Simulate Self-Heating Effect in $\mu$A741 Amplifier using VBIC Model

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Introduction

- VBIC model overview
- Simulation tools and settings
- Transistors’ temperature and their transition in \(\mu A741\)
- Isolated self-heating effect on the open loop gain
- Isolated self-heating effect on the slew rate
- Thermal coupling effect on the open loop gain
VBIC Model Overview\textsuperscript{[1]}

- More accurate model for Early effect
- Some parasitic capacitances are added
- Parasitic substrate transistor action is modeled
- **Self-heating is modeled**
- Avalanche effects model added
Simulation setting

- Simulated by Spectre (Ver. 4.4.6.061301)
- Analog Waveform is used to obtain graphic output
- Use the circuit posted on WEB (http://www-ee.uta.edu/Online/adavis/analog/f_opamp.cir)
- Transistor’s models are mapped into VBIC model using Mr. Li’s script (only one npn and pnp model used)
- Area of $Q_{13A}$ is 0.25; Area of $Q_{13B}$ is 0.75
- Areas of $Q_{14}$ and $Q_{20}$ are 3
- Areas of other transistors are 1
- Connect $\mu$A741 with $\pm$15V voltage supplies
Which transistor is the hottest?

- Configure μA741 as a voltage follower
- DC analysis result
- $R_{th}$ for all npn transistors is 5000K/W
- $R_{th}$ for all pnp transistors is 1000K/W
- No load is connected

$Q_{17}$ is 91 degrees higher than the ambient temperature!
Temperature transition (without $C_{th}$)

$Q_{17}$

$Q_{13}$

$(R_{th,npn}=5000 \text{ K/W}; R_{th,pnp}=1000 \text{ K/W})$
Temperature transition of Q₁７ (1)

- $R_{\text{th,npn}} = 5000 \text{K/W}$
- $C_{\text{th,npn}} = 1 \mu \text{sW/K}$
- $R_{\text{th,pnp}} = 1000 \text{K/W}$
- $C_{\text{th,pnp}} = 10 \mu \text{sW/K}$

Need about 60ms to reach the stable temperature
Temperature transition of Q\textsubscript{13} (1)

- $R_{th,npn}=5000\,\text{K/W}$
- $C_{th,npn}=1\mu\,\text{sW/K}$
- $R_{th,pnp}=1000\,\text{K/W}$
- $C_{th,pnp}=10\mu\,\text{sW/K}$

Need about 60\,ms to reach the stable temperature.
Temperature transition of Q17 (2)

- \( R_{th, npn} = 5000 \text{K/W} \)
- \( C_{th, npn} = 0.1 \mu\text{sW/K} \)
- \( R_{th, pnp} = 1000 \text{K/W} \)
- \( C_{th, pnp} = 10\mu \text{sW/K} \)

- Need about 40 ms to reach the stable temperature
- Temperature vibration increase
Temperature transition of $Q_{13}$ (2)

- $R_{th,npn} = 5000 \text{K/W}$
- $C_{th,npn} = 1 \mu \text{sW/K}$
- $R_{th,pnp} = 1000 \text{K/W}$
- $C_{th,pnp} = 1 \mu \text{sW/K}$

- Need about 10ms to reach the stable temperature
- Temperature vibration increase
Open loop gain is hard to measure straightforward, feedback technique is needed

DUT is the op amp to be tested

Nulling op amp is connected in a feedback mode

\[ G_{ol} = \frac{\Delta V_{O-DUT}}{\Delta V_{IN-DUT}} = -\left( \frac{R_1 + R_2}{R_1} \right) \frac{\Delta V_{SRC1}}{\Delta V_{O-NUL}} \]

Simulation parameters:

- \( R_1 = 100 \)
- \( R_2 = 1M \)
- \( R_3 = 1K \)
- \( V_{mid} = 0 \)
- \( V_{SRC1} \) sweeps from 0 to 1V
Typical simulation output
# Table of open loop gain

<table>
<thead>
<tr>
<th>( R_{th,pnp} ) (K/W)</th>
<th>50 K/W</th>
<th>100 K/W</th>
<th>200 K/W</th>
<th>500 K/W</th>
<th>1000 K/W</th>
<th>2000 K/W</th>
<th>4000 K/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 K/W</td>
<td>120.1011</td>
<td>113.5006</td>
<td>102.1505</td>
<td>78.6424</td>
<td>56.7842</td>
<td>36.3845</td>
<td>20.9343</td>
</tr>
<tr>
<td>100 K/W</td>
<td>86.6788</td>
<td>83.1874</td>
<td>76.9231</td>
<td>62.7477</td>
<td>47.9798</td>
<td>32.5454</td>
<td>19.5998</td>
</tr>
<tr>
<td>200 K/W</td>
<td>51.5198</td>
<td>50.2513</td>
<td>47.9157</td>
<td>42.0168</td>
<td>34.8554</td>
<td>25.9673</td>
<td>14.8302</td>
</tr>
<tr>
<td>900 K/W</td>
<td>1.8953</td>
<td>1.9051</td>
<td>1.9249</td>
<td>1.9842</td>
<td>2.0831</td>
<td>2.2821</td>
<td>2.6826</td>
</tr>
</tbody>
</table>

Note: Each value times \( 10^4 \)
Surface of open loop gain

- Interpolation used
- Decrease about 60 times!
Surface of open loop gain (dB view)

- Decrease about 36dB!
Slew rate (without $C_{th}$)

- Voltage follower is used
- Input signal
  - 5K pulse wave
  - rise and fall time: $1\mu S$
- Voltage level: 0 and 10V
- Rising edge is measured
- Unit: $V/\mu S$

<table>
<thead>
<tr>
<th>$R_{th,pp}$</th>
<th>50 K/W</th>
<th>200 K/W</th>
<th>1000 K/W</th>
<th>5000 K/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 K/W</td>
<td>0.6846</td>
<td>0.6832</td>
<td>0.6842</td>
<td>0.6860</td>
</tr>
<tr>
<td>200 K/W</td>
<td>0.6830</td>
<td>0.6832</td>
<td>0.6834</td>
<td>0.6840</td>
</tr>
<tr>
<td>500 K/W</td>
<td>0.6800</td>
<td>0.6798</td>
<td>0.6802</td>
<td>0.6815</td>
</tr>
<tr>
<td>1000 K/W</td>
<td>0.6698</td>
<td>0.6700</td>
<td>0.6712</td>
<td>0.6751</td>
</tr>
</tbody>
</table>

Only 2% variation
Slew rate (including $C_{th}$ )

Set $R_{th,n} = 5000 \, K/W$ and $R_{th,p} = 1000 \, K/W$

<table>
<thead>
<tr>
<th>$C_{th,n}$</th>
<th>$0.1 \mu s/W/K$</th>
<th>$10 \mu s/W/K$</th>
<th>$1 m s/W/K$</th>
<th>$100 m s/W/K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \mu s/W/K$</td>
<td>0.6673</td>
<td>0.6658</td>
<td>0.6656</td>
<td>0.6657</td>
</tr>
<tr>
<td>$100 \mu s/W/K$</td>
<td>0.6667</td>
<td>0.6650</td>
<td>0.6649</td>
<td>0.6649</td>
</tr>
<tr>
<td>$10 m s/W/K$</td>
<td>0.6666</td>
<td>0.6649</td>
<td>0.6649</td>
<td>0.6649</td>
</tr>
<tr>
<td>$1 s/W/K$</td>
<td>0.6667</td>
<td>0.6649</td>
<td>0.6649</td>
<td>0.6649</td>
</tr>
</tbody>
</table>

- Only **0.4%** variation when $C_{th}$ changes
- Comparing with $C_{th} = 0$ case (0.6751, circled value at previously table), only **1.5%** variation
- Self-heating (isolated) has no significant effect on slew rate
Thermal coupling effect on open-loop gain

- Use the same circuit discussed previously
- Set $R_{th,npn}=4000 \text{ K/W}$ and $R_{th,pnp}=900 \text{ K/W}$ and $C_{th,npn}=C_{th,pnp}=0$
- The hottest transistor is $Q_{17}$
- The amplificatory transistors at 1\text{st} stage are $Q_3$ and $Q_4$
- Temperature node of $Q_{17}$ is connected with temperature node of $Q_3$ and $Q_4$ by two identical thermal resistors $R_C$

<table>
<thead>
<tr>
<th>$R_C$</th>
<th>$A_V$</th>
<th>$\Delta T$ of $Q_{17}$</th>
<th>$\Delta T$ of $Q_3$</th>
<th>$\Delta T$ of $Q_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without coupling</td>
<td>$2.68\times 10^4$</td>
<td>59.062</td>
<td>0.1207</td>
<td>0.1196</td>
</tr>
<tr>
<td>$1\times 10^6 \text{ K/W}$</td>
<td>$2.68\times 10^4$</td>
<td>58.595</td>
<td>0.1732</td>
<td>0.1721</td>
</tr>
<tr>
<td>$1\times 10^5 \text{ K/W}$</td>
<td>$2.618\times 10^4$</td>
<td>54.733</td>
<td>0.6067</td>
<td>0.6078</td>
</tr>
<tr>
<td>$1\times 10^4 \text{ K/W}$</td>
<td>$2.326\times 10^4$</td>
<td>34.115</td>
<td>2.9275</td>
<td>2.9263</td>
</tr>
<tr>
<td>$1\times 10^3 \text{ K/W}$</td>
<td>$2.02\times 10^4$</td>
<td>11.433</td>
<td>5.4793</td>
<td>5.4784</td>
</tr>
<tr>
<td>$1\times 10^2 \text{ K/W}$</td>
<td>$1.961\times 10^4$</td>
<td>6.67</td>
<td>6.0149</td>
<td>6.0147</td>
</tr>
<tr>
<td>$1\times 10^1 \text{ K/W}$</td>
<td>$1.953\times 10^4$</td>
<td>6.141</td>
<td>6.074</td>
<td>6.074</td>
</tr>
</tbody>
</table>
Open-loop gain reduced by thermal coupling

- Interpolation is used to obtain this curve
- Decrease about 25.4%!
Conclusion

- VBIC model is useful to analyze the thermal effect
  - We are able to numerically calculate each transistor’s temperature and its transition in μA741

- Isolated self-heating
  - We show isolated self-heating can significantly lower the μA741’s open loop gain
  - We find isolated self-heating has no remarkable effect on the μA741’s slew rate

- Preliminary study on thermal coupling effect
  - We show the open loop gain will be reduced considerably if the remarkable thermal coupling exists between 1st and 2nd stage
Problems may need further studies

- Typical values (or estimations) of thermal resistors and capacitors in real ICs, including the coupling thermal resistors and capacitors

- Other parameters that may be affected by heat? Including self-heating and thermal coupling
  - Band width, stability, CMRR, distortion, noise…

- Theoretically explain the thermal effect on the circuit’s performance
Reference


- Burns and Robert, *An introduction to mixed-signal testing*, Oxford University Press, 1999 Copyright Texas Instruments