Fast, efficient and accurate: via models that correlate to 20 GHz

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Understand the Physics.
Baseline Circuit Model
Baseline Transmission Line Model

W line RLGC Model

- Causal dielectric with constant loss tangent (Djordjevic et. al.)
- Conductor roughness (Brist et. al.)
- Conductor internal impedance (Ramo, Whinnery and Van Duzer)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Stripline routing layers</th>
<th>Dual stripline layer</th>
<th>Published range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric constant Dk at 1 GHz</td>
<td>3.55</td>
<td>3.67</td>
<td>3.4-3.6</td>
</tr>
<tr>
<td>Dielectric loss tangent Df</td>
<td>0.005</td>
<td>0.006</td>
<td>0.004-0.006</td>
</tr>
<tr>
<td>Differential impedance Z0o</td>
<td>90.3Ω</td>
<td>88.6Ω</td>
<td></td>
</tr>
<tr>
<td>Conductor roughness</td>
<td>0.15μm</td>
<td>0.15μm</td>
<td></td>
</tr>
</tbody>
</table>
Baseline Via Model

Barrel modeled as transmission line.

Equivalent circuits for upper and lower pad current paths

Baseline Correlation

TDR
(Time Domain Reflectometry)

Red: Model
Blue: Measured

Insertion Loss

Model underestimates loss at high frequencies

Reduce loss discrepancy
Hypotheses

• Transmission line losses
  – Increased dielectric loss tangent at higher frequencies
  – Increased conductor roughness losses at higher frequencies
  – Differential skew due to weave effects

• Via losses
  – Via barrel losses
  – Losses at transition from stripline to via
Predictions

• Transmission line losses
  – Increased dielectric loss tangent at higher frequencies
    If so, loss discrepancy will be a linear function of trace length.
  – Increased conductor roughness losses at higher frequencies
    If so, loss discrepancy will be a linear function of trace length.
  – Differential skew due to weave effects
    If so, loss discrepancy will increase with trace length.

• Via losses
  – Via barrel losses
    If so, loss discrepancy will be a linear function of via length.
  – Losses at transition from stripline to via
    If so, loss discrepancy will be constant for all cases.
Loss Discrepancy vs. Trace Length

Original data set
Loss Discrepancy vs. Via Length

Original data set
• Transmission line losses
  – Increased dielectric loss tangent at higher frequencies
    If so, loss discrepancy will be a linear function of trace length.
  – Increased conductor roughness losses at higher frequencies
    If so, loss discrepancy will be a linear function of trace length.
  – Differential skew due to weave effects
    If so, loss discrepancy will increase with trace length.

• Via losses
  – Via barrel losses
    If so, loss discrepancy will be a linear function of via length.
  – Losses at transition from stripline to via
    If so, loss discrepancy will be constant for all cases.
Continued Hypothesis Testing

• Via losses
  – Via barrel losses
    If so, loss discrepancy will be a linear function of via length.
    If so, then adding more loss to via barrel at high frequencies will improve correlation across a wide range of cases.
  – Losses at transition from stripline to via
    If so, loss discrepancy will be constant for all cases.
    If so, then adding some constant loss at high frequencies will improve correlation across a wide range of cases.
Empirical Model

Additional via series impedance per meter $z(f)$

$$z(f) = (1 + j)r_v \left( \frac{f}{f_0} \right)^p$$

<table>
<thead>
<tr>
<th>Via Length</th>
<th>$r_v$</th>
<th>$p$</th>
<th>$f_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.298”</td>
<td>60Ω</td>
<td>3</td>
<td>5.0 GHz</td>
</tr>
<tr>
<td>0.293”</td>
<td>60Ω</td>
<td>3</td>
<td>5.0 GHz</td>
</tr>
<tr>
<td>0.280”</td>
<td>60Ω</td>
<td>3</td>
<td>5.0 GHz</td>
</tr>
<tr>
<td>0.181”</td>
<td>60Ω</td>
<td>3</td>
<td>5.0 GHz</td>
</tr>
<tr>
<td>0.125”</td>
<td>60Ω</td>
<td>3</td>
<td>5.0 GHz</td>
</tr>
<tr>
<td>0.083”</td>
<td>60Ω</td>
<td>3</td>
<td>3.5 GHz</td>
</tr>
<tr>
<td>0.068”</td>
<td>60Ω</td>
<td>3</td>
<td>3.5 GHz</td>
</tr>
</tbody>
</table>

A bit more loss for shorter vias
Baseline Case 1

26.9” path length and 0.298” via length

RED: Measured  BLUE: Baseline Model  GOLD: Modified via model
Baseline Case 2

7.5” path length and 0.293” via length

RED: Measured  BLUE: Baseline Model  GOLD: Modified via model
Baseline Case 3

8.0” path length and 0.280” via length

RED: Measured  BLUE: Baseline Model  GOLD: Modified via model
Baseline Case 4

5.5” path length and 0.181” via length

RED: Measured  BLUE: Baseline Model  GOLD: Modified via model

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Baseline Case 5

16.8” path length and 0.125” via length

RED: Measured  BLUE: Baseline Model  GOLD: Modified via model
Baseline Case 6

5.4” path length and 0.068” via length

RED: Measured  BLUE: Baseline Model  GOLD: Modified via model
Baseline Case 7

27.6” path length and 0.181” via length

RED: Measured  BLUE: Baseline Model  GOLD: Modified via model
Baseline Case 8

28.3” path length and 0.083” via length

RED: Measured  BLUE: Baseline Model  GOLD: Modified via model
New Data: Via Stitch Board

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Total Length</th>
<th>Vias</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>1.34”</td>
<td>2</td>
</tr>
<tr>
<td>1.6</td>
<td>11.9”</td>
<td>8</td>
</tr>
<tr>
<td>4.1</td>
<td>2.2”</td>
<td>2</td>
</tr>
<tr>
<td>4.2</td>
<td>8.1”</td>
<td>2</td>
</tr>
<tr>
<td>4.3</td>
<td>12.0”</td>
<td>2</td>
</tr>
</tbody>
</table>

FR4 dielectric required different dielectric constant and dielectric loss tangent. All other model parameters remained the same.
Configuration 1.1
Configuration 1.6
Configuration 4.1
Configuration 4.2
Configuration 4.3
• Via losses
  – Via barrel losses
    If so, loss discrepancy will be a linear function of via length.
    If so, then adding more loss to the barrel at high frequencies will improve correlation across a wide range of cases.
  – Losses at transition from stripline to via
    If so, loss discrepancy will be constant for all cases.
    If so, then adding some constant loss at high frequencies will improve correlation across a wide range of cases.

• Follow-on hypothesis: The losses occur in the ground return path.

_Let’s start working on some physics!_
Ground Currents in Differential Mode
Via Barrel Losses

Energy is sprayed out between the ground planes. The energy only returns if the ground vias are closer than $\lambda/4$.

![Diagram of via barrel losses with symbols and equations]

$$I_g = I_s \left(1 - \frac{2}{\pi} \arctan \left( \frac{b}{s} \right) \right)$$

Loss is proportional to $I_g^2$
Ground Vias Closer Than $\lambda/4$

Chong Ding, et. al., “A Simple Via Experiment”, paper 5-TP2, DesignCon2009, February 3, 2009

$\frac{\lambda}{4} = 0.8''$

$\frac{\lambda}{4} = 0.2''$
Current needs to get from under the stripline to the via antipad.

When ground vias are farther away than $\lambda/4$, ground currents are inductively coupled by higher order radial TEM waves. This mechanism is not efficient.
In Conclusion ...

- Empirical model of via losses is consistent with measured data.
- Analysis of ground path losses is qualitatively consistent with empirical model.
  - When ground vias are closer than $\lambda/4$, ground path losses are relatively low.
  - When ground vias are farther away than $\lambda/4$, ground path losses increase rapidly.
- PREDICTION: Maximizing via even mode impedance while maintaining matched odd mode impedance will reduce losses when ground vias are farther away than $\lambda/4$. 