A New Frequency-Variant Transmission Line Parameter Determination Technique for Very High-Speed Signal Propagation Characterization

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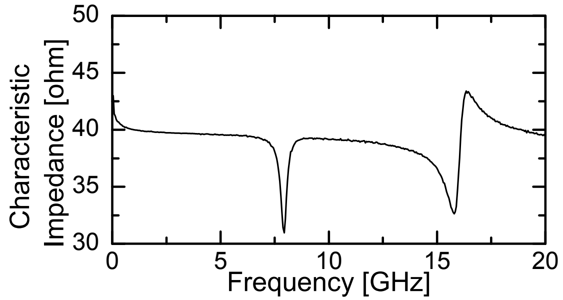
INTRODUCTION

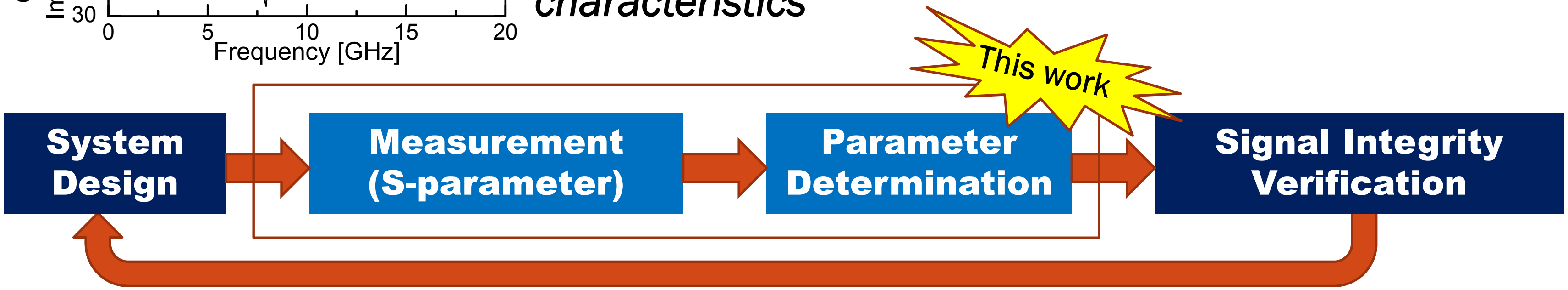
- Next generation integrated system will exceed several **tens of GHz** in its operating frequency.
- **Performance** of high-speed integrated system is **limited by interconnect lines.**
- **Signal integrity verification** of the data links is an integral part of high-speed circuit design.
- As data rate increases, signal loss mechanism in the interconnect lines becomes more complicated.
  - *Conductive loss (skin effect, metal roughness)*
  - *Dielectric loss (dielectric polarization, conductive leakage)*
- Due to **frequency-variant characteristics and non-ideal effects,**

Experimental characterization of transmission line is essential !!



Problem Definition

Inherent resonance effects during measurements make it difficult to understand experimental transmission line characteristics



Previous work

- D. F. Williams, R. B. Marks and A. Davidson, "Comparison of on-wafer calibrations," in *conf. ARFTG Dig.-Winter*, 1991, pp.68-81.
- D. F. Williams and R. B. Marks, “Accurate transmission line characterization,” *IEEE Trans. Microw. Guid. Wave Lett.*, vol. 3, pp.247-249, Aug. 1993.
- R. Torres-Torres, “Extracting characteristic impedance in low-loss substrates,” *Electronics Letters*, vol. 47, no. 3, pp. 191-193, Feb. 2011

Resonance-Effect-Free Parameter Determination

START

STEP 1

Determine characteristic impedance (Z_A) and propagation constant (γ_A) by using [3]

$$e^{-\gamma_A \ell} = \left[\frac{1 - S_{11}^2 + S_{21}^2}{2S_{21}} \pm \sqrt{\frac{(S_{11}^2 - S_{21}^2 + 1)^2 - (2S_{11})^2}{(2S_{21})^2}} \right], \qquad (Z_A)^2 = Z_{ref}^2 \frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}$$

STEP 2

Determine per-unit-length (PUL) transmission line(TL) parameters by using [3]

STEP 3

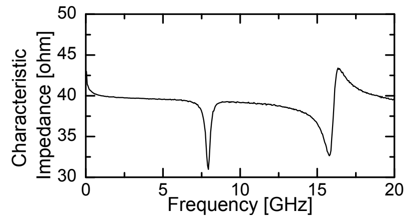
Determine effective loss tangent ($\tan\delta_{eff}$)

$$Z_A = \frac{\beta_A + \alpha_A \tan\delta_{eff}}{\omega C_A (1 + \tan^2 \delta_{eff})} - j \frac{\alpha_A + \beta_A \tan\delta_{eff}}{\omega C_A (1 + \tan^2 \delta_{eff})}, \qquad k \triangleq \frac{\mathrm{Re}(Z_A)}{\mathrm{Im}(Z_A)} = \frac{\beta + \alpha \tan\delta_{eff}}{-\alpha + \beta \tan\delta_{eff}}, \qquad \tan\delta_{eff} = \left| \frac{-\beta - k\alpha}{\alpha + k\beta} \right|$$

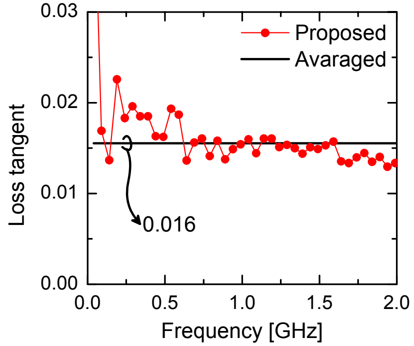
STEP 4

Determine resonance-effect-free (REF) capacitance (C_B) using different line lengths

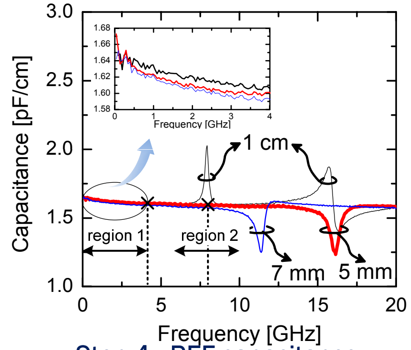
$$C_B(\omega) = \begin{cases} C_A(\omega) & f \le f_{stable} \\ C_A(\omega_{stable}) & f > f_{stable} \end{cases}, \qquad f_{resonance} = \frac{c}{\sqrt{\varepsilon_r}} \cdot \frac{1}{\lambda} = \frac{c}{\sqrt{\varepsilon_r}} \cdot \frac{1}{2l}$$



Step 1: Resonance-sensitive characteristic impedance



Step 3 : effective loss tangent



Step 4 : REF capacitance

[3] Y. Eo and W. R. Eisenstadt, "High-speed VLSI interconnect modeling based on S-parameter measurements," *IEEE Trans. Compon., Hybrids, Manuf. Technol.*, vol. 16, no. 5, pp. 555-562, Aug. 1993.

Resonance-Effect-Free Parameter Determination

STEP 5

Determine REF conductance (G_B) using C_B and $\tan\delta_{eff}$

$$G_B(\omega) = \tan\delta_{eff} \cdot \omega C_B(\omega)$$

STEP 6

Determine REF resistance (R_B) and inductance (L_B)

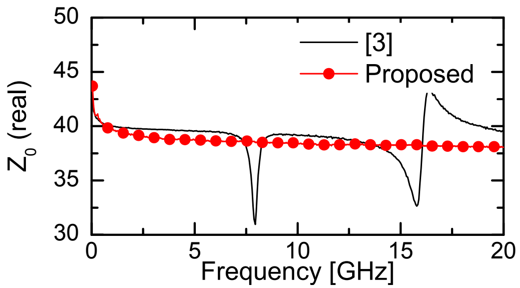
$$R_B(\omega) = \mathrm{Re}\left[\gamma_A^2(\omega)/\left(G_B(\omega)+j\omega C_B(\omega)\right)\right], \quad L_B(\omega) = \mathrm{Im}\left[\gamma_A^2(\omega)/\left(G_B(\omega)+j\omega C_B(\omega)\right)\right]/\omega$$

DONE !!

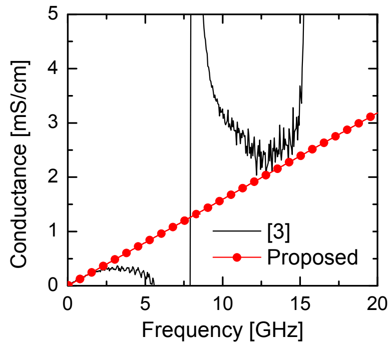
RESULT

REF Characteristic impedance (Z_B)

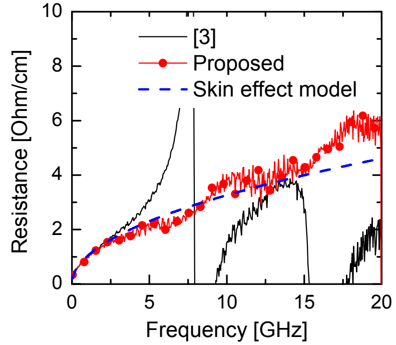
$$Z_B(\omega) = \sqrt{(R_B(\omega)+j\omega L_B(\omega))/(G_B(\omega)+j\omega C_B(\omega))}$$



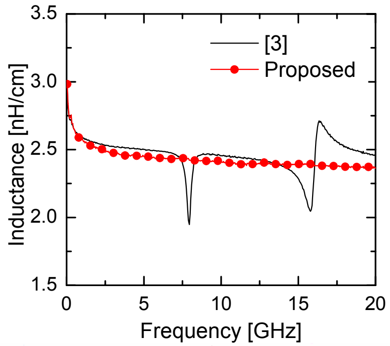
Resonance-Effect-Free characteristic impedance



Step 5 : REF conductance



Step 6 : REF resistnace

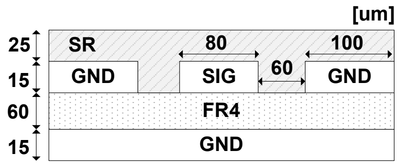


Step 6 : REF inductance

VERIFICATION

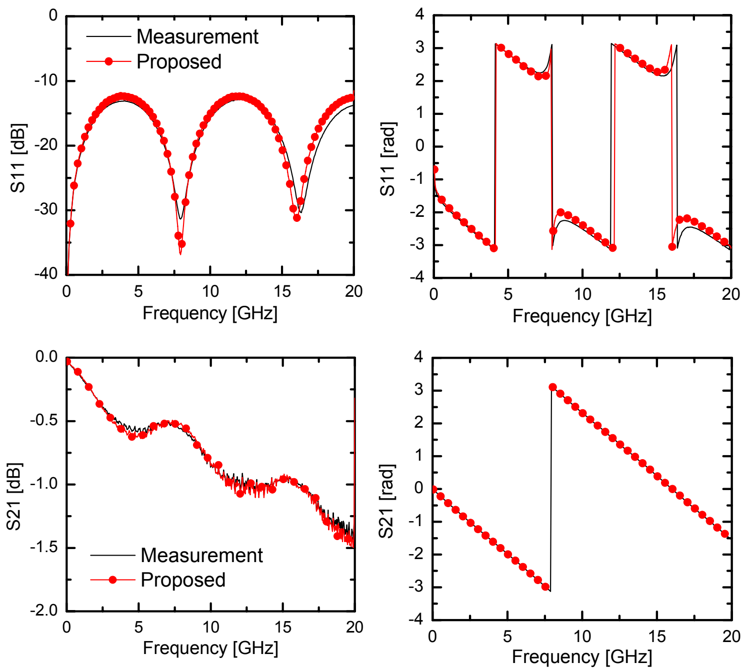
MEASUREMENT SETUP AND VERIFICATION PROCEDURE

1. Self-Verification



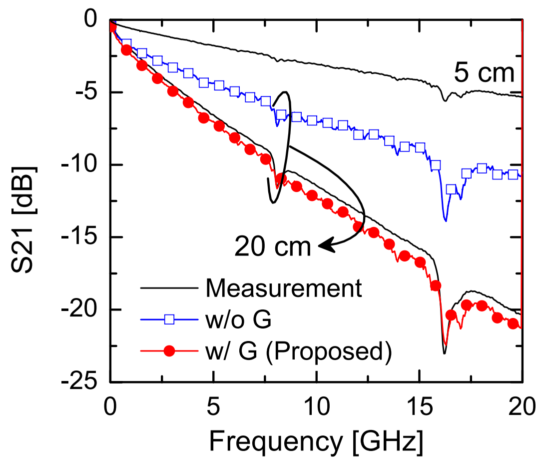
Nominal cross-section dimension

$\varepsilon_r = 4.2$
$\tan\delta = 0.011$ @ 1 GHz
$\tan\delta_{eff} = 0.016$ (proposed)

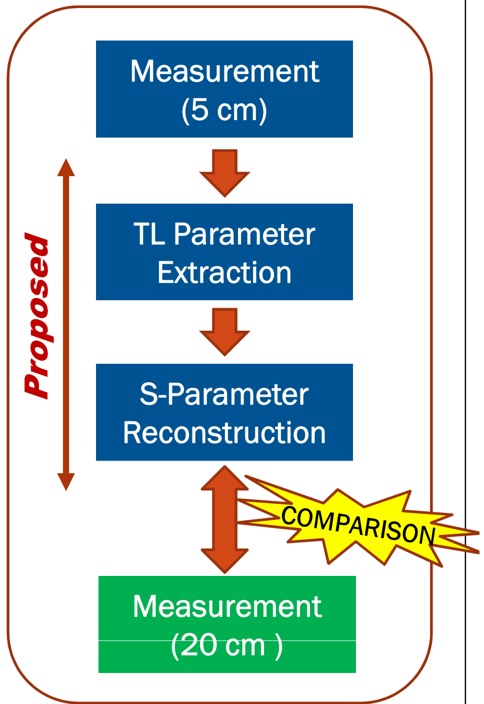


S-parameters of the measured and reconstructed data by the proposed method (1 cm)

2. Verification (Long line)



S-parameters of the measured and reconstructed data by proposed method



Measurement Setup	Model (Specification)
Probe	GGB, 40A-GSG-150-LP
ISS	Cascade, 101-190 B
Calibration	SOLT
VNA	Anritsu, 3724D
Frequency range	40 MHz ~ 20 GHz
Pad size	100 um X 100 um

CONCLUSION

- ***In High-speed circuits, various loss mechanisms should be considered.***
- ***Test patterns were experimentally characterized up to 20GHz by using VNA.***
- ***The resonance-effect-free network parameters for arbitrary line lengths were reconstructed.***
- ***The proposed technique is very helpful to understand transmission line characteristics.***
- ***Usefully exploited for the Accurate Signal Integrity Verification and Data Link Design of High-Performance Integrated Electronic Systems !!***