Turnkey Methodology for Characteristic Impedance Extraction of Embedded Transmission Lines

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Context and Motivation

HF characterizations of Devices in integrated circuits (IC) necessary

- Feed back for designers
- Validation of circuits and materials performance
- Predictive studies from feed back
Accesses necessary to connect the DUT to the VNA
Context and Motivation

Illustration of HF characterization of a Device Under Test (DUT)

Structure to analyse

Characteristic Impedance $Z_C$ of coplanar lines required for establishing an equivalent electrical (R, L, G, C) model of the DUT.
Features of the proposed method

- Structure to analyze => Transmission Line with short accesses (<< \(\lambda\))
- S param Measurements under LRRM calibration => Ref Impedance 50 Ohms
- LRL De-embedding improved procedure to determine \(Z_C\) and \(\gamma\)
Methodology of $Z_C$ and $\gamma$ extraction

1 - Analyzed structure In terms of Quadrupoles $Q$ and associated Transfer Matrices

Knowledge of
\[
\begin{bmatrix}
[T_{L\_access}] & \times & [T_{TL}] & \times & [T_{R\_access}]
\end{bmatrix}
\]

$[T_{Meas}]$ => determination of $\gamma$

$[T_{L\_access}]$ or $[T_{R\_access}]$ => determination of $Z_C$
Methodology of $Z_C$ and $\gamma$ extraction

2 - Calculation of $[T_{TL}]$ and $[T_{L\text{access}}]$ Transfer Matrices

A : S parameters Measurements of LINE 1, LINE 2, REFLECT standards

- Same accesses
- Coplanar Transmission Lines with the same cross section
- Reflect with CPW Length = $L_1/2$
- S parameters referenced to 50 $\Omega$
Methodology of $Z_C$ and $\gamma$ extraction

2 - Calculation of $[T_{TL}]$ and $[T_{L\_access}]$ Transfer matrices

B : LRL de-embedding procedure
Methodology of $Z_C$ and $\gamma$ extraction

3 - Calculation of the exponent of propagation $\gamma$ from $[T_{TL}]$ Matrix

$$[T_{TL}] = \begin{pmatrix} t_{TL11} & t_{TL12} \\ t_{TL21} & t_{TL22} \end{pmatrix} = \begin{pmatrix} e^{-\gamma(L_2-L_1)} & 0 \\ 0 & e^{\gamma(L_2-L_1)} \end{pmatrix}$$

$$\gamma = \frac{\cosh^{-1}\left(\frac{t_{TL11} + t_{TL22}}{2}\right)}{L_2 - L_1}$$
Methodology of $Z_C$ and $\gamma$ extraction

4 - Calculation of the characteristic impedance $Z_C$ from $[T_{L\_access}]$ Matrix

$$Z_R = 50 \ \Omega$$
Reference impedance

$Y_{Pad}$ $Y_{ST}$

Electrical equivalent model of the left access
Methodology of $Z_C$ and $\gamma$ extraction

4 - Calculation of the characteristic impedance $Z_C$ from $[T_{L\_access}]$ Matrix - b

\[
[Z_C] = [T_{YPad + YST}] \times [T_{L\_IT}] \times [Z_R]
\]

with

\[
\Gamma = \frac{Z_C - Z_R}{Z_C + Z_R}
\]

Known, determined from measurements

\[
[t_{L\_acc11} \quad t_{L\_acc12} \quad t_{L\_acc21} \quad t_{L\_acc22}] = \frac{2 - (Y_{pad} + Y_{ST}) \times Z_R}{2} \left( \frac{Y_{pad} + Y_{ST}}{2} \right) \frac{1}{\sqrt{1 - \Gamma^2}}
\]

Reference impedance

$Z_R = 50 \, \Omega$

\[
Z_C = Z_R \times \frac{1 + \Gamma}{1 - \Gamma}
\]
Experimental results

Analyzed structures: 130 nm CMOS technology node

Coplanar transmission lines and accesses

Cross section

Dielectric 5 µm
Copper 1 µm
Silicon 800 µm
Results of Extracted $\gamma$ and $Z_C$ - Comparisons to Q3D simulations

**Exponent of propagation $\gamma$**

- Experimental results
- Q3D simulations

**Characteristic impedance $Z_C$**

- Experimental results
- Q3D simulations

Good agreement over the frequency band => method is validated
Experimental results

R, L parameters results - Comparisons to Q3D simulations

**R parameter**

- Experimental results
- Q3D simulations

**L parameter**

- Experimental results
- Q3D simulations
Experimental results

C, G parameters results - Comparisons to Q3D simulations

C parameter

G parameter

Deviation beyond 30 GHz for G. Difficult to obtain G with accuracy due to its low impact on propagated signals at High Frequencies (G << Cω)
Robustness of the Method

What happens if the access has series impedances not negligible?

Impact of the proposed method on extracted value of $Z_C$?

Electrical equivalent model used in the proposed method
Robustness of the Method

Process for checking the robustness

Electrical models of the 3 standards with series impedances $Z_S$ included in accesses

Fabrication of 3 sets of S parameters

Applying the proposed method

Deviation ?

Access

$L_1 = 25 \, \mu m$

$L_2 = 100 \, \mu m$

$Z_S = 0.015 + j \times 10^{-11} \times \omega \, (\Omega)$

$Y_P = 10^{-5} + j \times 10^{-13} \times \omega \, (S)$

$R = 9 \, k\Omega /m$

$L = 1 \, \mu H/m$

$G = 1 \, \mu S /m$

$C = 300 \, pF/m$
Robustness of the Method

Results of Extracted $Z_C$
Comparison to the true characteristic impedance

Real part of $Z_C$
Deviation under 4% at 67 GHz

Imaginary part of $Z_C$
Deviation under 14% at 67 GHz

Good agreement over the frequency band => good robustness
Conclusion

- Turnkey extraction method of a T.L. characteristic impedance proposed

- Reliable method: good agreement with simulations

- Robust method for short accesses

- Perspective: Materials characterizations
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Thanks for your attention!