Boundary Condition Independence of Cauer RC Ladder Compact Thermal Models

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Presentation Plan

- Generation of RC ladder compact thermal models
  - thermal transient recording
  - time constant spectrum
  - thermal structure functions
- Experimental investigation
  - internal package structure identification
  - thermal interface characterization
  - cooling effectiveness assessment
- Conclusions
- DELPHI compact thermal models (JEDEC JESD15-4) are generated in a complex way and their elements do not have any physical significance.

- RC ladder models are more convenient for many practical engineering applications, e.g. for prediction of junction temperature in electro-thermal simulations.

- RC ladder models might have physically significant model elements when generated in a proper way employing the Network Identification by Deconvolution method.
generation of accurate RC ladder models requires good quality transient temperature measurements recorded on the logarithmically equidistant time scale hence allowing the identification of all thermal time constants ranging from microseconds to hours.
RC Ladder Compact Thermal Models

\[ z = \ln(t) \]

\[ a(t) = \int_{0}^{\infty} R_{th}(\tau)[1 - \exp(-t/\tau)]d\tau \]

\[ \frac{d}{dz} a(z) = \int_{0}^{\infty} R_{th}(\xi) \cdot w_z(z - \xi)d\xi \]
the thermal time constant spectrum identified after the deconvolution represents a system in the form of distributed RC Foster ladder which cannot be physically correct because it implies the infinite speed of temperature response propagation throughout the system.
the Foster RC ladder needs to be converted to its Cauer counterpart which could be physically correct, but for a large number of RC stages the conversion is numerically unstable.
after the conversion to the RC Cauer ladder it is possible to construct cumulative thermal structure functions reflecting the entire heat flow path from the junction to the ambient.
RC Ladder Compact Thermal Models

cumulative

differential

structure function

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our approach is to discretize the heat flow path into individual regions already at the stage of the time constant spectrum and then to convert it to the Cauer form which is a more numerically stable operation and it can be done in a simple spreadsheet

the discretisation should be done at the locations of the minima in the time constant spectra which correspond to the change of a material in a heat flow path
Experimental Results

CASE 1

Dual SiC power diode in TO-247 package

Considered cooling configurations:

- still air cooling
- package submerged in a recipient with water
- device with a loosely attached multifinned heat sink
- device with a tightly attached multifinned heat sink
Experimental Results

recorded heating curves
Experimental Results

Cumulative structure functions
Experimental Results

time constant spectra

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**Experimental Results**

<table>
<thead>
<tr>
<th>$\tau$ (s)</th>
<th>R (K/W)</th>
<th>C (J/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>in air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.87E-04</td>
<td>6.19E-01</td>
<td>4.64E-04</td>
</tr>
<tr>
<td>9.81E-03</td>
<td>1.73E+00</td>
<td>5.67E-03</td>
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<tr>
<td>8.04E+00</td>
<td>4.72E+00</td>
<td>1.71E+00</td>
</tr>
<tr>
<td>5.62E+01</td>
<td>3.14E+01</td>
<td>1.79E+00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\tau$ (s)</th>
<th>R (K/W)</th>
<th>C (J/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>in water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.79E-04</td>
<td>6.95E-01</td>
<td>4.01E-04</td>
</tr>
<tr>
<td>6.19E-03</td>
<td>1.50E+00</td>
<td>4.13E-03</td>
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<tr>
<td>1.61E+01</td>
<td>5.05E+00</td>
<td>3.19E+00</td>
</tr>
<tr>
<td>1.42E+03</td>
<td>8.53E+00</td>
<td>1.67E+02</td>
</tr>
</tbody>
</table>

- individual RC stages correspond to real heat flow path
- improved cooling forces 1D heat flow and reduces temperature setting time
- possible estimation of package or heat sink heat capacity
- assessment of thermal interface resistance or heat transfer coefficient
CASE 2

SiC power diodes in TO-220 packages

Considered cooling configuration:

-still air cooling with a tightly attached multifinned heat sink

Experimental Results

recorded heating curves
Experimental Results

The cumulative structure function

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Experimental Results

Time constant spectra

Thermal resistance (K/W)

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## Experimental Results

### Diode 1

<table>
<thead>
<tr>
<th>τ (s)</th>
<th>R (K/W)</th>
<th>C (J/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.58E-04</td>
<td>8.62E-01</td>
<td>8.79E-04</td>
</tr>
<tr>
<td>1.72E-03</td>
<td>2.04E+00</td>
<td>8.44E-04</td>
</tr>
<tr>
<td>2.40E-01</td>
<td>9.24E-01</td>
<td>2.60E-01</td>
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<tr>
<td>4.75E+00</td>
<td>4.32E-01</td>
<td>1.10E+01</td>
</tr>
<tr>
<td>6.21E+01</td>
<td>5.84E-01</td>
<td>1.06E+02</td>
</tr>
</tbody>
</table>

### Diode 2

<table>
<thead>
<tr>
<th>τ (s)</th>
<th>R (K/W)</th>
<th>C (J/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.85E-04</td>
<td>2.50E-01</td>
<td>7.39E-04</td>
</tr>
<tr>
<td>3.32E-03</td>
<td>1.73E+00</td>
<td>1.92E-03</td>
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<tr>
<td>2.10E-01</td>
<td>7.86E-01</td>
<td>2.67E-01</td>
</tr>
<tr>
<td>4.98E+00</td>
<td>4.32E-01</td>
<td>1.15E+01</td>
</tr>
<tr>
<td>5.66E+01</td>
<td>5.05E-01</td>
<td>1.12E+02</td>
</tr>
</tbody>
</table>
CASE 3

Power amplifier in a 12-pin SIP package

Considered cooling configurations:

- still air cooling with a loosely or tightly attached multifinned heat sink
- forced air cooling at different air velocity

Experimental Results

recorded cooling curves

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Experimental Results

recorded cooling curves
Experimental Results

cumulative structure functions
Experimental Results

cumulative structure functions
Experimental Results

time constant spectra
Experimental Results

time constant spectra

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## Experimental Results

<table>
<thead>
<tr>
<th>Grease</th>
<th>Tight</th>
<th>Loose</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau) (s)</td>
<td>(R) (K/W)</td>
<td>(C) (J/K)</td>
</tr>
<tr>
<td>7.58 E-2</td>
<td>4.62 E-1</td>
<td>1.64 E-1</td>
</tr>
<tr>
<td>2.88 E+0</td>
<td>5.04 E-1</td>
<td>5.71 E+0</td>
</tr>
<tr>
<td>5.02 E+2</td>
<td>4.46 E+0</td>
<td>1.12 E+2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>0.0 m/s</th>
<th>1.5 m/s</th>
<th>3.0 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau) (s)</td>
<td>(R) (K/W)</td>
<td>(C) (J/K)</td>
</tr>
<tr>
<td>8.50 E-3</td>
<td>9.63 E-1</td>
<td>8.83 E-3</td>
</tr>
<tr>
<td>7.48 E-2</td>
<td>4.01 E-1</td>
<td>1.87 E-1</td>
</tr>
<tr>
<td>2.91 E+0</td>
<td>5.03 E-1</td>
<td>5.77 E+0</td>
</tr>
<tr>
<td>3.91 E+2</td>
<td>3.30 E+0</td>
<td>1.18 E+2</td>
</tr>
</tbody>
</table>

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Conclusions & Future Tasks

- Logarithmically equidistant sampling of system thermal response is the key issue in the identification of system time constant spectra; only when all time constants are included in reduced thermal models the entire heat flow path from the junction to the ambient is properly characterized.

- Opposed to the blind pole matching, the proposed method for the generation of reduced thermal models from time constant spectra allows for the physical interpretation of individual model element values.

- Resulting reduced RC ladder thermal models of a system predict accurately junction temperature in dynamic states and they can be easily included in standard electrical simulators.
Conclusions & Future Tasks

- Conversion from Foster to Cauer network performed for a limited number of RC stages is more numerically stable.
- Generally Cauer RC ladder models are not boundary condition independent, but not significant changes of boundary conditions can be taken into account without the necessity to regenerate the entire model.
- The NID method is developed based on a linear circuit theory, thus special care must be taken when large temperature gradients occur.
- In future research, both temperature and boundary condition dependence of RC ladder model elements should be investigated in more detail.