Turnkey Methodology for Characteristic Impedance Extraction of Embedded Transmission Lines

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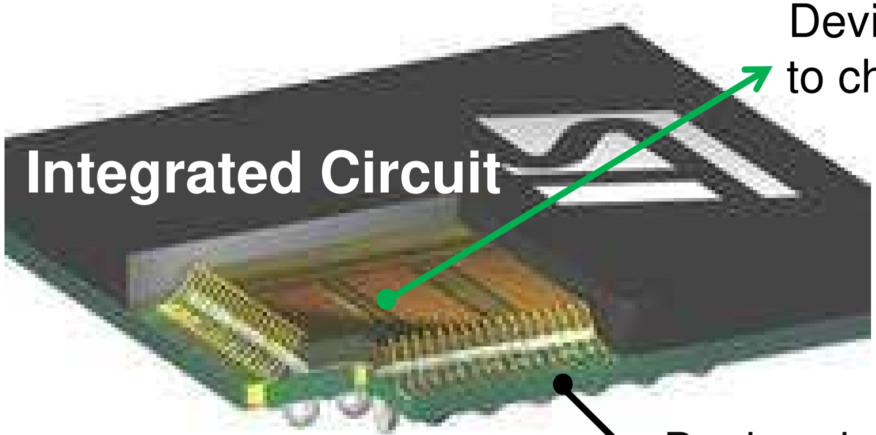
23RD IEEE WORKSHOP ON SIGNAL AND POWER INTEGRITY

Context and Motivation

HF characterizations of Devices in integrated circuits (IC) necessary



Devices in die
to characterize

Devices in multi layers
substrate to characterize

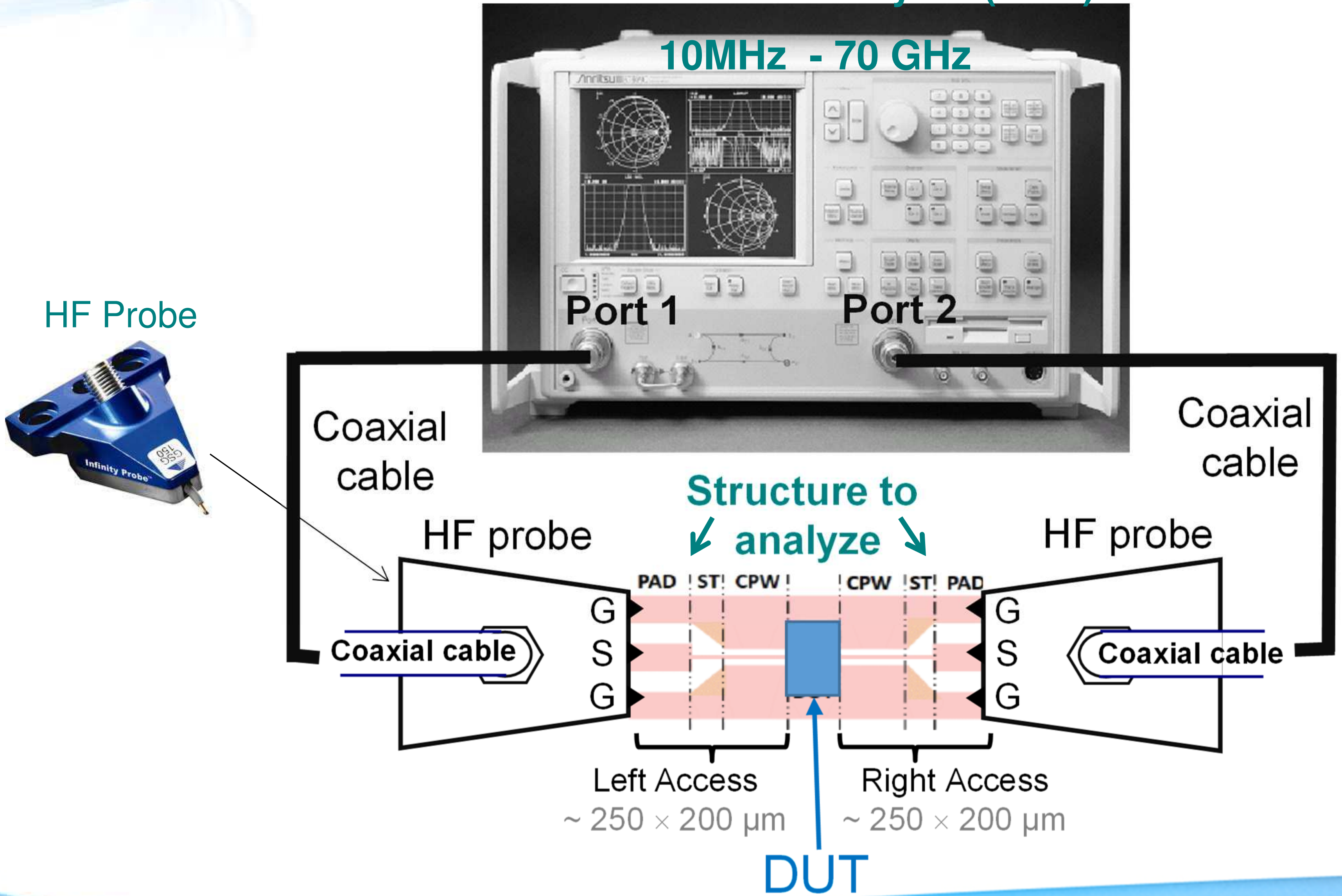
Needs of IC for High Frequency and High Speed Applications

- Feed back for designers
- Validation of circuits and materials performance
- Predictive studies from feed back

Context and Motivation

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

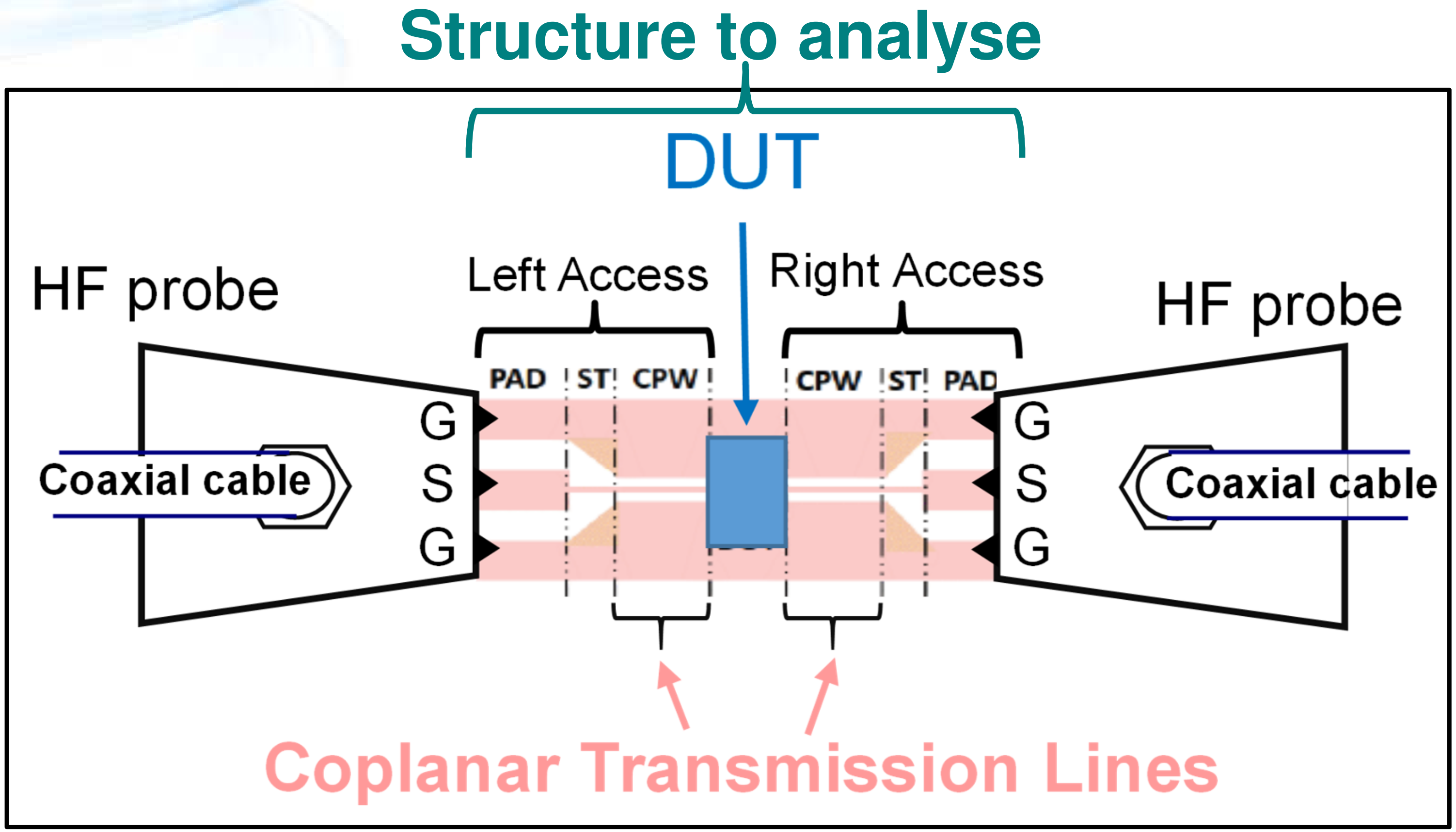
Vector Network Analyzer (VNA)

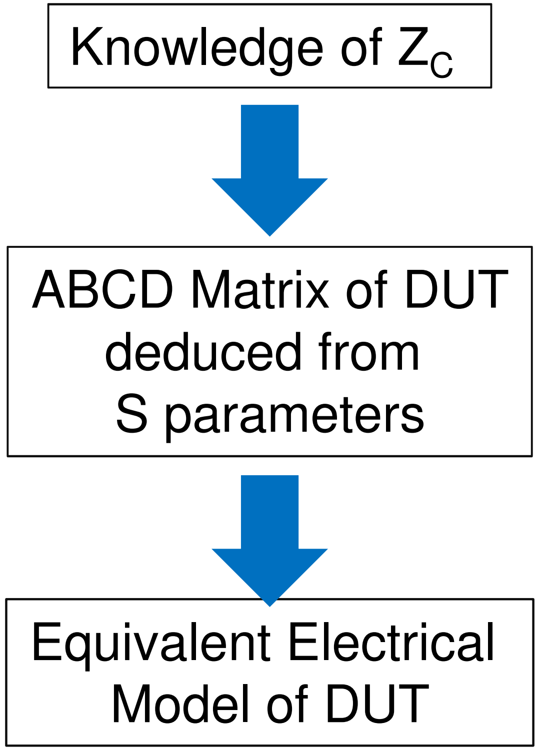


Accesses necessary to connect the DUT to the VNA

Context and Motivation

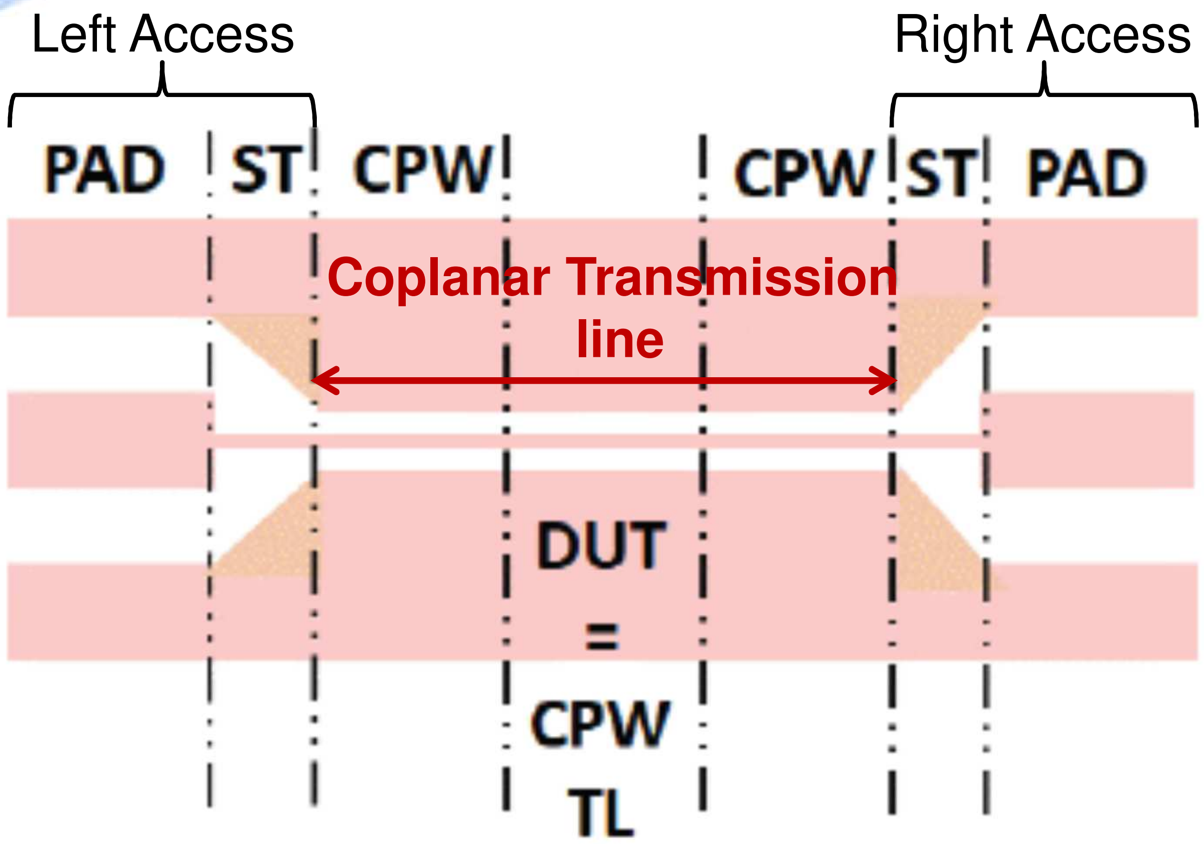
illustration of HF characterization of a Device Under Test (DUT)





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

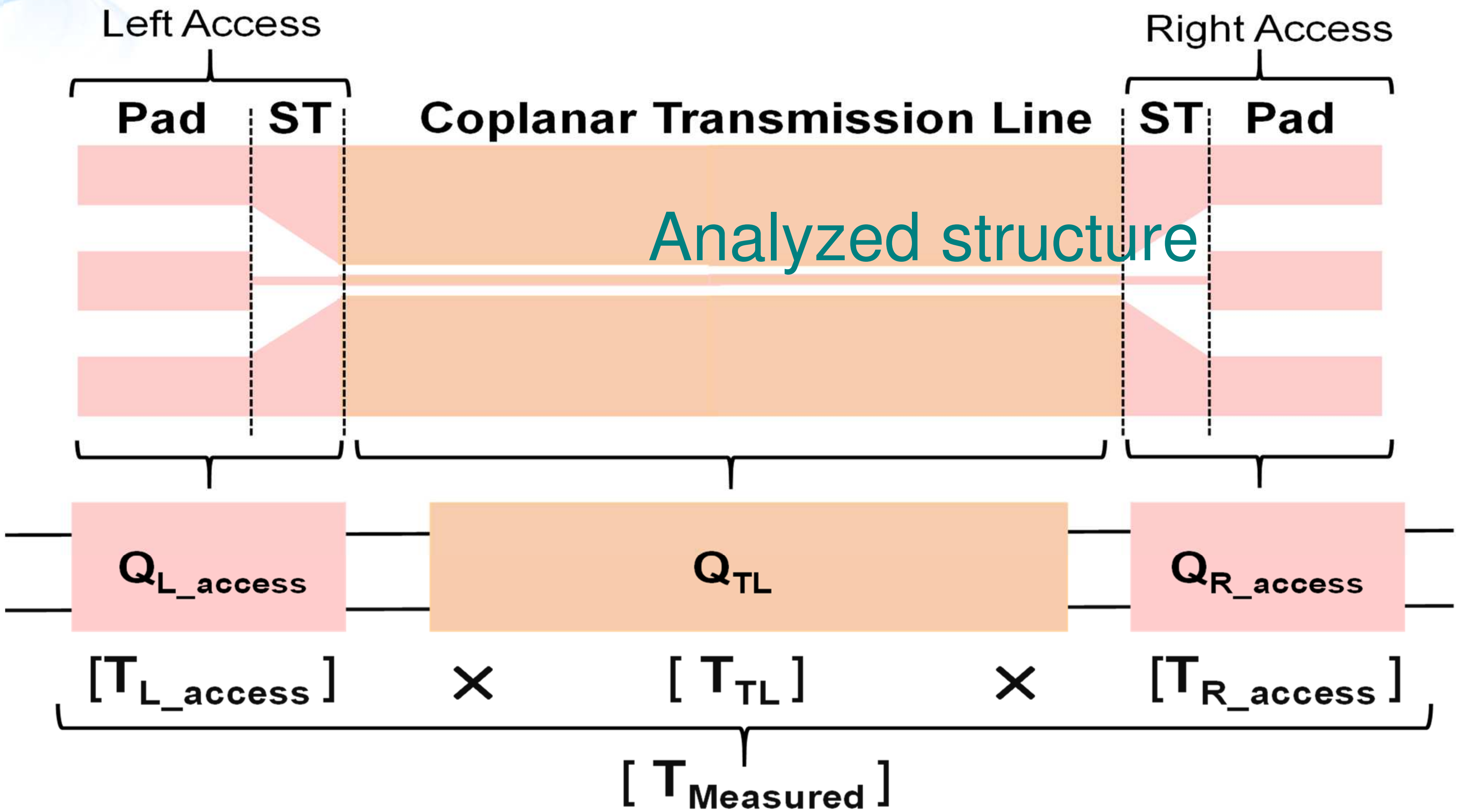
Features of the proposed method



- Structure to analyze => Transmission Line with short accesses (<< λ)
- S param Measurements under LRRM calibration => Ref Impedance 50 Ohms
- LRL De-embedding improved procedure to determine Z_C and γ
- Procedure based on a combination of previous works (Williams and Pantoja - Ref [3] and [4] of the paper)

Methodology of Z_C and γ extraction

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

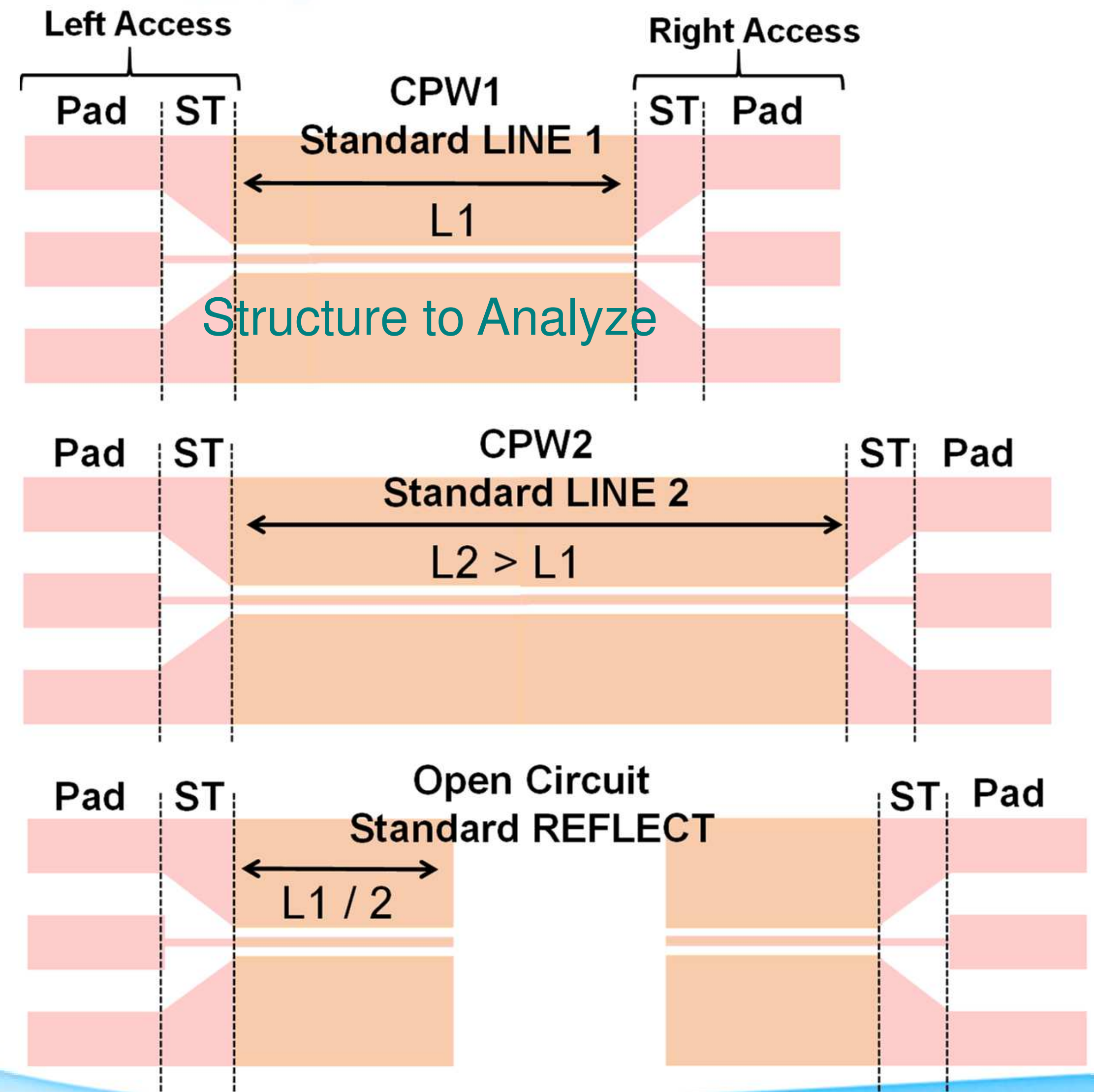


Knowledge of
- $[T_{TL}]$ => determination of γ
- $[T_{L\_access}]$ or $[T_{R\_access}]$ => determination of Z_C

Methodology of Z_C and γ extraction

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

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

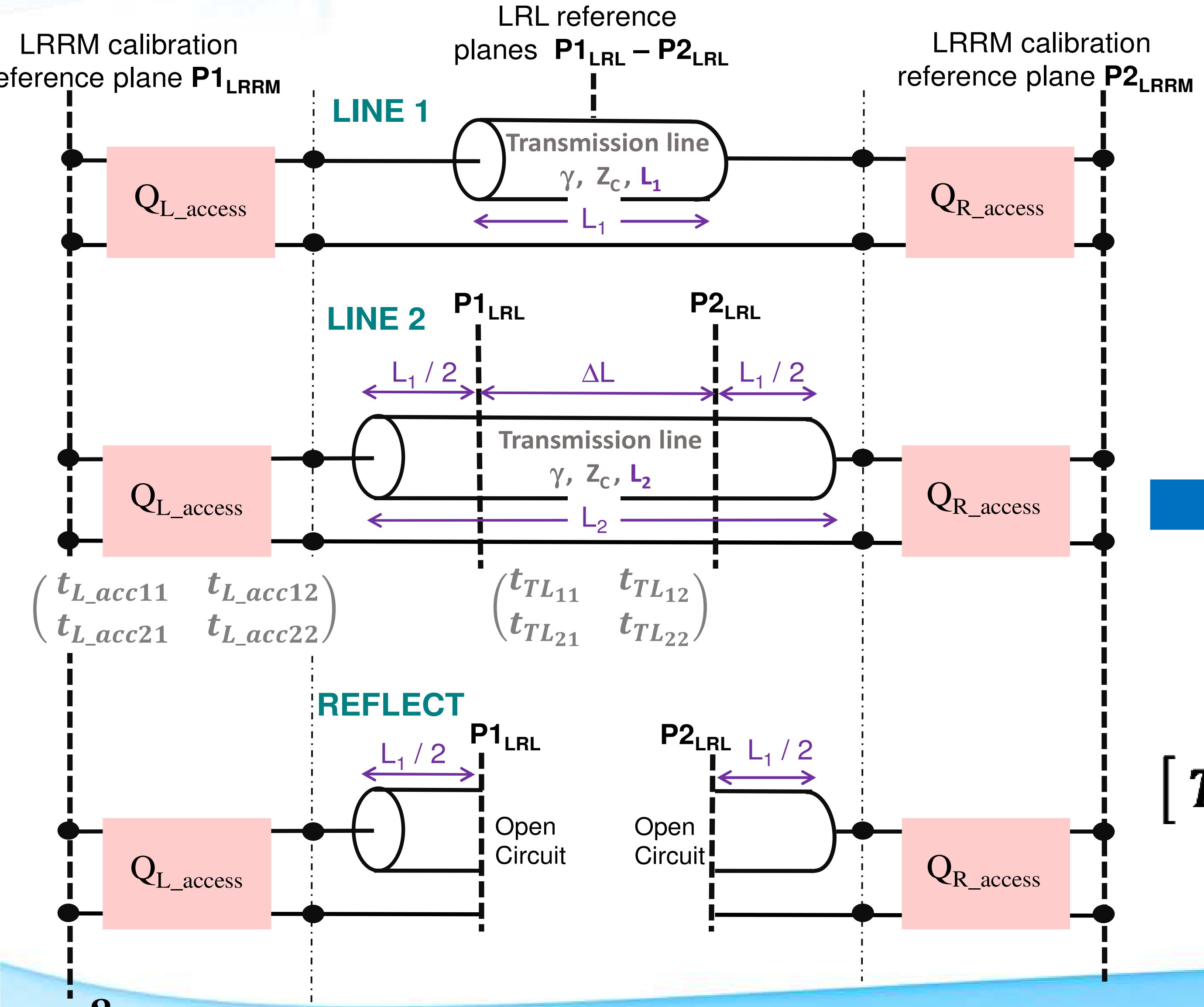


- Same accesses
- Coplanar Transmission Lines with the same cross section
- Reflect with CPW Length = L1/2
- S parameters referenced to 50 Ω

Methodology of Z_C and γ extraction

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

B : LRL de-embedding procedure



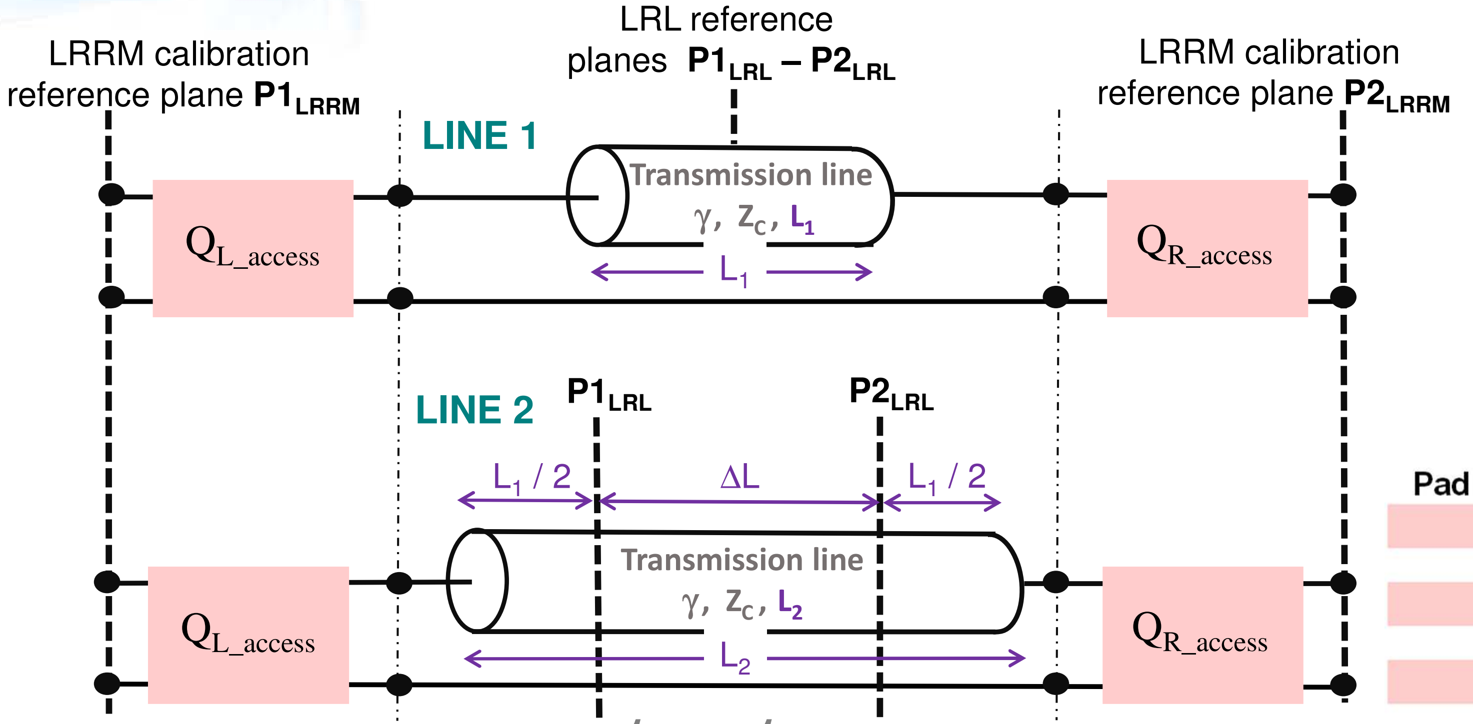
$$[T_{TL}] = \begin{pmatrix} t_{TL11} & t_{TL12} \\ t_{TL21} & t_{TL22} \end{pmatrix}$$

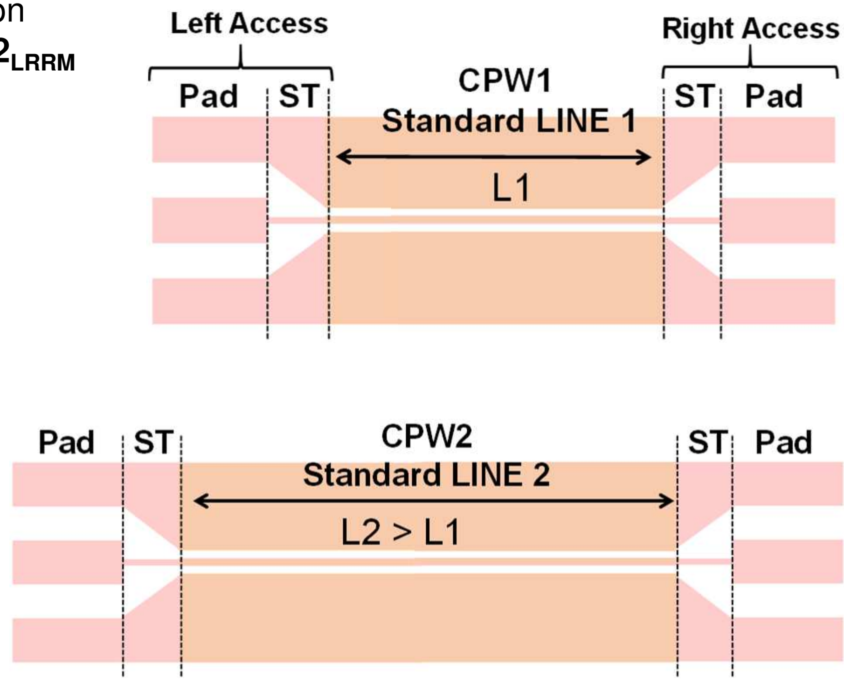
LRL de-embedding Procedure on standards S parameters

$$[T_{L\_access}] = \begin{pmatrix} t_{L\_acc11} & t_{L\_acc12} \\ t_{L\_acc21} & t_{L\_acc22} \end{pmatrix}$$

Methodology of Z_C and γ extraction

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





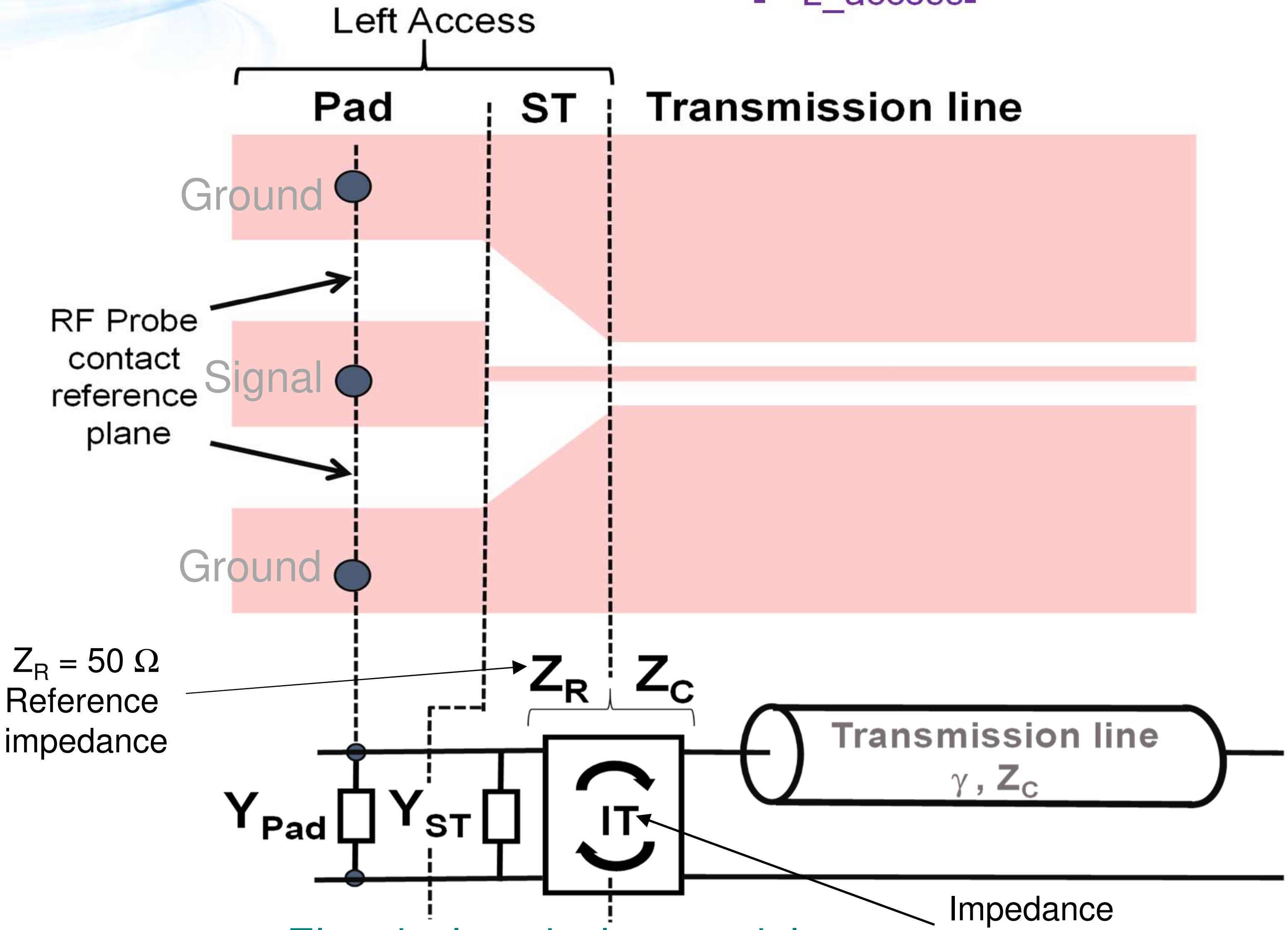
$$[T_{TL}] = \begin{pmatrix} t_{TL_{11}} & t_{TL_{12}} \\ t_{TL_{21}} & t_{TL_{22}} \end{pmatrix}$$

$$[T_{TL}] = \begin{pmatrix} t_{TL_{11}} & t_{TL_{12}} \\ t_{TL_{21}} & t_{TL_{22}} \end{pmatrix} = \begin{pmatrix} e^{-\gamma(L_2-L_1)} & 0 \\ 0 & e^{\gamma(L_2-L_1)} \end{pmatrix} \quad \boxed{1}$$

$$\boxed{\gamma = \frac{\cosh^{-1}\left(\frac{t_{TL_{11}} + t_{TL_{22}}}{2}\right)}{L_2 - L_1}} \quad \boxed{2}$$

Methodology of Z_C and γ extraction

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

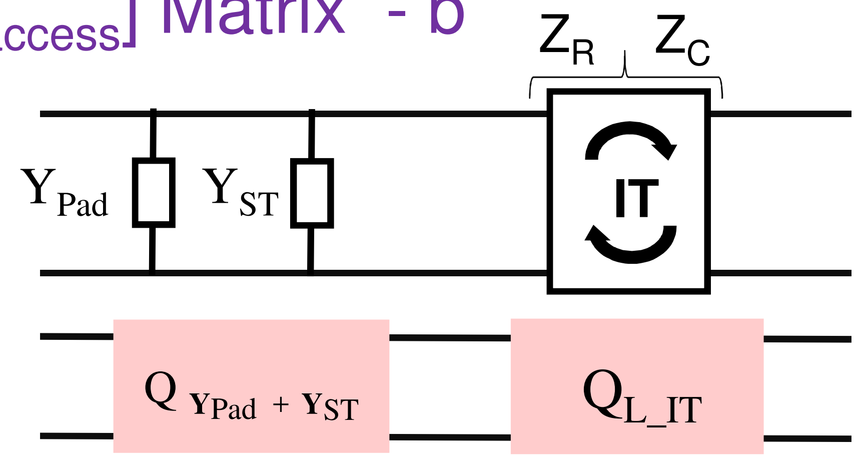


Electrical equivalent model of the left access

Methodology of Z_C and γ extraction

IMEP-LAHC

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



Known, determined from measurements

Z_R = 50 Ω Reference impedance

$$\underset{Z_R}{}[T_{L\_access}]_{Z_C} = \underset{Z_R}{}[T_{YPad+YST}]_{Z_R} \times \underset{Z_R}{}[T_{L\_IT}]_{Z_C}$$

$$\boxed{1}\quad \begin{pmatrix} t_{L\_acc11} & t_{L\_acc12} \\ t_{L\_acc21} & t_{L\_acc22} \end{pmatrix} = \begin{pmatrix} \dfrac{2-(Y_{pad}+Y_{ST})\times Z_R}{2} & \dfrac{-(Y_{pad}+Y_{ST})\times Z_R}{2} \\ \dfrac{(Y_{pad}+Y_{ST})\times Z_R}{2} & \dfrac{2+(Y_{pad}+Y_{ST})\times Z_R}{2} \end{pmatrix} \times \begin{pmatrix} \dfrac{1}{\sqrt{1-\Gamma^2}} & \dfrac{\Gamma}{\sqrt{1-\Gamma^2}} \\ \dfrac{\Gamma}{\sqrt{1-\Gamma^2}} & \dfrac{1}{\sqrt{1-\Gamma^2}} \end{pmatrix}$$

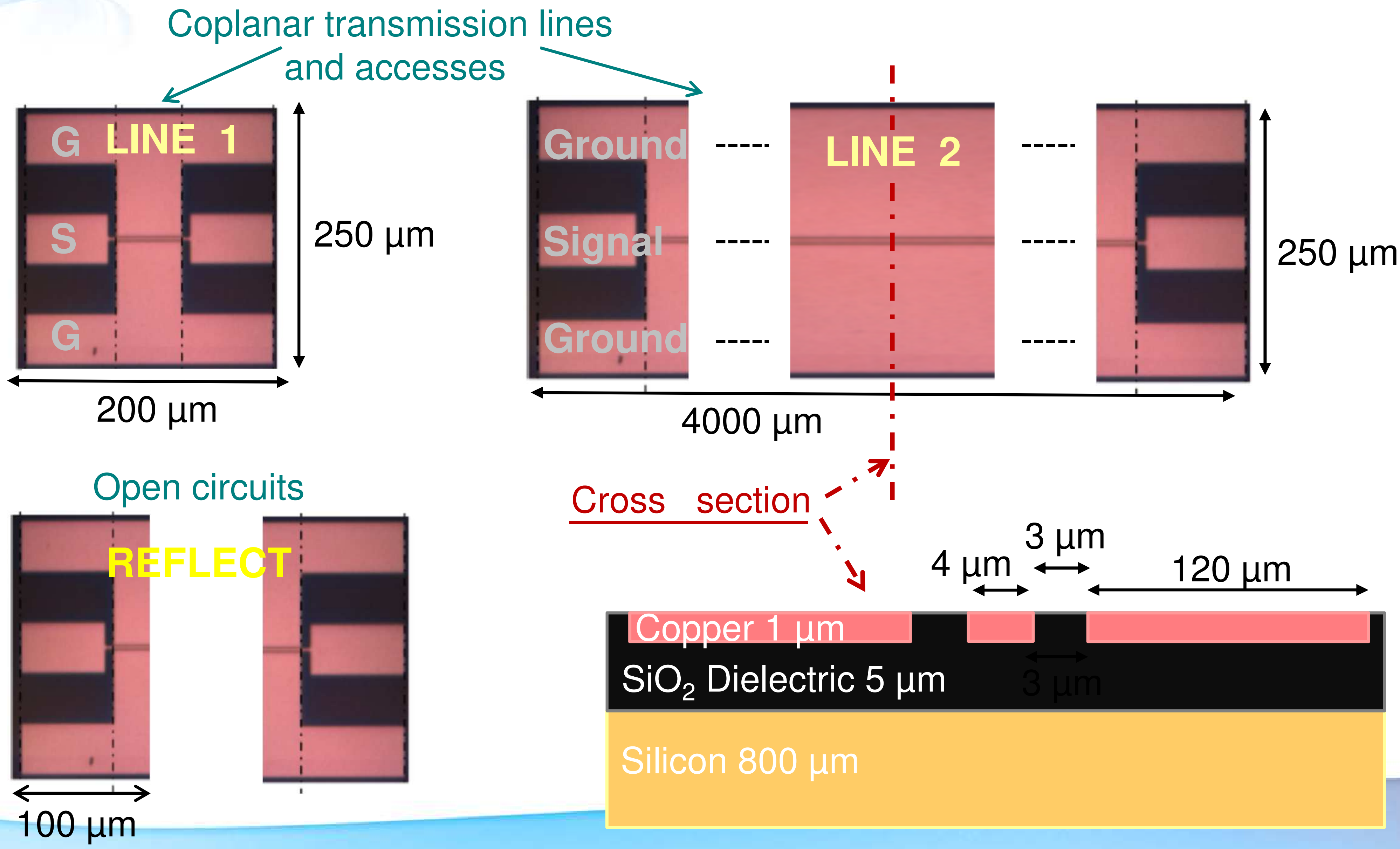
with $\boxed{2}\quad \Gamma = \dfrac{Z_C - Z_R}{Z_C + Z_R}$

$$\boxed{3}\quad \Gamma \cong \sqrt{\frac{(t_{L\_acc12} + t_{T\_acc21})^2}{4 + (t_{L\_acc12} + t_{L\_acc21})^2}}$$

$$\boxed{4}\quad Z_C = Z_R \times \frac{1+\Gamma}{1-\Gamma}$$

Experimental results

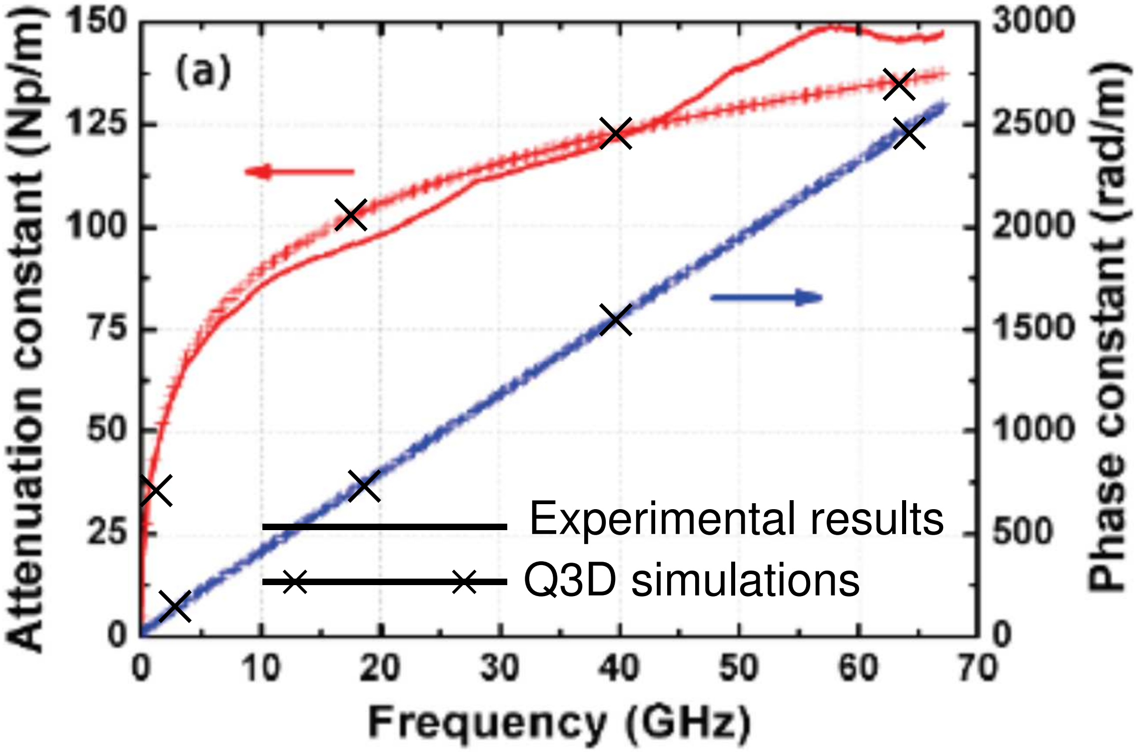
Analyzed structures : 130 nm Cmos technology node



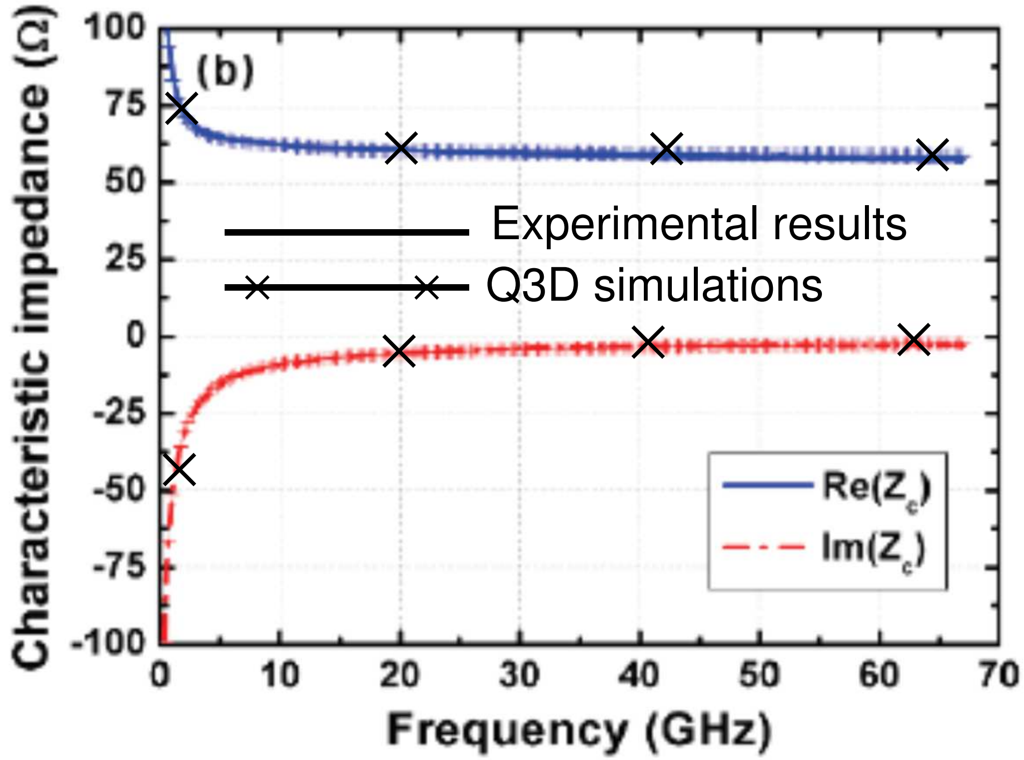
Experimental results

Results of Extracted γ and Z_C - Comparisons to Q3D simulations

Exponent of propagation γ



Characteristic impedance Z_C

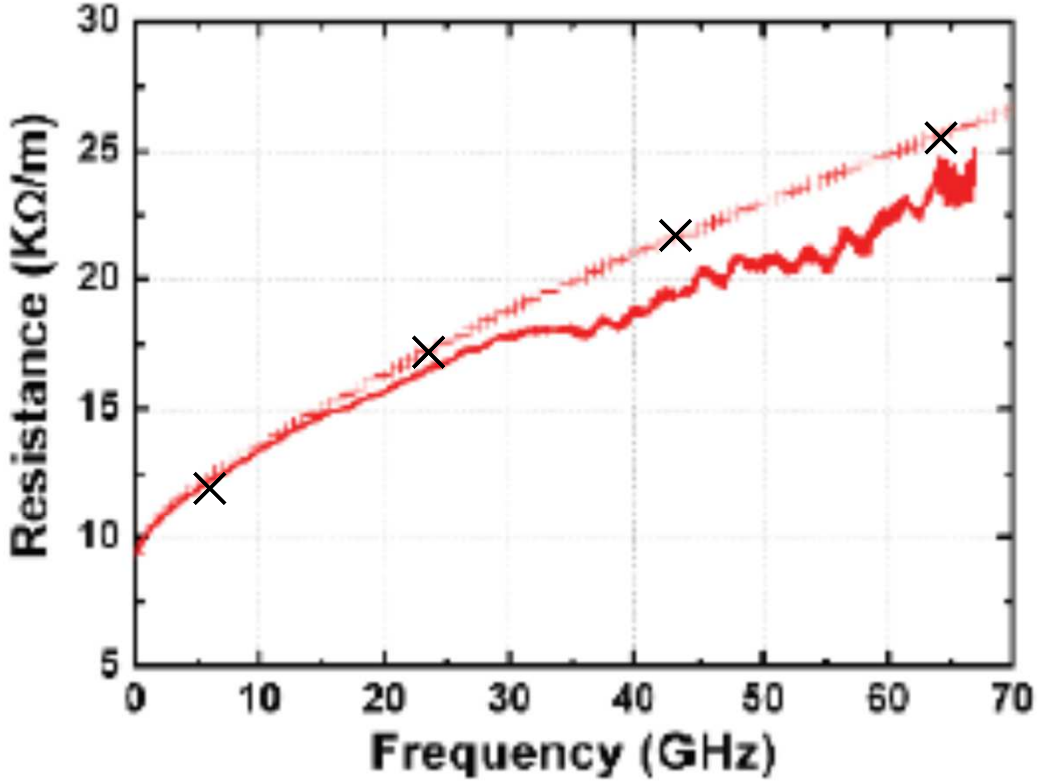


Good agreement over the frequency band => method is validated

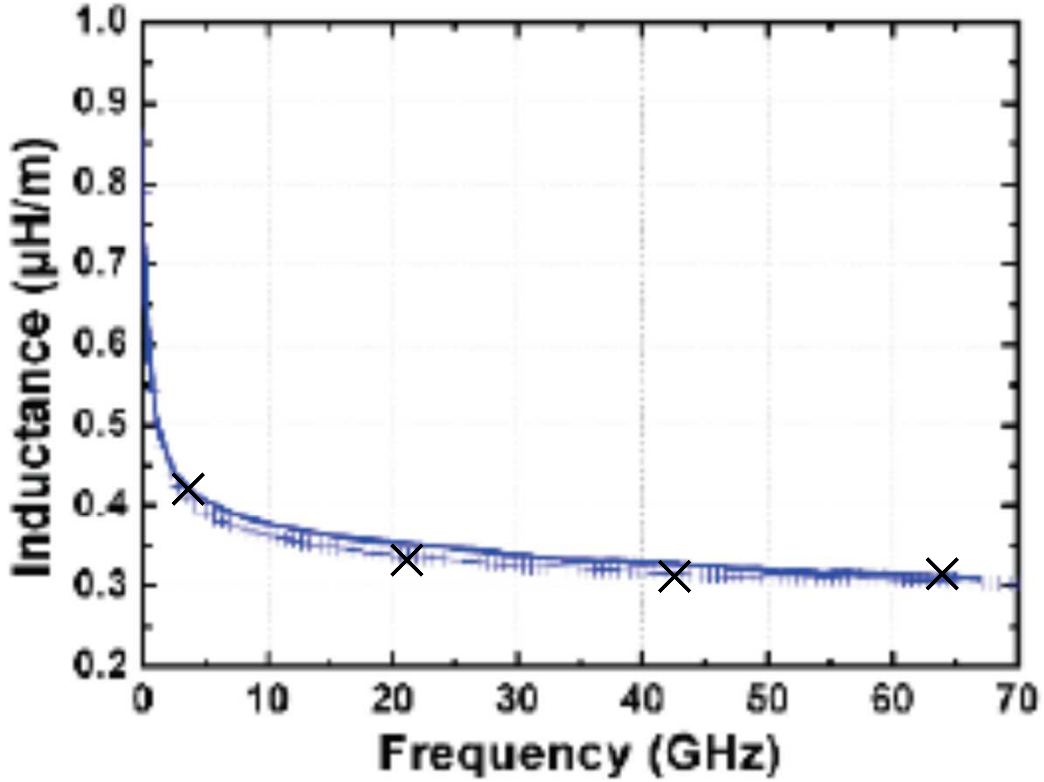
Experimental results

R, L parameters results - Comparisons to Q3D simulations

R parameter



L parameter



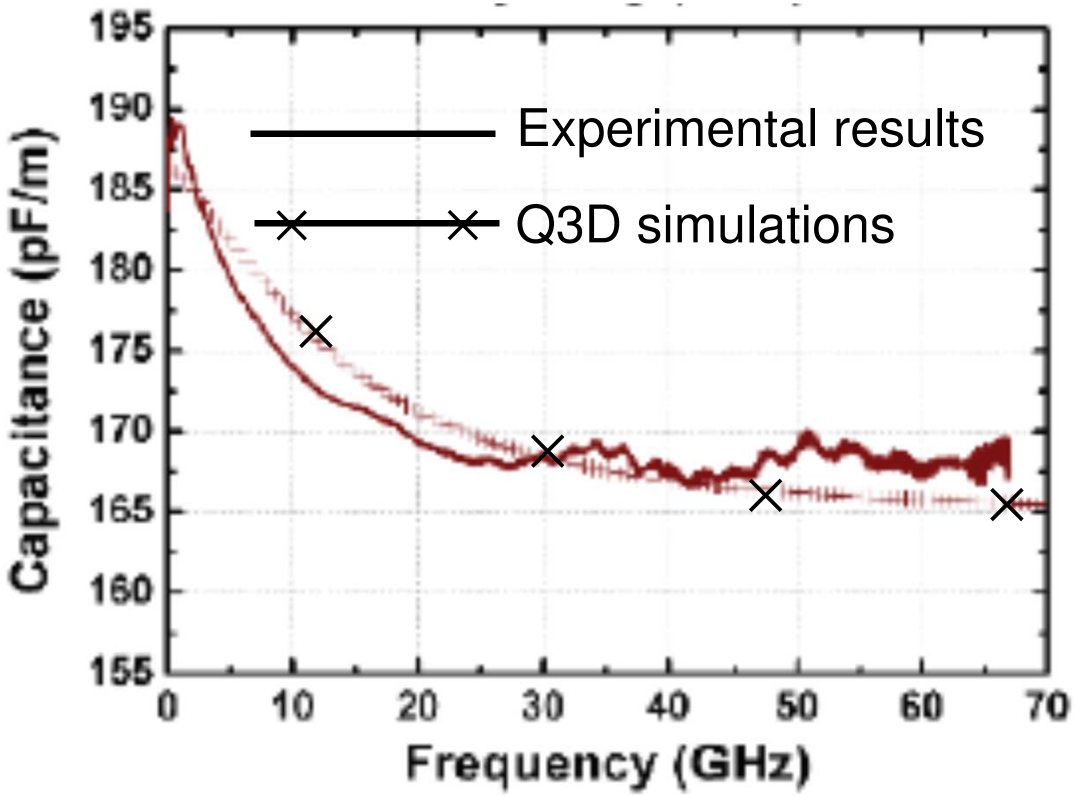
Experimental results

Q3D simulations

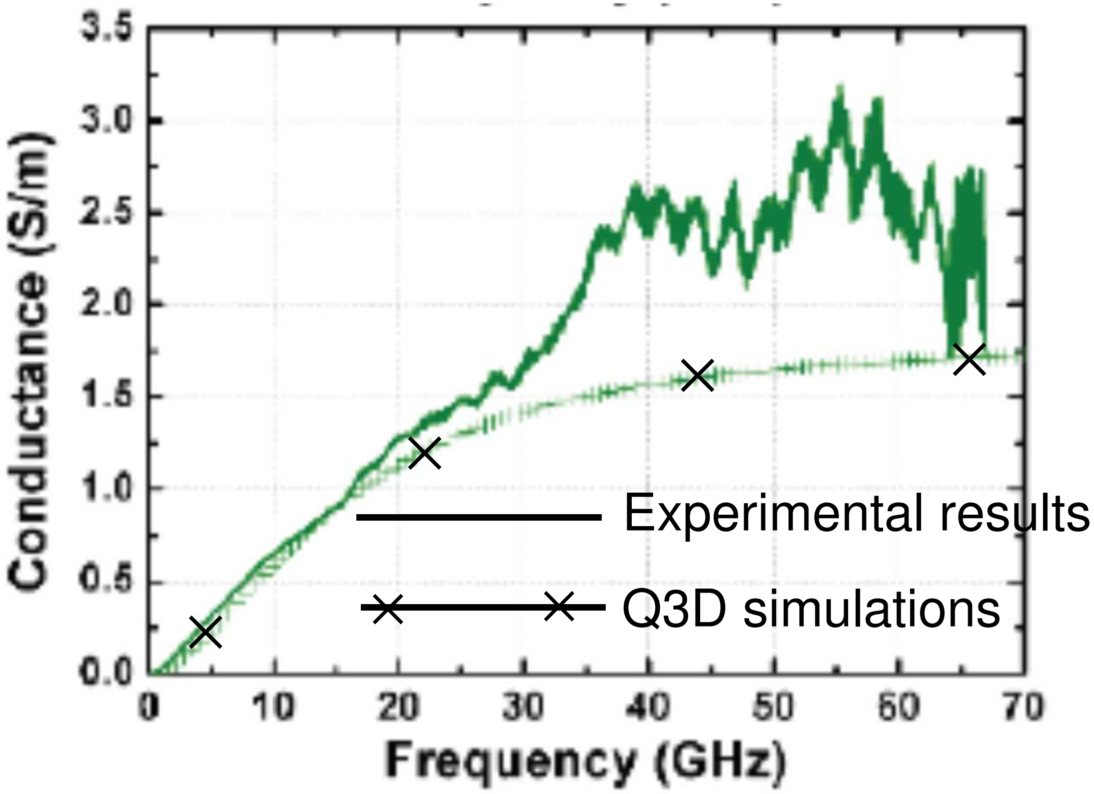
Experimental results

C, G parameters results - Comparisons to Q3D simulations

C parameter



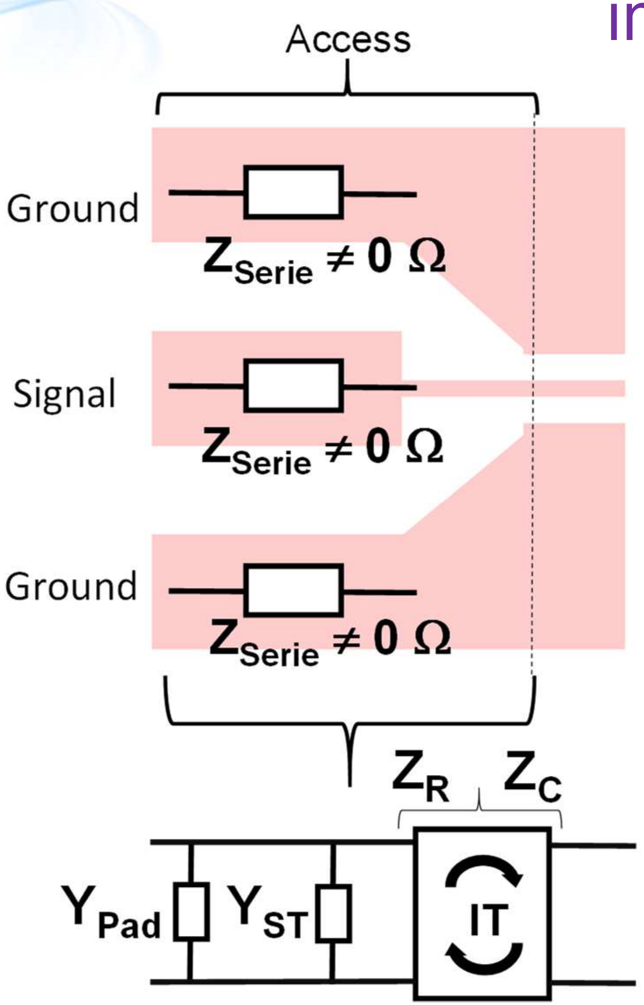
G parameter



Deviation beyond 30 GHz for G. Difficult to obtain G with accuracy due to its low impact on propagated signals at High Frequencies (G << C ω)

Robustness of the Method

What happens if the access has series impedances not negligible ?



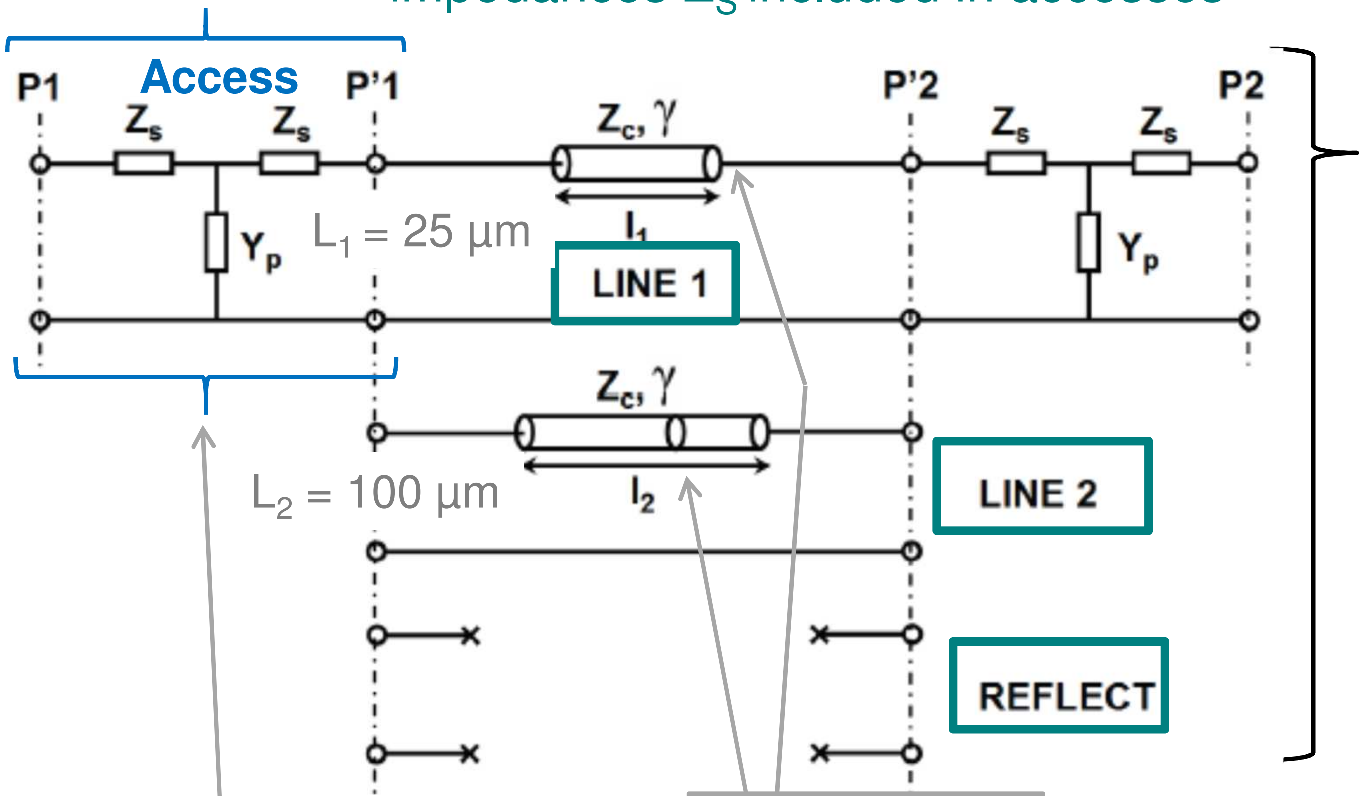
Electrical equivalent model used in the proposed method

Impact of the proposed method on extracted value of Z_C ?

Robustness of the Method

Process for checking the robustness

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



$Z_S = 0{,}015 + j\ 10^{-11} \times \omega$ (Ω)

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

R = 9 kΩ /m
L = 1 µH/m
G = 1 µS /m
C = 300 pF/m

Fabrication of 3 sets of S parameters

Applying the proposed method

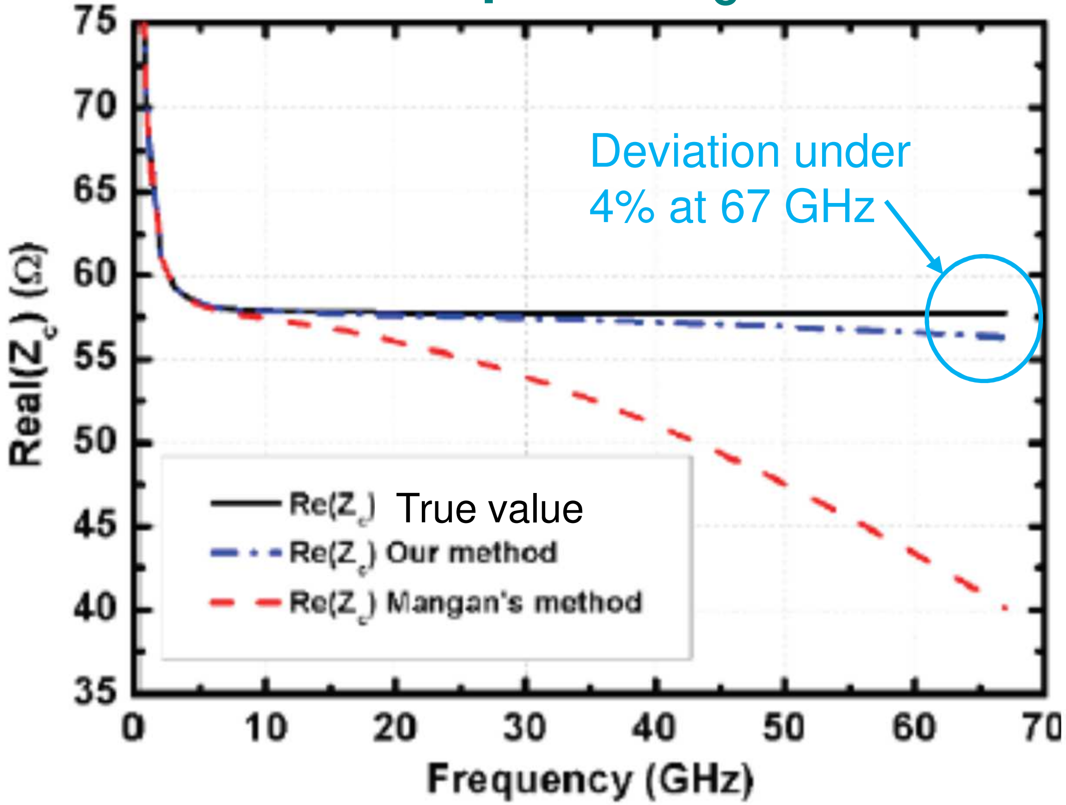
Deviation ?

Robustness of the Method

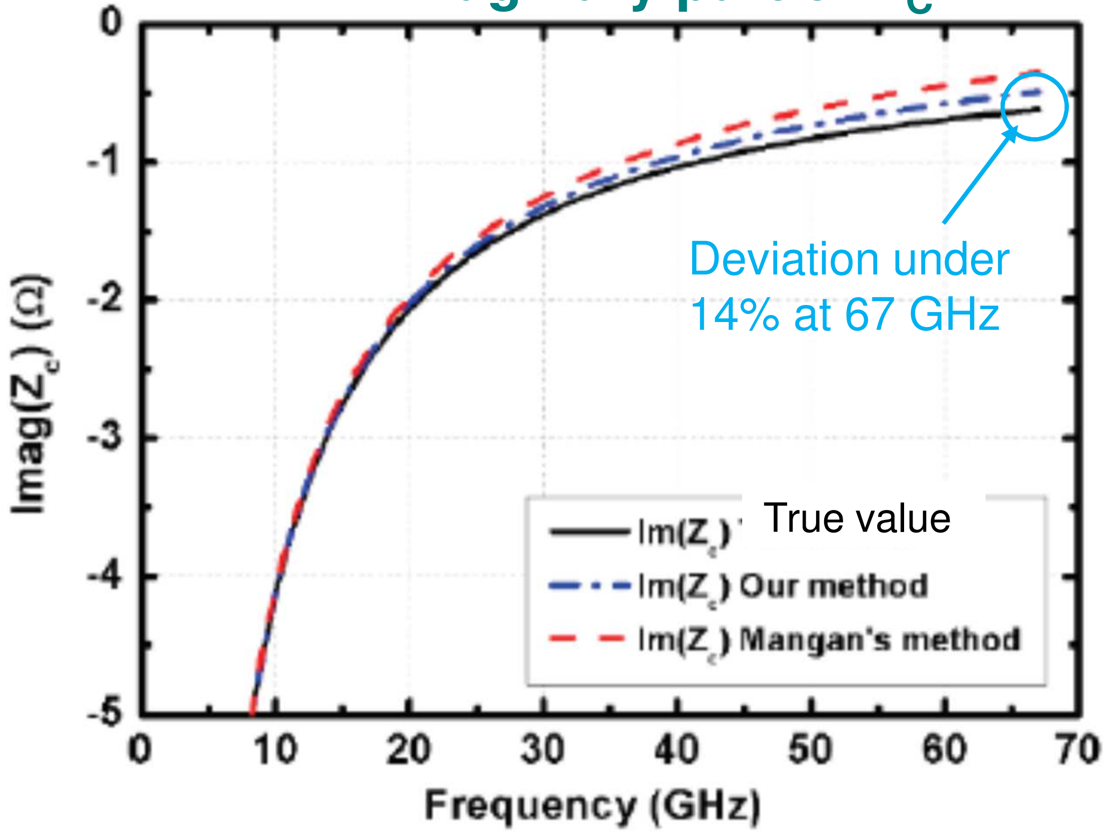
Results of Extracted Z_C

Comparison to the true characteristic impedance

Real part of Z_C



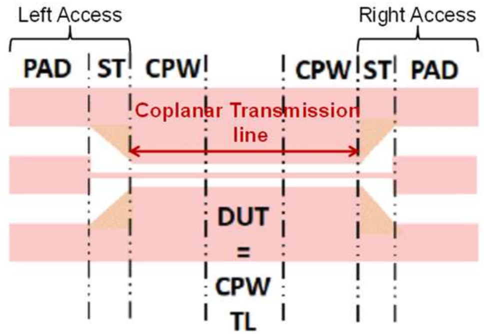
Imaginary part of Z_C



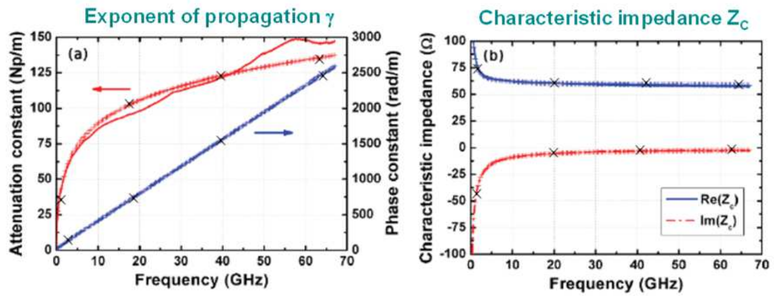
Good agreement over the frequency band => good robustness

Conclusion

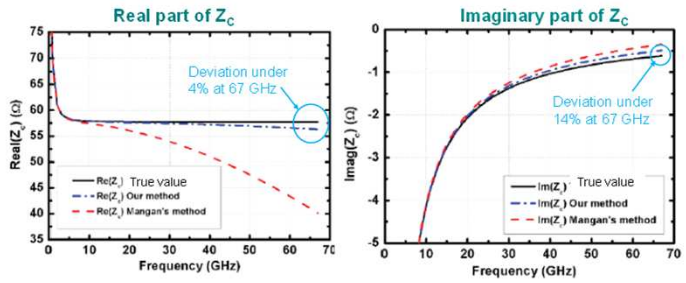
- Turnkey extraction method of a T.L. characteristic impedance proposed



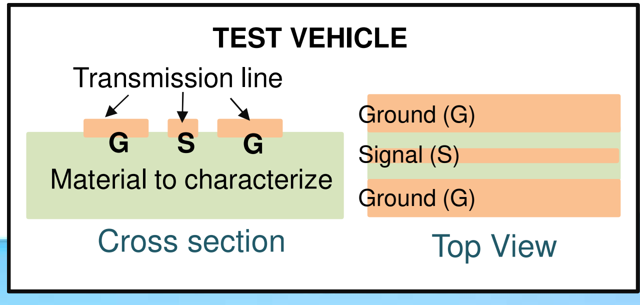
- Reliable method : good agreement with simulations



- Robust method for short accesses



- Perspective : Materials characterizations



Acknowledgement

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Thanks for your attention !

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