensitivity (C/Watt)

<table>
<thead>
<tr>
<th>Monitor Point</th>
<th>Sensitivity (C/Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>10.2</td>
</tr>
<tr>
<td>Point 2</td>
<td>8.88</td>
</tr>
<tr>
<td>Point 3</td>
<td>7.07</td>
</tr>
<tr>
<td>Point 4</td>
<td>10.4</td>
</tr>
<tr>
<td>Point 5</td>
<td>9.17</td>
</tr>
<tr>
<td>Point 6</td>
<td>7.62</td>
</tr>
</tbody>
</table>
The two figures show temperature contours on the chip and PCB for a specified power.
Thank You

Questions?