A Multi-Line De-Embedding Technique for mm-Wave CMOS Circuits

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Outline

• Background
• De-embedding
  – Conventional Methods
  – Proposed Method
  – Experimental Results
• Conclusion
Background

• CMOS 60GHz RF Circuits
  – Available wide frequency range without licensees
  – High data rate wireless communication
  – IEEE 802.15.3c
    • 1.7 GHz  4 ch
    • QPSK  14 Gbps, 16QAM  28 Gbps

Available frequency range

IEEE 802.15.3c
De-Embedding

• On-wafer probing measurement
  – Contact pads are needed.
  – Measurement data include the parasitics of pads.
  – At high frequency, parasitic elements becomes problematic.

• De-Embedding
  – Remove parasitic elements from measurement data
Open-Short Method (Conventional 1)

- **Open-Structure and Short-Structure**
  - $Z_P$: Parallel element of contact pad
  - $Z_s$: Series element of contact pad

- **Problem at high frequency**
  - Nonideality of short cannot be neglected.

$$\begin{align*}
\text{Open-Structure} & = Z_S + Z_P \\
\text{Short-Structure} & = Z_S + Z_P
\end{align*}$$
Thru-only Method (Conventional 2)

• Short-Line-Structure
  – Replace the measurement result with the “K”-Model
  – Separate in two symmetric parts

• Issue of this method at high frequency
  – Lumped components
  – The line length must be short.
  – The measurement error has large influence.

Short-Line-Structure

Models of Pads
Proposed Method

• Multi-Lines De-embedding
  – The Length of the lines are L and 2L
    • Not need “Short” or “Short-Line”
  – De-embed transmission lines from the measurement data
  – Build the model of the contact pad
  – Remove the pad from other TEG

Two transmission lines

\[ \text{Length} = L \quad \text{Length} = 2L \]
Canceling Parallel Elements

- Use T-parameters
  - \( T_{2L} \times (T_L)^{-1} = T_{X1} \)
  - T-para \( \Rightarrow \) Y para : \( T_{X1} \Rightarrow Y_{X1} \)
  - \( Y_{X1} + \text{Swap} (Y_{X1}) = Y_{X2} \)

- The parallel components are canceled
Intrinsic Transmission Line

- Intrinsic Transmission Line: $Y_{TL}$
  - Symmetrical matrix
- $Y_{X3} = Y_{TL}$ with $Z_s$ and $-Z_s$
- $Y_{X2} = Y_{X3} + \text{Swap}(Y_{X3})$
  - $Y_{X2} = 2Y_{TL}$

\[
Y_{TL} = \begin{bmatrix}
Y_{TL_{-1}} & Y_{TL_{-2}} \\
Y_{TL_{-2}} & Y_{TL_{-1}}
\end{bmatrix}
\]

\[
Y_{X3} \equiv \begin{bmatrix}
Y_{TL_{-1}} - X & Y_{TL_{-2}} \\
Y_{TL_{-2}} & Y_{TL_{-1}} + X
\end{bmatrix}
\]

\[
X = Z_s(Y_{TL_{-1}}^2 - Y_{TL_{-2}}^2)
\]
Parallel Element

- Parallel element of pad : $Z_P$
  - Measurement data of TL : $Y_{TL}^M$
  - $Y_{TL}^M - Y_{TL} = Y_{X4}$
  - $Y_{X4}(1,1) + Y_{X4}(1,2) = 1 / Z_P$

  - Using approximation

\[
Y_{TL}^M - Y_{TL} = Y_{X4}
\]

Requirement of the approximation

\[
\frac{(Y_{TL\_1} + Y_{TL\_2})^2 \cdot Z_S \cdot Z_P}{1 + (Y_{TL\_1} + Y_{TL\_2}) \cdot Z_S} << 1
\]
Lumped Components

• Series element of pad : $Z_s$
  – Subtract $Z_P$ from $Y_{TL}^M$
  – Approximate by Lumped Components
    • Inductance and Resistance
Series Element

- Plot the calculated Inductances
  - $L_0$: Offset of Inductance
- Perform the Same Process about $R$
- $Z_S: L_0/2$ and $R_0/2$
Experimental Results

- CMOS 65nm process
- TL structure
  - CPW with bottom ground metal
  - $W = 10 \, \mu m$, $H = 8 \, \mu m$, $G = 15 \, \mu m$
  - Length of TLs: 200, 400 $\mu m$
- Pad structure
  - Signal pad: 40x60 $\mu m^2$

Photo of TLs
Structure of TL

GND

Si

GND

\[ \text{Si} \]

\[ \text{GND} \]

\[ \text{GND} \]

\[ G \]

\[ \text{G} \]

\[ W \]

\[ H \]

\[ \text{Dummy Metals} \]
Method of Evaluation

- Make pad models by each methods
- De-embedding of different-length TLs
- Calculate $Z_0$ of TL from S-parameter
- Compare $Z_0$
  - Calculated from 200mm-TL
  - Calculated from 400mm-TL

\[ Z^2 = Z_0^2 \frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2} \]

$Z_0$ : Normalized Impedance
$Z$ : Characteristic Impedance

Experimental Results (Conventional)

- **Open-Short Method**
  - Characteristic Impedances of 200µm and 400µm don’t agree with each other.

- **Thru-only Method**
  - The results are unstable.

![Open-Short Method graph](image1)

![Thru-only Method graph](image2)
Experimental Results (Proposed)

• Characteristic Impedance of TLs
  – The Impedances of $200\,\mu\text{m}$ and $400\,\mu\text{m}$ agree with each other.
  – The results are stable.

Frequency [GHz]

$Z_0$ [Ω]

- 200 $\mu\text{m}$
- 400 $\mu\text{m}$

0 20 40 60
Conclusion

• The de-embedding method for designing mm-Wave circuits is proposed.
• This method can be applied to not only TLs but also other TEGs.
• Using this method, the characteristic impedances of different-length TLs agree with each other and the result are stable compared with conventional methods.
Thank you for your attention!