Broadband Electromagnetic and Stochastic Modelling and Signal Analysis of Multiconductor Interconnections

Electrical & Computer Engineering

University of Toronto

Distinguished Lecture Series 2017-2018

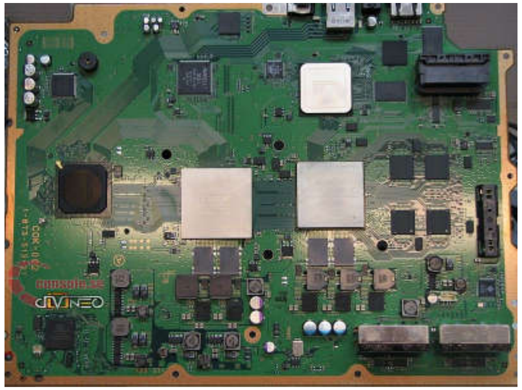
Daniël De Zutter (Fellow IEEE)

Ghent University
Dept. of Information Technology
Electromagnetics Group

Overview

- introduction
- RLGC-modelling of multiconductor lines
- variability analysis along the signal propagation direction
- analysis of statistical signals resulting from random variations in geometry, material properties, component values, linear and non-linear drivers and loads
- brief conclusions
- questions & discussion

How to model signal integrity?



PlayStation 3 motherboard

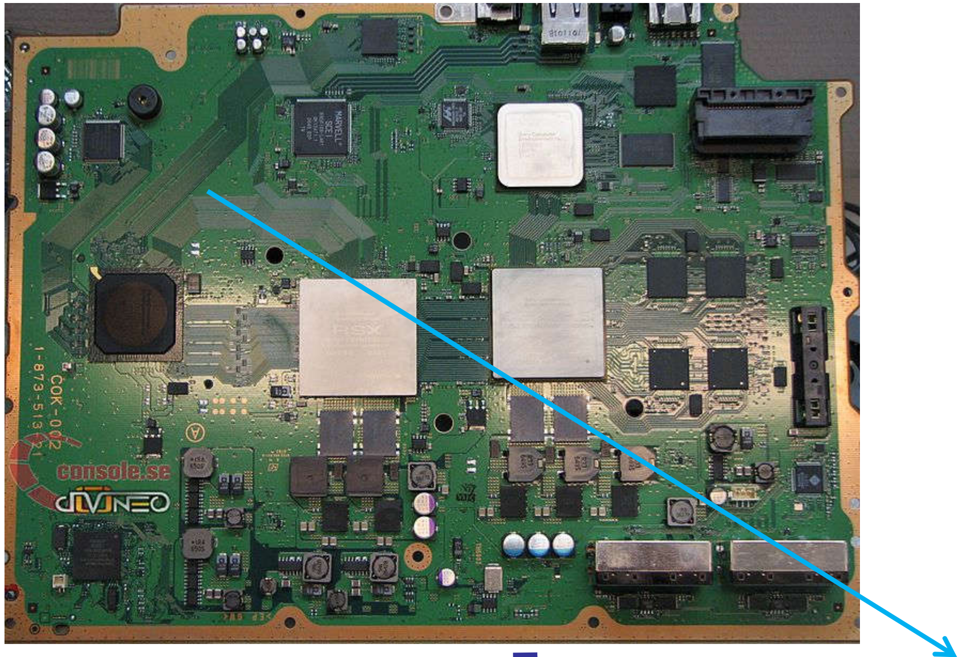
- full 3D numerical tools
  - → direct access to multiport S-parameters and time-domain data
  - → holistic but time-consuming
  - → (some times too easily) believed to be accurate

- divide and conquer
  - → **multiconductor lines**, vias, connectors, packages, chips, ….
  - → model each of them with a dedicated tool
  - → derive a circuit model for each part
  - → obtain the S-parameters and time-domain data (eye-diagram, BER, crosstalk) from overall circuit representation
  - → gives more insight to the designer (optimisation)
  - → overall accuracy might be difficult to assess

Multiconductor Transmission Lines

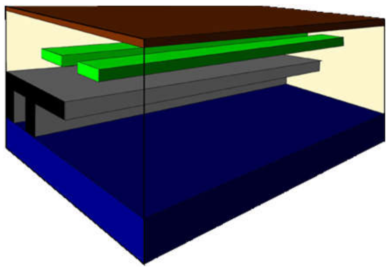
simplify (idealize) to a 2D problem

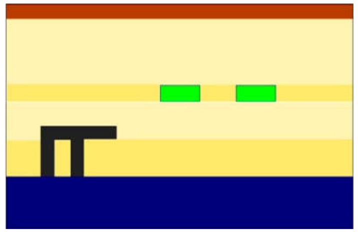
2D fields, charges, currents



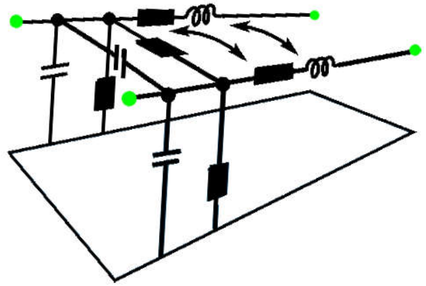
PlayStation 3 motherboard

3D fields, charges, currents





RLGC



Transmission lines voltages & currents

Telegrapher's equations (RLGC)

$$\frac{\partial \mathbf{i}}{\partial z} = -j\omega\tilde{\mathsf{C}}\mathbf{v} \qquad \tilde{\mathsf{C}} = \mathsf{C} + \mathsf{G}/j\omega$$

$$\frac{\partial \mathbf{v}}{\partial z} = -j\omega\tilde{\mathsf{L}}\mathbf{i} \qquad \tilde{\mathsf{L}} = \mathsf{L} + \mathsf{R}/j\omega$$

N+1 conductors one of which

plays the role of reference conductor

i : Nx1 current vector

v : Nx1 voltage vector

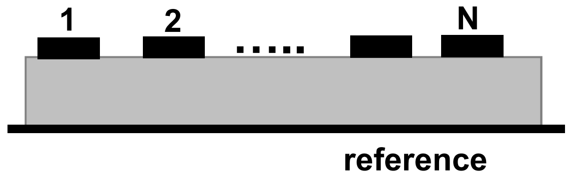
C : NxN capacitance matrix

L : NxN inductance matrix

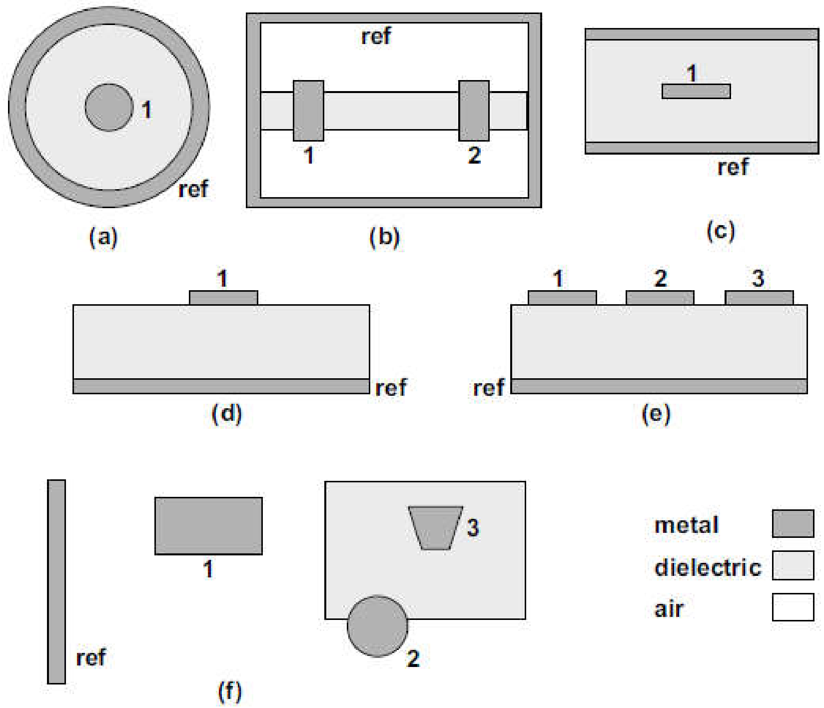
G : NxN conductance matrix

R : NxN resistance matrix

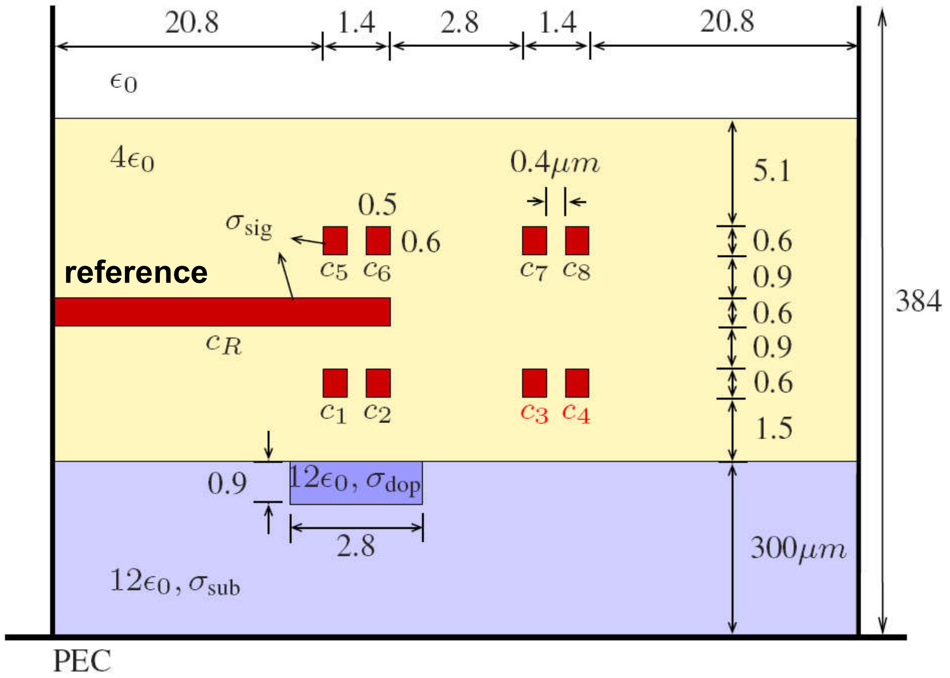
schematically



many possibilities



wish list number 1



- broadband results (time-domain)
- many regions (some semi-conducting)
- good conductors (e.g. copper)
- small details
- exact current crowding and skin effect modelling

+

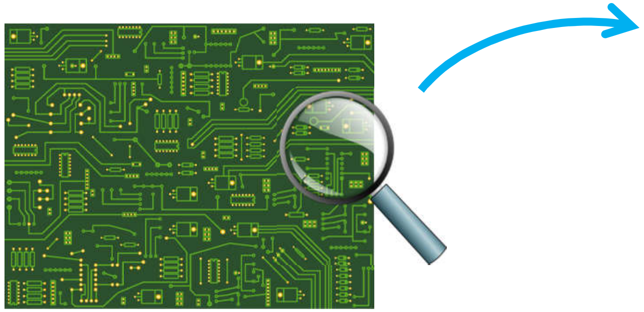
wish list number 2

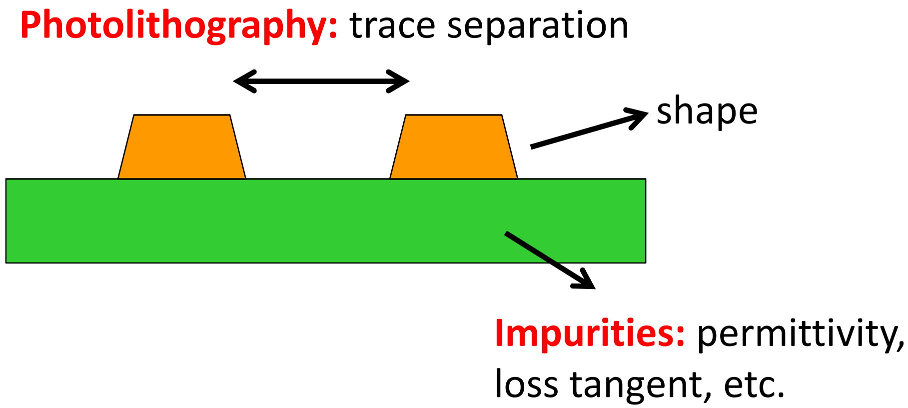
- variability in cross-section
- variability along propagation direction
- stochastic responses
- prediction of stochastics for overall interconnects (sources, via's, lines, ..)

on-chip interconnect example:

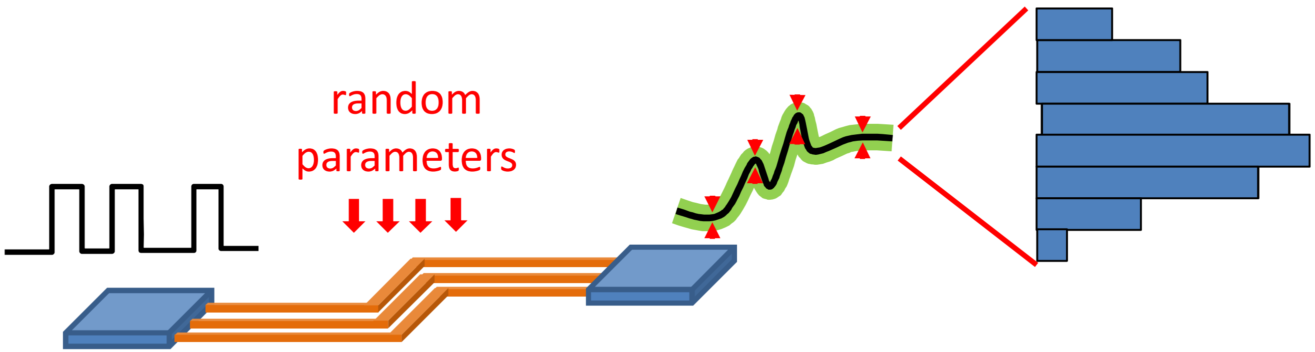
- 4 differential line pairs
- semi-conducting region
- unusual reference conductor

- The manufacturing process introduces **variability** in the geometrical and material properties but also along the signal propagation direction





- Deterministic excitations produce **stochastic responses**

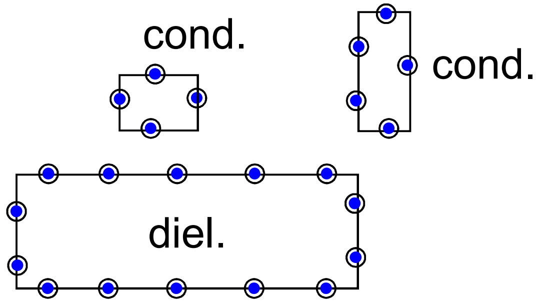


Overview

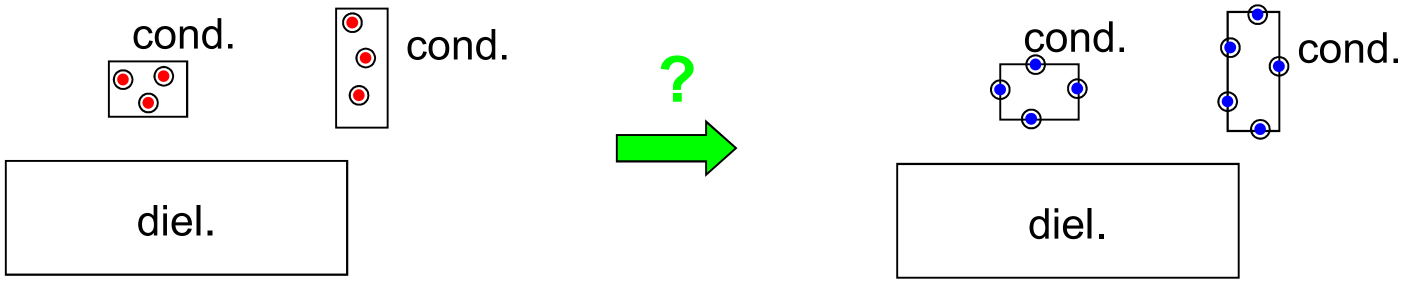
- *introduction*
- RLGC-modelling of multiconductor lines
- *variability analysis along the signal propagation direction*
- *analysis of statistical signals resulting from random variations in geometry, material properties, component values, linear and non-linear drivers and loads*
- *brief conclusions*
- *questions & discussion*

C and G can be found by solving a *classical potential problem* in the cross-section:

- sources/unknowns : (equivalent) boundary charges
- preferred method: boundary integral equation
- relation between total charges and voltages **Q** = $\boldsymbol{C}$ **V**

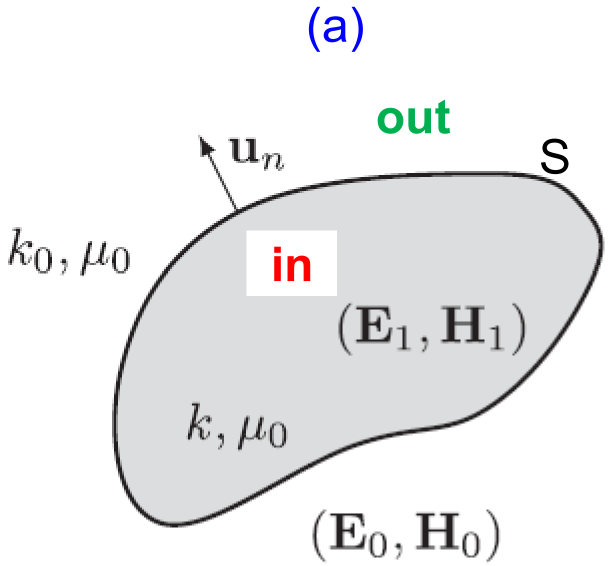


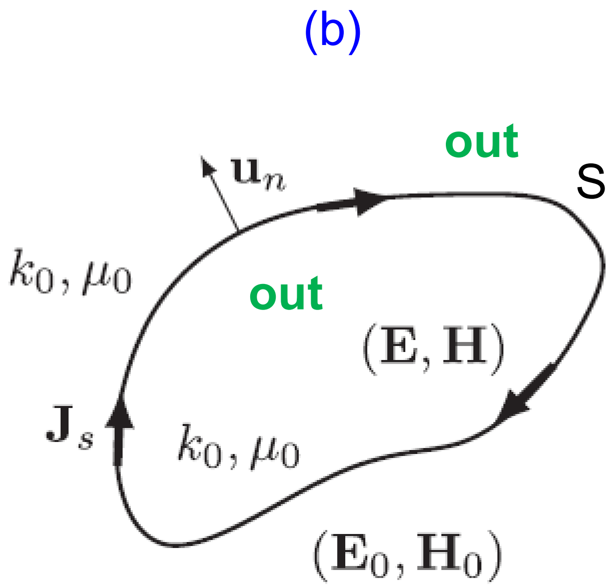
L and R could be found by determining the magnetic fields due to equivalent contrast currents $j_{eq,z} = (\sigma + j\omega(\epsilon - \epsilon_0))\, e_z$ placed in free space



Suppose we find a way to replace these currents by equivalent ones on the boundaries:

- sources/unknowns : equivalent boundary currents
- preferred method: EFIE with $e_z = -j\omega A_z - \dfrac{\partial \phi}{\partial z} \overset{on\ conductor}{=} -j\omega A_z - j\omega \tilde{L}\mathbf{i}$





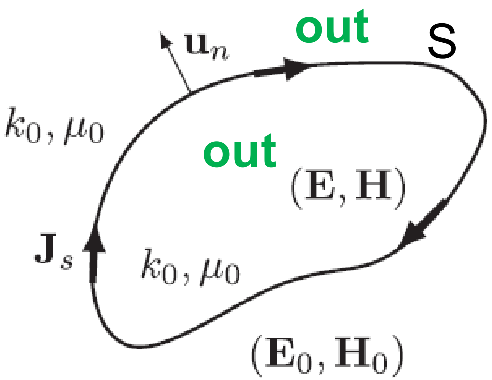
- two non-magnetic media “out” & “in”

(conductor, semi-conductor, dielectric)

- separated by surface S
- fields inside $\mathbf{E}_1$, $\mathbf{H}_1$
- fields outside $\mathbf{E}_0$, $\mathbf{H}_0$

- we introduce a fictitious (differential) surface current $\mathbf{J}_s$
- a single homogeneous medium “out”
- fields inside differ: $\mathbf{E}$, $\mathbf{H}$
- fields outside remain identical: $\mathbf{E}_0$, $\mathbf{H}_0$

Advantages



- modelling of the volume current crowding /skin-effect is avoided
- less unknowns are needed (volume versus surface)
- homogeneous medium: simplifies Green's function
- valid for all frequences
- losses from DC to skin effect + *"internal"* inductance

can all be derived from $\mathbf{J}_s$ and $\mathbf{E}_{tang}$ on S

Disadvantage or Challenge ☺

The sought-after $\mathbf{J}_S$ is related to $\mathbf{E}_{tang}$ through a non-local surface admittance operator

$$\mathbf{J}_S(\mathbf{r}) = \int_S \mathcal{Y}(\mathbf{r}, \mathbf{r}')\mathbf{E}_{tan}(\mathbf{r}')dS(\mathbf{r}') \quad \text{in 3D}$$

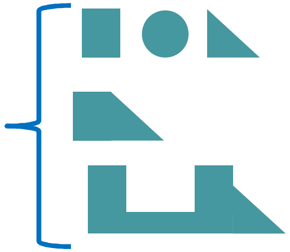
How to obtain $\mathcal{Y}$?

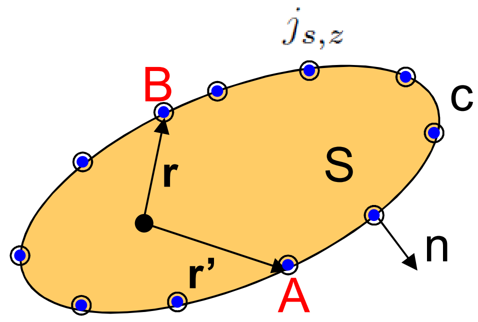
$$j_{s,z}(\mathbf{r}) = \int_c \mathcal{Y}(\mathbf{r}, \mathbf{r}')e_z(\mathbf{r}')dc(\mathbf{r}') \quad \text{in 2D}$$

admittance operator similar to $j_z(\mathbf{r}) = \sigma\, e_z(\mathbf{r})$ but no longer purely local !

in 2D $$j_{s,z}(\mathbf{r}) = \int_c \mathcal{Y}(\mathbf{r},\mathbf{r}')e_z(\mathbf{r}')dc(\mathbf{r}')$$

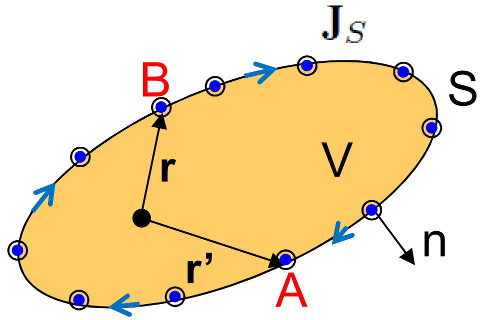
- analytically using the Dirichlet eigenfunctions of S



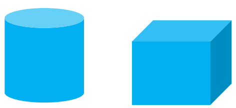


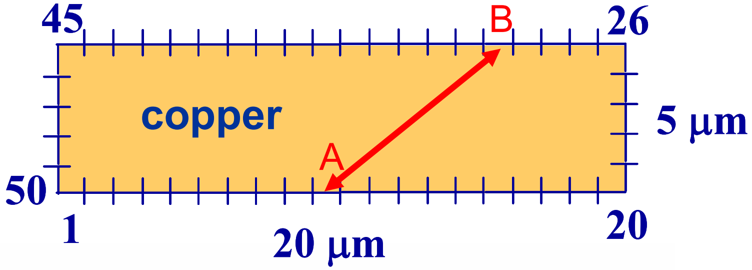
- numerically for any S using a 2D integral equation (prof. P. Triverio)

in 3D $$\mathbf{J}_S(\mathbf{r}) = \int_S \mathcal{Y}(\mathbf{r},\mathbf{r}')\mathbf{E}_{tan}(\mathbf{r}')dS(\mathbf{r}')$$

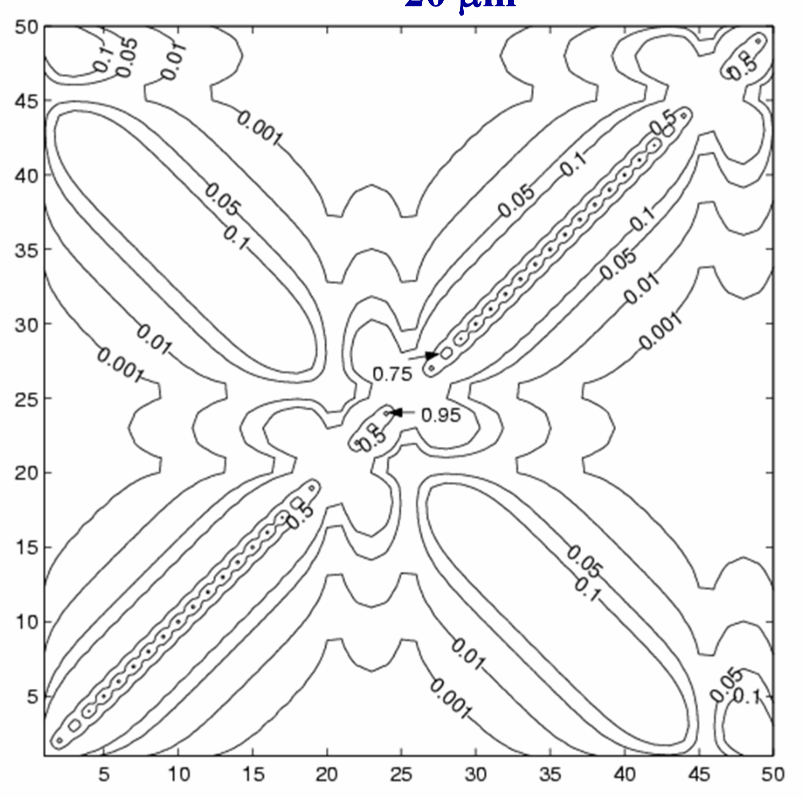


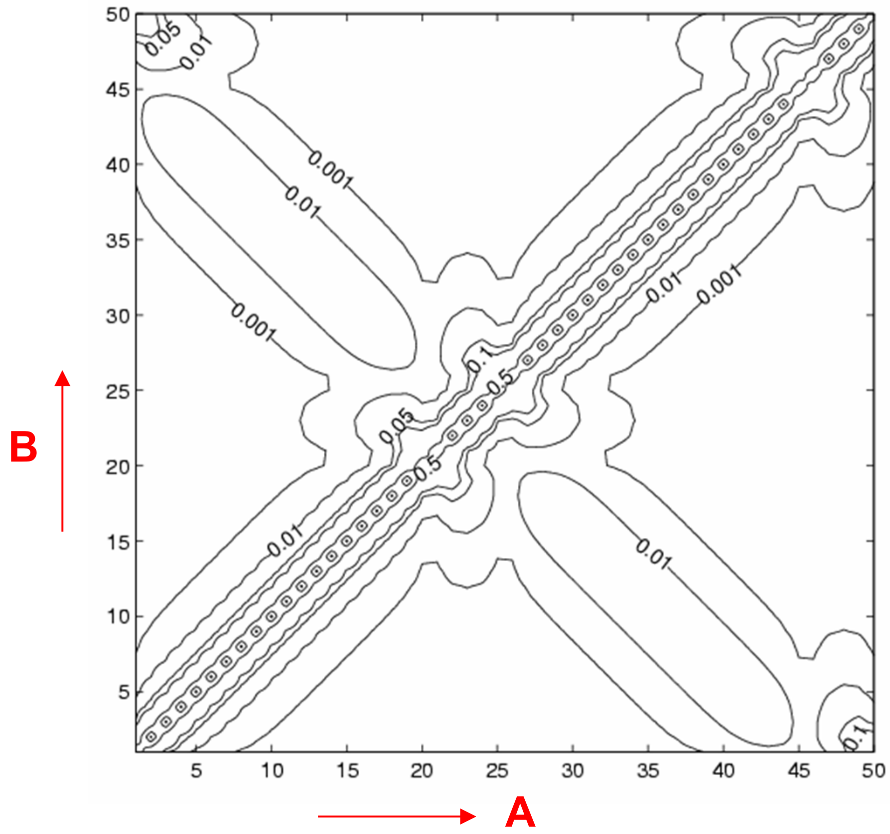
- analytically using the solenoidal eigenfunctions of the volume V
- see e.g. Huynen et al. AWPL, 2017, p. 1052





$$j_{c,z}(\mathbf{r}) = \int_{c_n} \underline{\mathcal{Y}(\mathbf{r},\mathbf{r}')} e_z(\mathbf{r}) dc(\mathbf{r}')$$

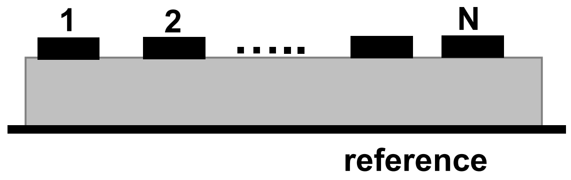




79.1 MHz - skin depth δ = 7.43 µm

10 GHz - skin depth δ = 0.66 µm $\left(\mathcal{Y}_{s,local} = \sqrt{\frac{j\omega\mu}{\sigma}}\right)$

Telegrapher's equations (RLGC)



$$\frac{\partial \mathbf{i}}{\partial z} = -j\omega \tilde{\mathsf{C}} \mathbf{v} \qquad \tilde{\mathsf{C}} = \mathsf{C} + \mathsf{G}/j\omega$$

$$\frac{\partial \mathbf{v}}{\partial z} = -j\omega \tilde{\mathsf{L}} \mathbf{i} \qquad \tilde{\mathsf{L}} = \mathsf{L} + \mathsf{R}/j\omega$$

Final result:

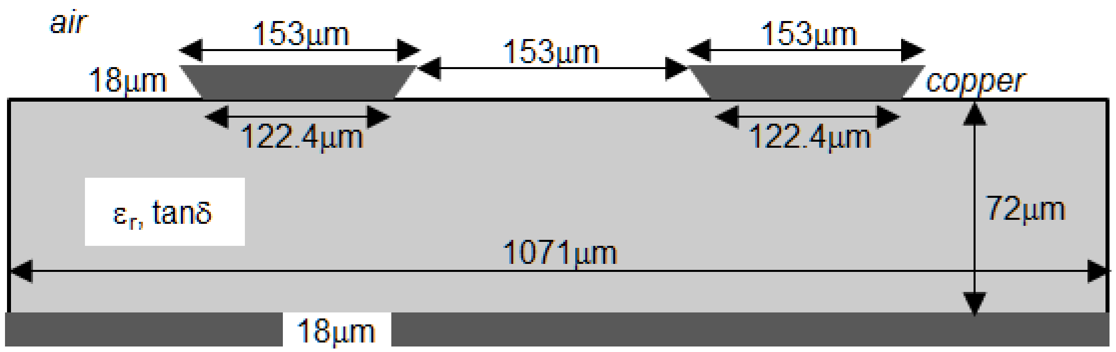
The 2-D per unit of length (p.u.l.) transmission line matrices **R, L, G,** and **C**, as a function of frequency

(see ref. [5])

wish list number 1

- broadband results ☺
- many regions (some semi-conducting) ☺
- good conductors (e.g. copper) ☺
- small details ☺
- exact skin effect modelling ☺

Differential line pair



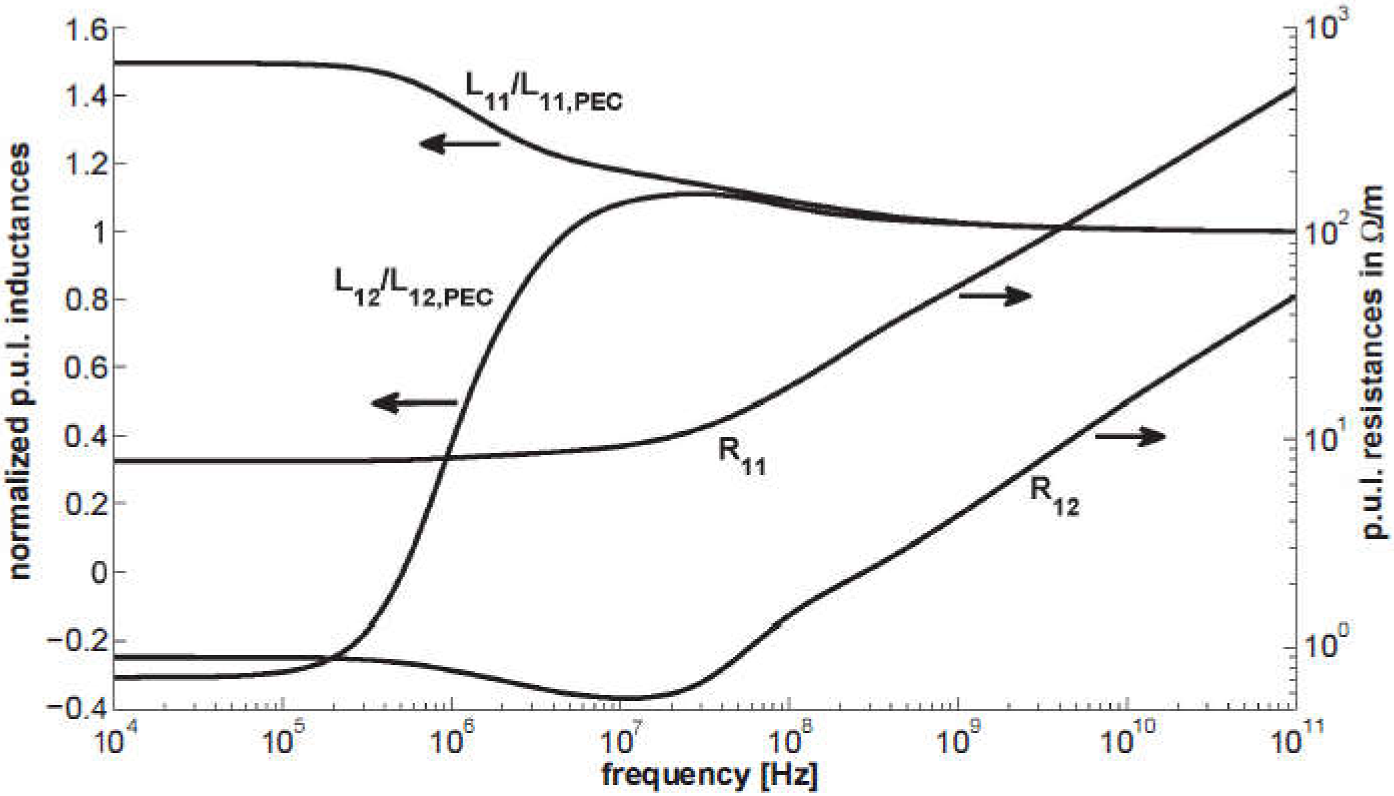
$\varepsilon_r = 3.2$

$\sigma_{copper} = 5.8\ 107$

$\tan\delta = \sigma/\omega\varepsilon_0\varepsilon_r = 0.008$

$\tilde{C}_{11} = \tilde{C}_{22} = (96.16 - j0.64)pF/m$ and $\tilde{C}_{12} = \tilde{C}_{21} = (-4.19 + j0.002)pF/m$

Differential line pair



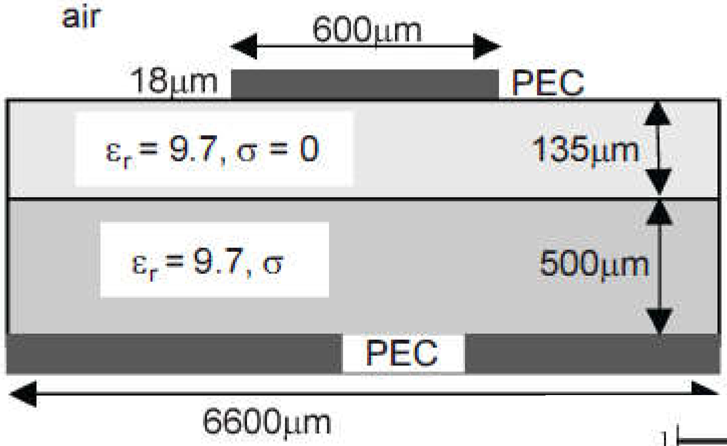
$L_{11,PEC}$=281.49nH/m $R_{11,DC}$=7.85Ω/m

$L_{12,PEC}$=30.15nH/m $R_{11,DC}$=7.85Ω/m

$L_{11} = L_{22}$ $R_{11} = R_{22}$

$L_{12} = L_{21}$ $R_{12} = R_{21}$

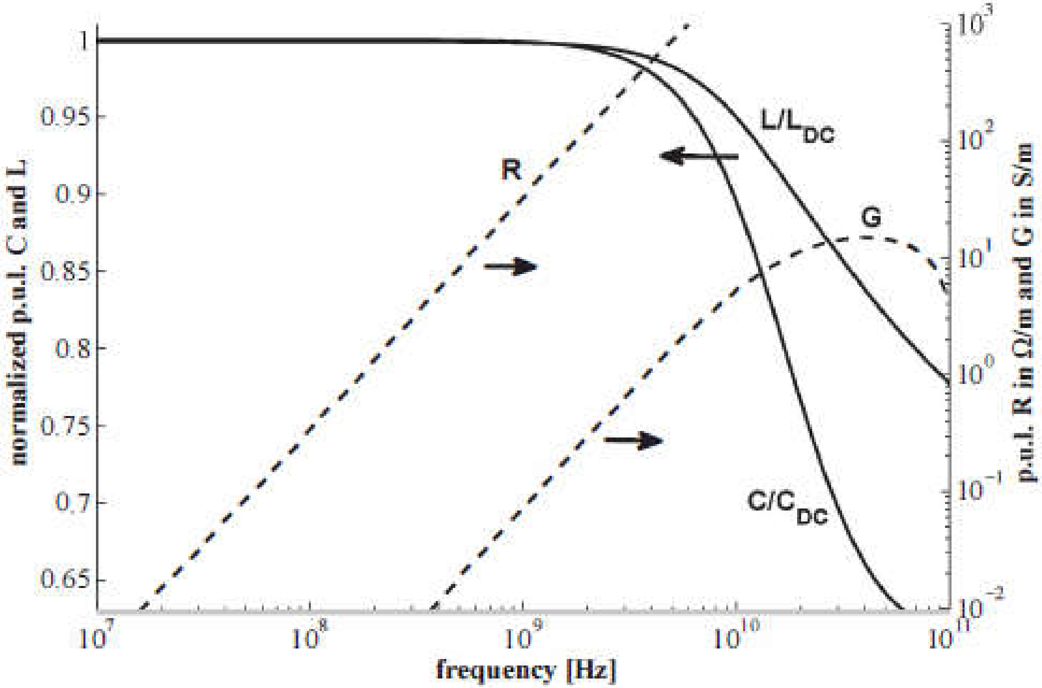
Metal Insulator Semiconductor (MIS) line



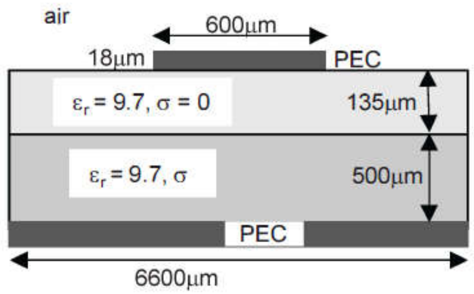
σ = 50S/m

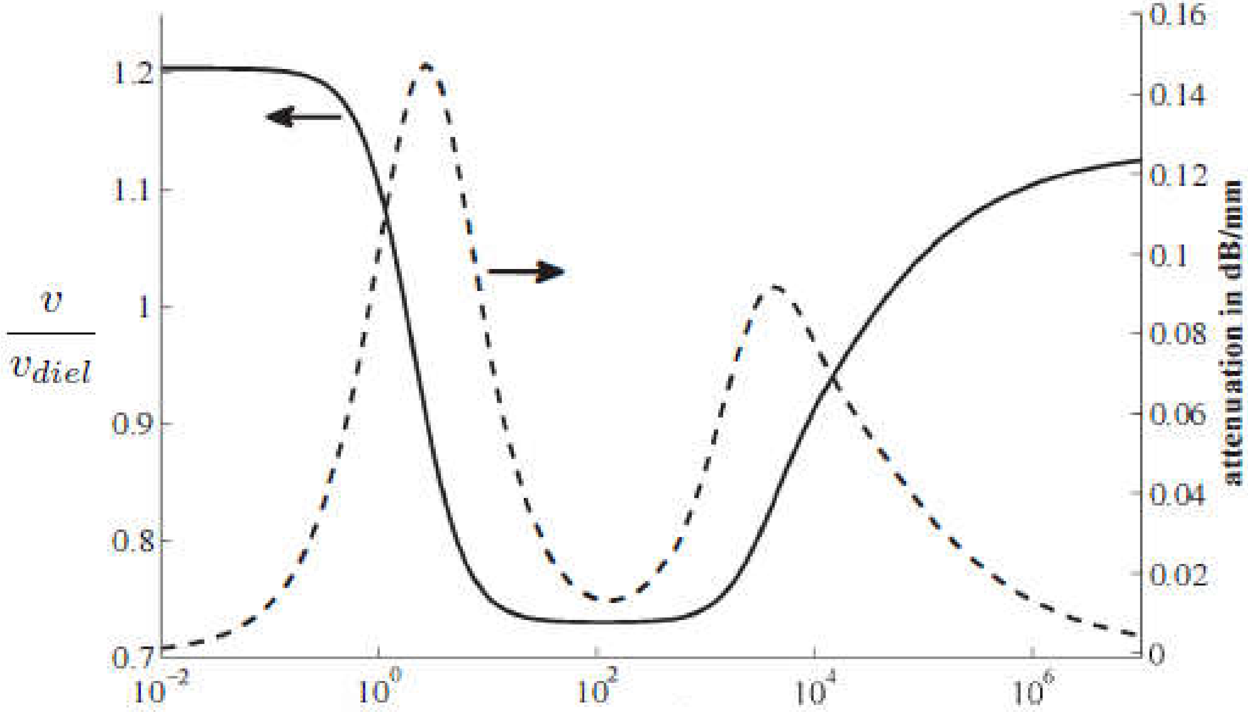
L_{DC} = 422.73nH/m

C_{DC} = 481.71pF/m



Metal Insulator Semiconductor (MIS) line @ 1GHz





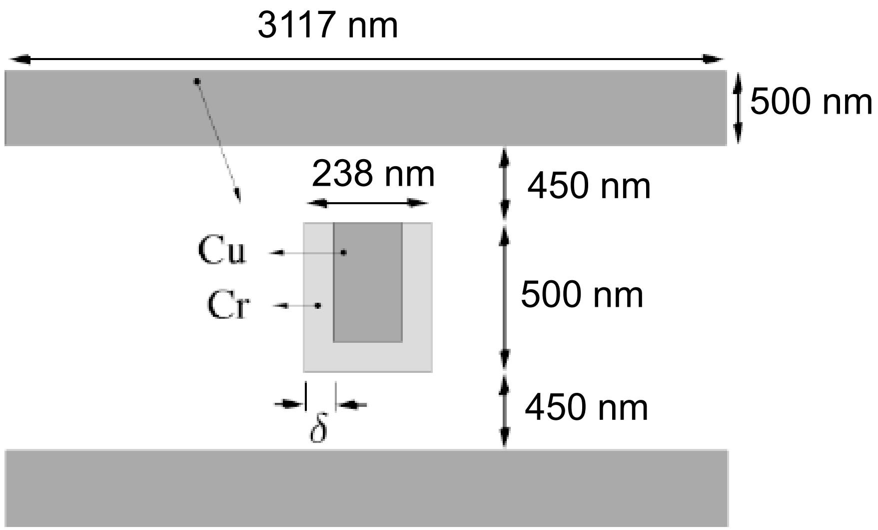
good dielectric $\tan\delta = \frac{\sigma}{\omega\epsilon}$ good conductor

$$v_{diel} = \frac{c}{\sqrt{\epsilon_r}} = 3.10^8/\sqrt{9.7} \ \ m/s$$

$$10^{-2} < \tan\delta < 10^7$$

$$0.0054 \ \ S/m < \sigma < 5.4\ 10^6 \ \ S/m$$

Coated submicron signal conductor



copper: 1.7 μΩcm

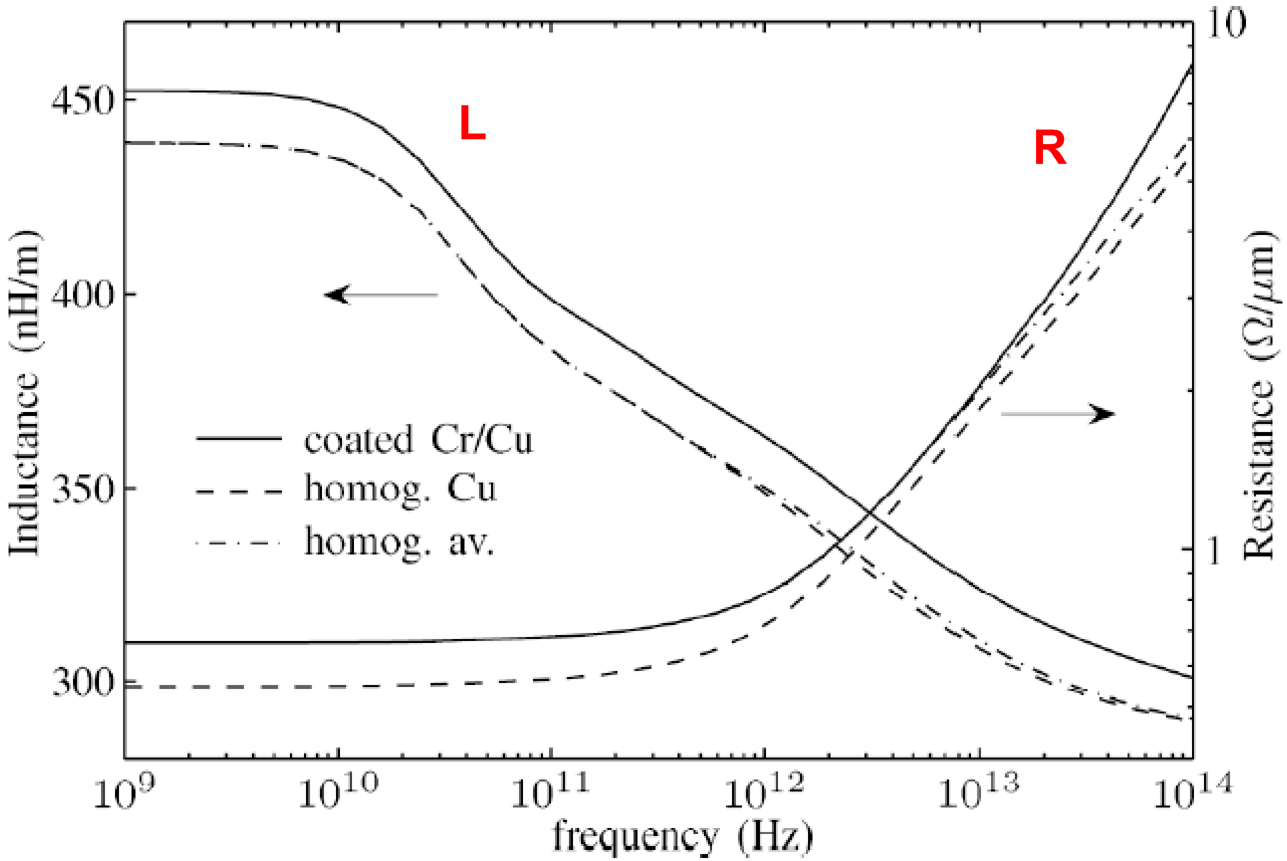
chromium: 12.9 μΩcm

coating thickness δ: 10 nm

UNIVERSITEIT GENT

FACULTY OF ENGINEERING

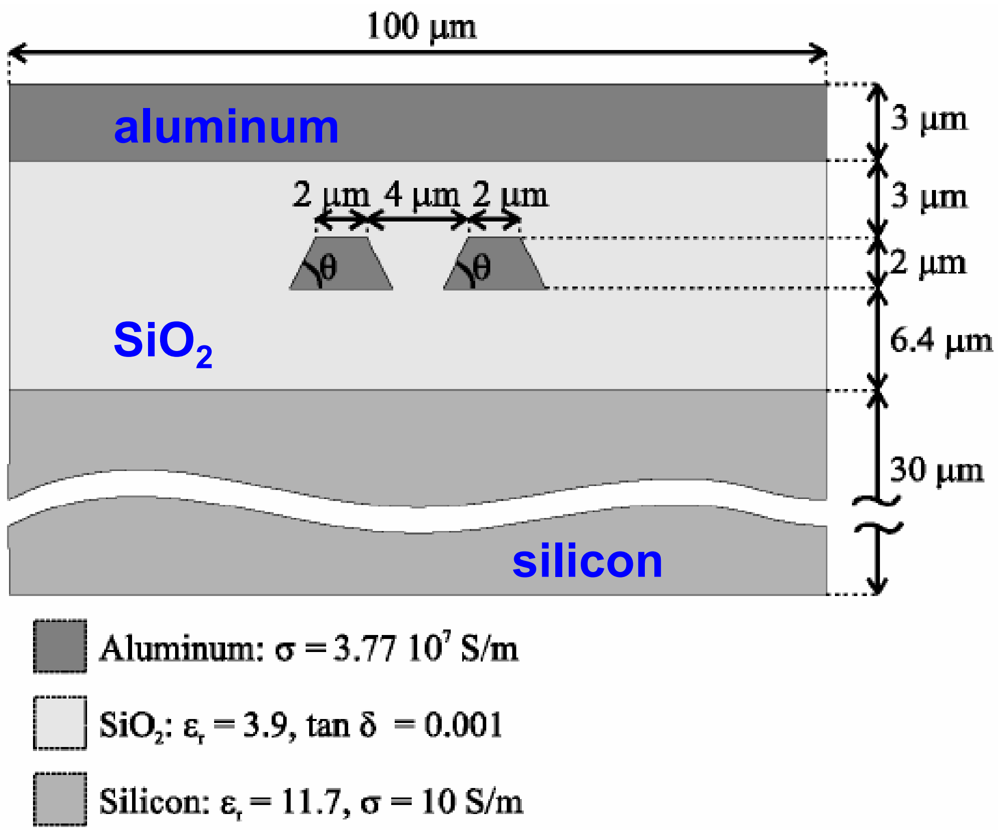
Coated submicron signal conductor



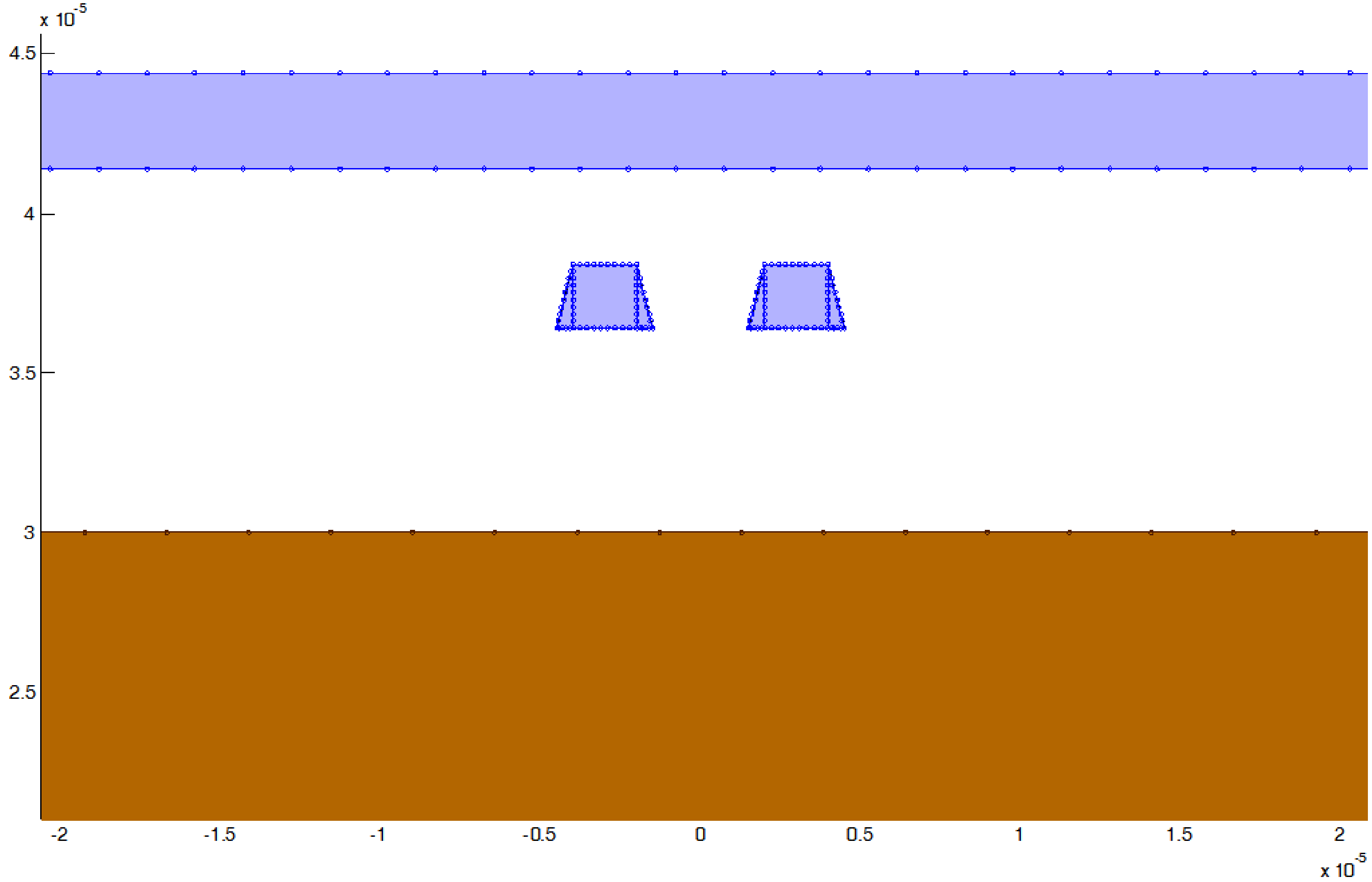
inductance and resistance p.u.l

as a function of frequency

Pair of coupled inverted embedded on-chip lines

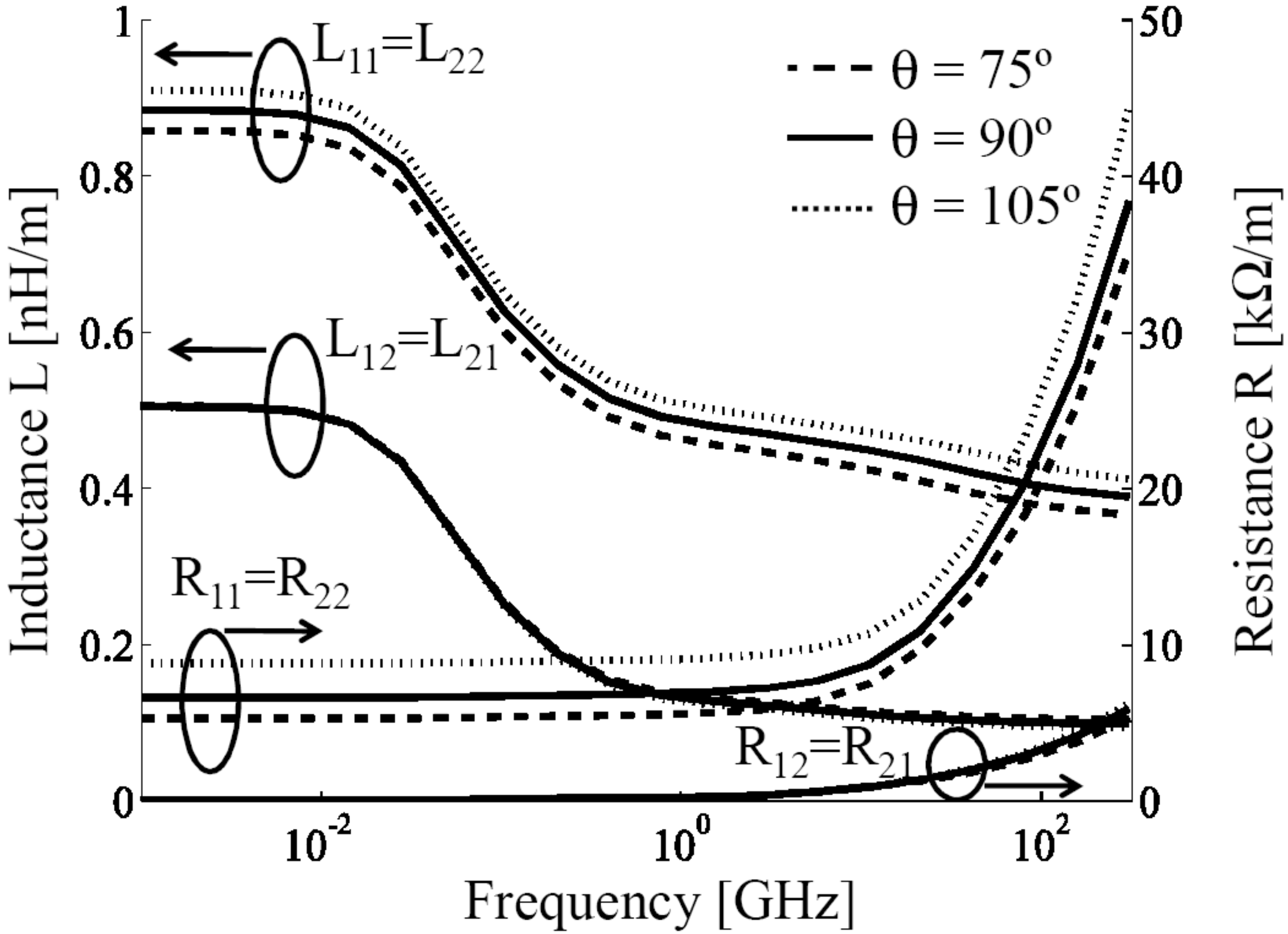


Pair of coupled inverted embedded on-chip lines



Discretisation for solving the RLGC-problem

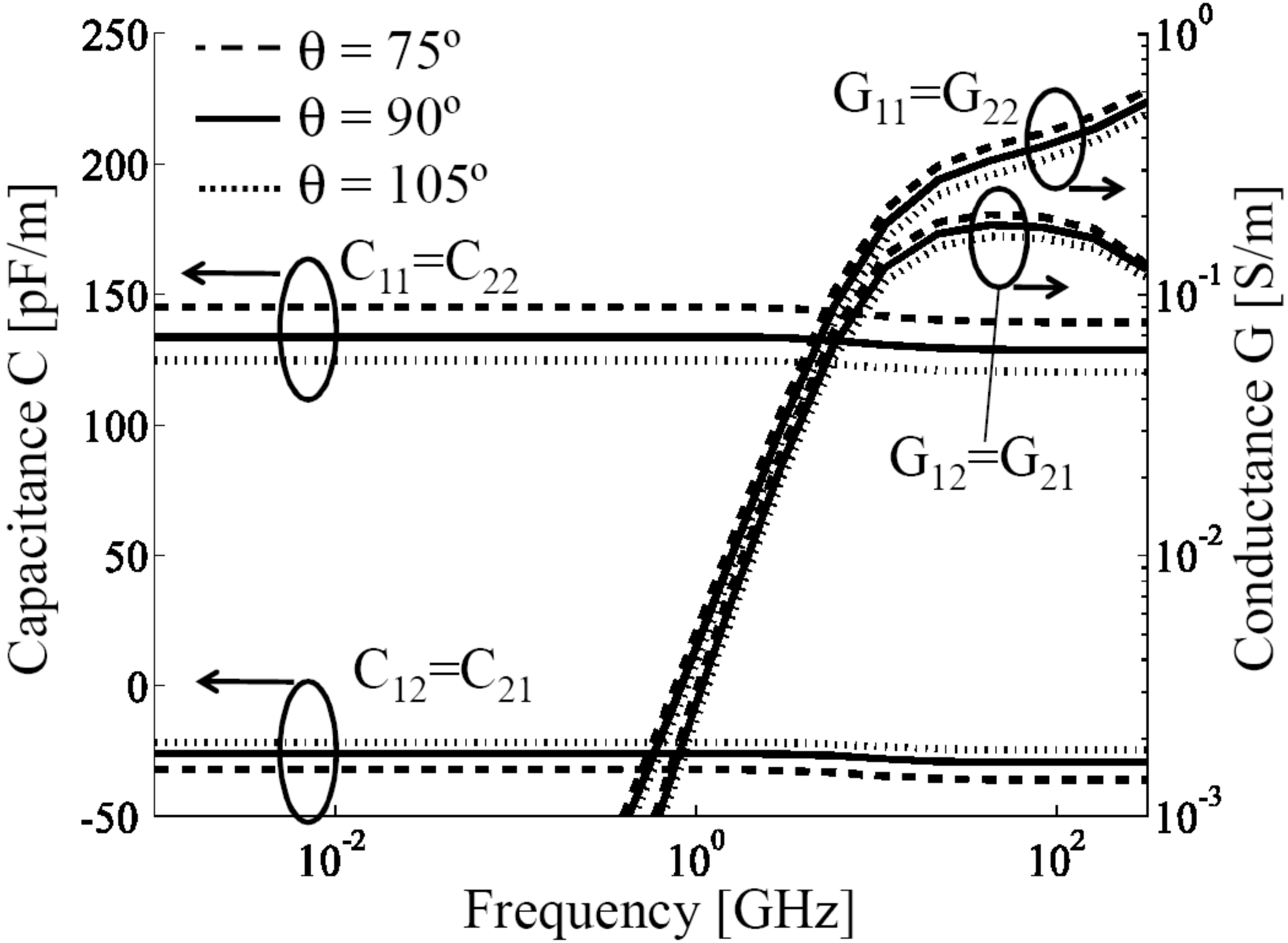
Pair of coupled inverted embedded on-chip lines: L and R results



UNIVERSITEIT GENT

FACULTY OF ENGINEERING

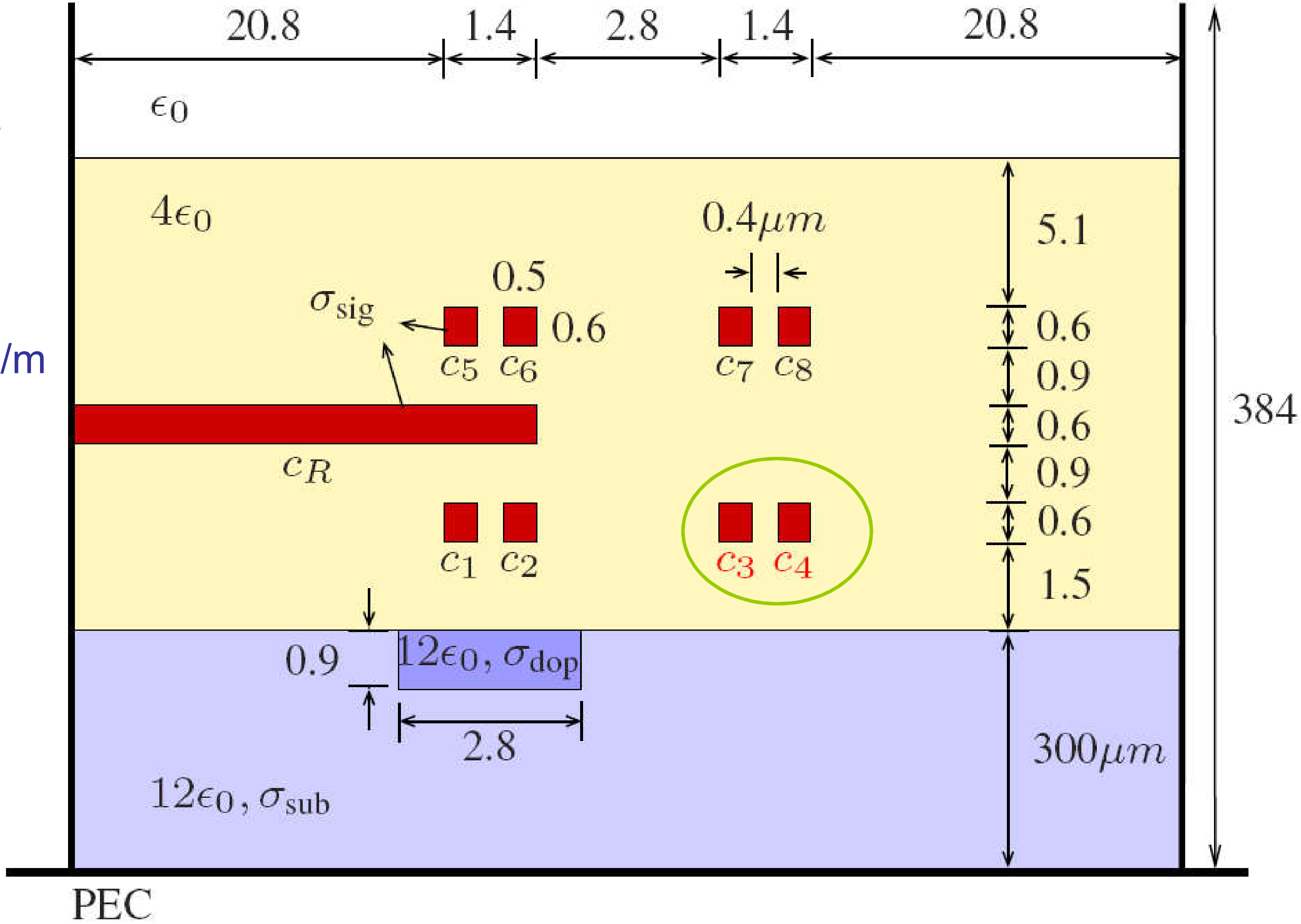
Pair of coupled inverted embedded on-chip lines: G and C results



UNIVERSITEIT GENT

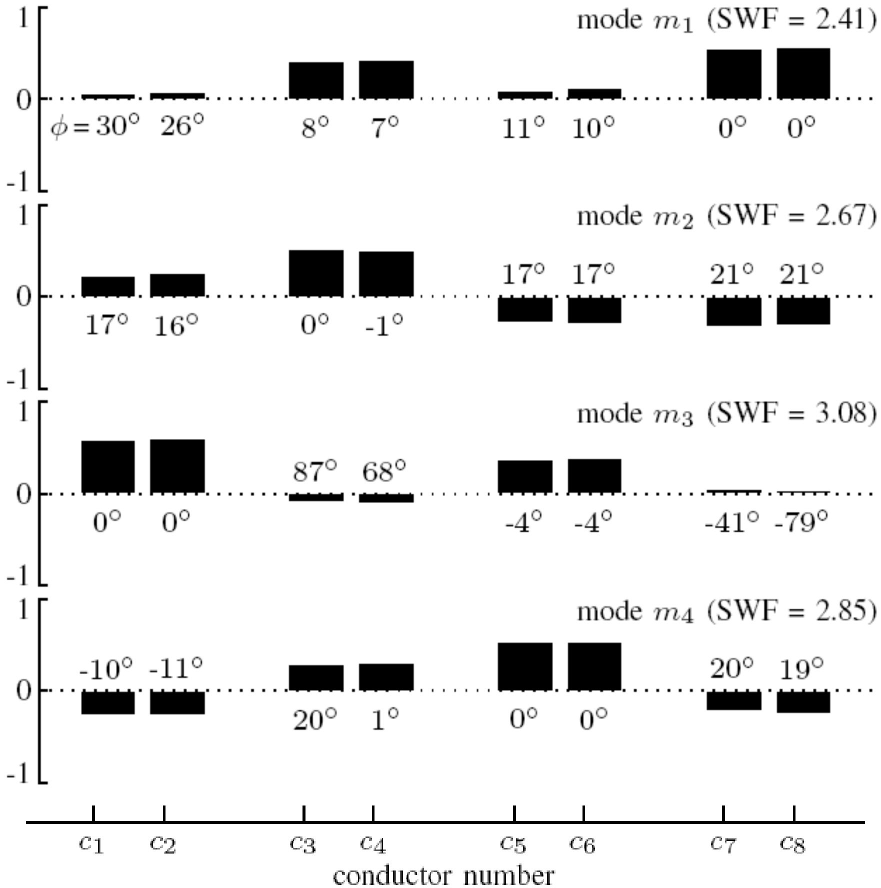
4 differential pairs on chip interconnect

+ all dimensions in μm
+ σ_{sig} = 40MS/m
+ σ_{sub} = 2S/m
+ σ_{dop} = 0.03MS/m

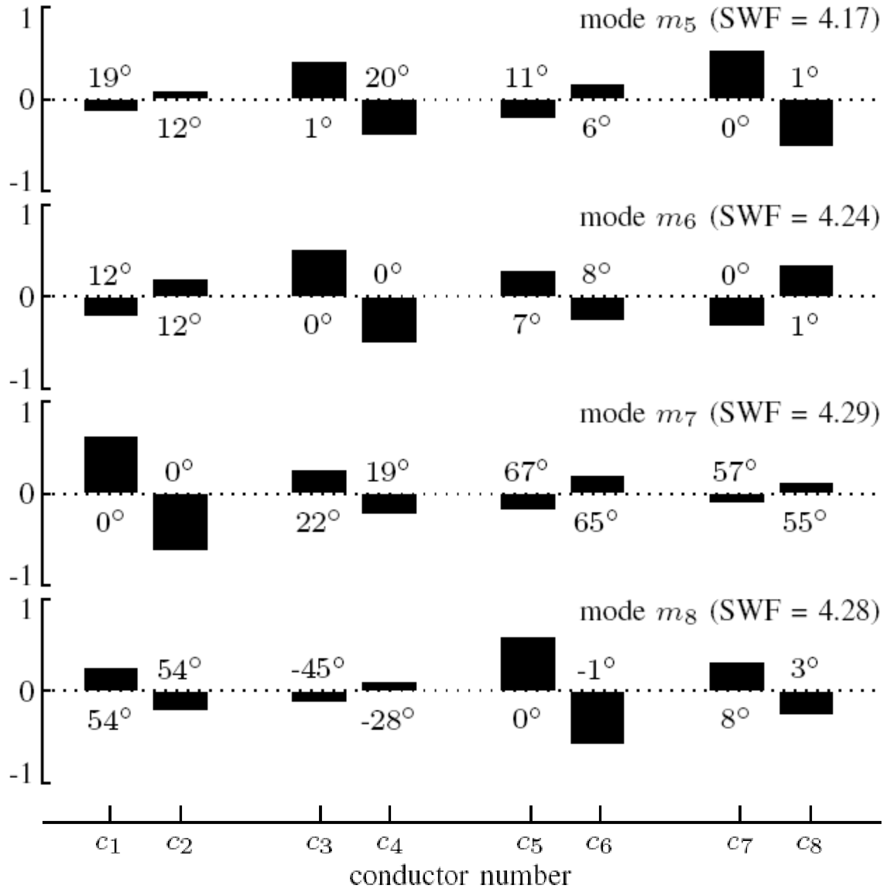


eight quasi-TM modes

quasi-even



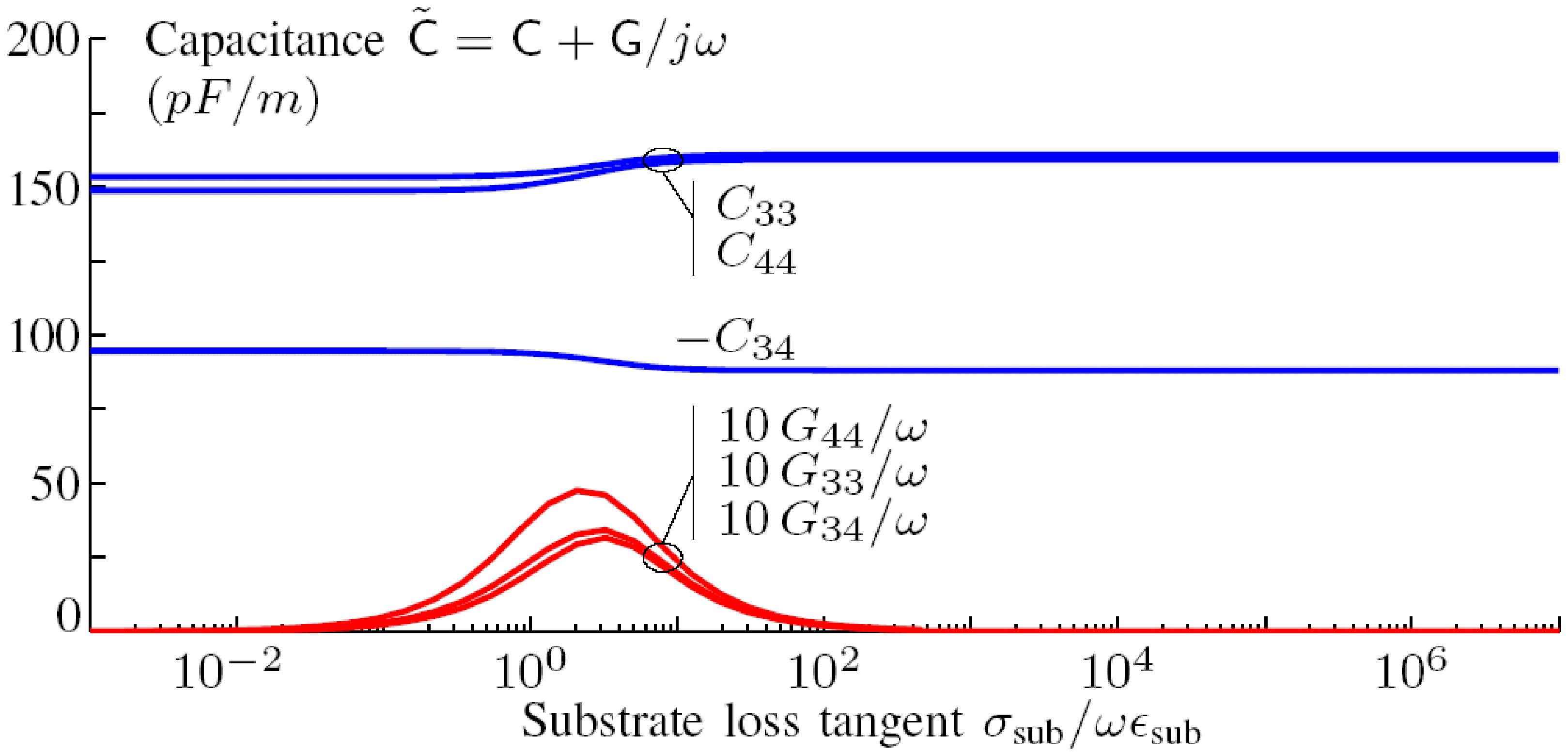
quasi-odd



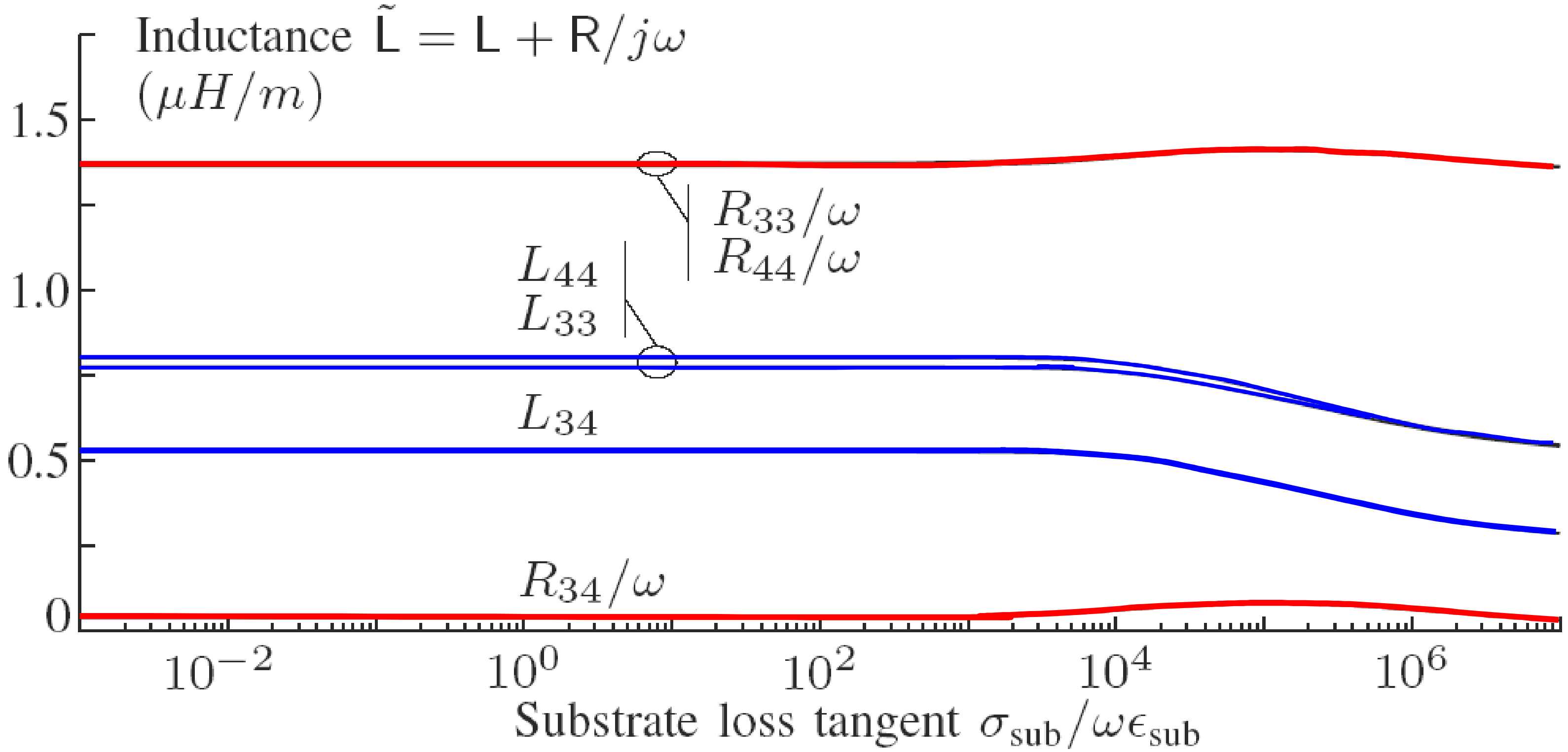
the modal voltages V = V_0exp(-jϕ) are displayed (V_0 = ■) @ 10GHz

slow wave factor:
mode prop. velocity v = c/SWF

complex capacitance matrix @10GHz



complex inductance matrix @10GHz



- *introduction*
- *RLGC-modelling of multiconductor lines*
- variability analysis along the signal propagation direction
- *analysis of statistical signals resulting from random variations in geometry, material properties, component values, linear and non-linear drivers and loads*
- *brief conclusions*
- *questions & discussion*

What if the cross-section varies along the propagation direction?

→ use a perturbation approach !

Quick illustration for a single line (with L & C complex – hence R & G are included)

$$\frac{dV(z)}{dz} = -j\omega L(z)I(z)$$
$$\frac{dI(z)}{dz} = -j\omega C(z)V(z)$$

+ perturbation around nominal value

$$\begin{aligned} V(z) &= \tilde{V}(z) + \Delta V_1(z) + \Delta V_2(z) + \cdots \\ I(z) &= \tilde{I}(z) + \Delta I_1(z) + \Delta I_2(z) + \cdots \\ C(z) &= \tilde{C} + \Delta C(z) \\ L(z) &= \tilde{L} + \Delta L(z). \end{aligned}$$

$$\frac{d^2\tilde{V}}{dz^2} + k_0^2\tilde{V} = 0$$

nominal

$$\frac{d^2\Delta V_1}{dz^2} + k_0^2\Delta V_1 = -k_0^2\tau_C\tilde{V} - jk_0\frac{d}{dz}(\tau_L Z_0\tilde{I})$$

perturbation step 1

$$\frac{d^2\Delta V_2}{dz^2} + k_0^2\Delta V_2 = -k_0^2\tau_C\Delta V_1 - jk_0\frac{d}{dz}(\tau_L Z_0\Delta I_1)$$

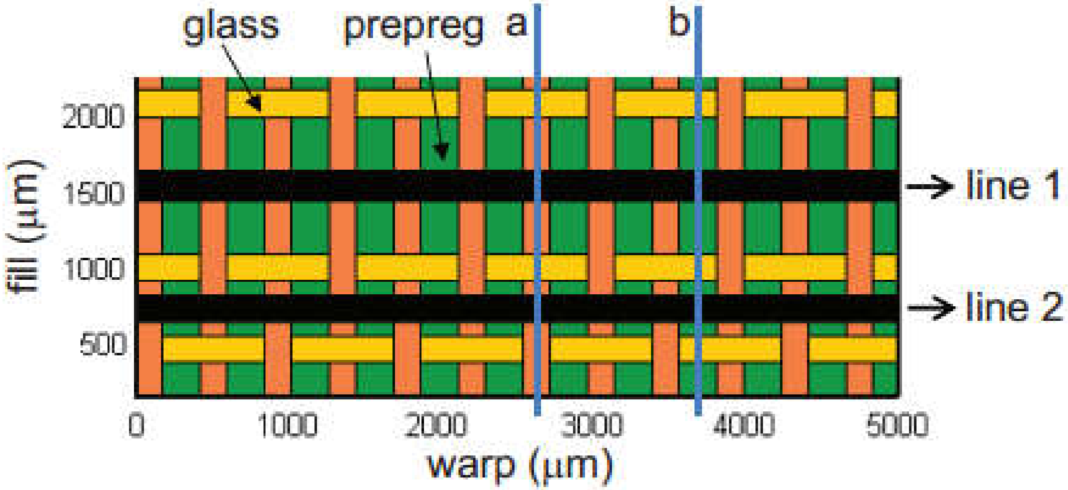
perturbation step 2

including this second order is CRUCIAL !

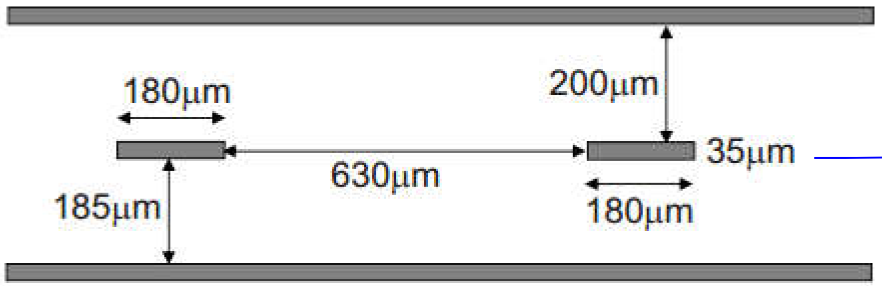
$$k_0 = \omega\sqrt{\tilde{L}\tilde{C}} \qquad \tau_C = (\Delta C)/(\tilde{C})$$

$$Z_0 = \sqrt{\tilde{L}/\tilde{C}} \qquad \tau_L = (\Delta L)/(\tilde{L})$$

Fibre weave: differential stripline pair on top of woven fiberglass substrate



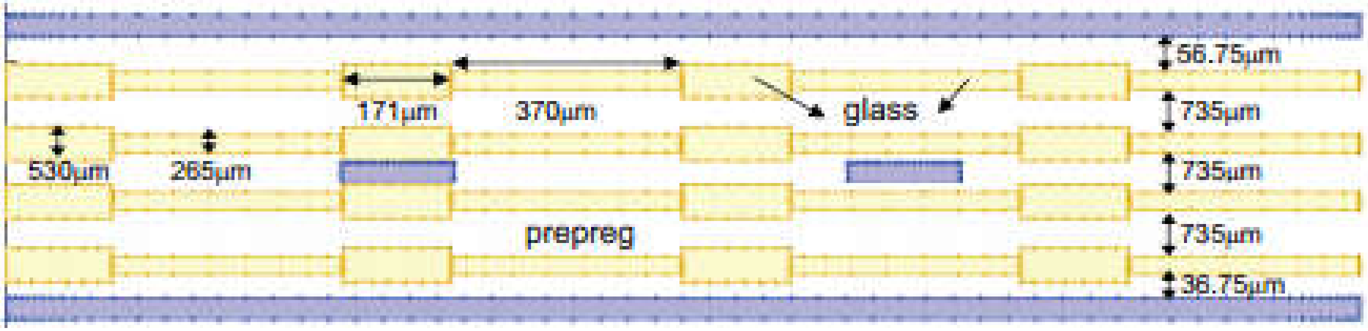
differential stripline pair



copper

cross-section of differential stripline pair

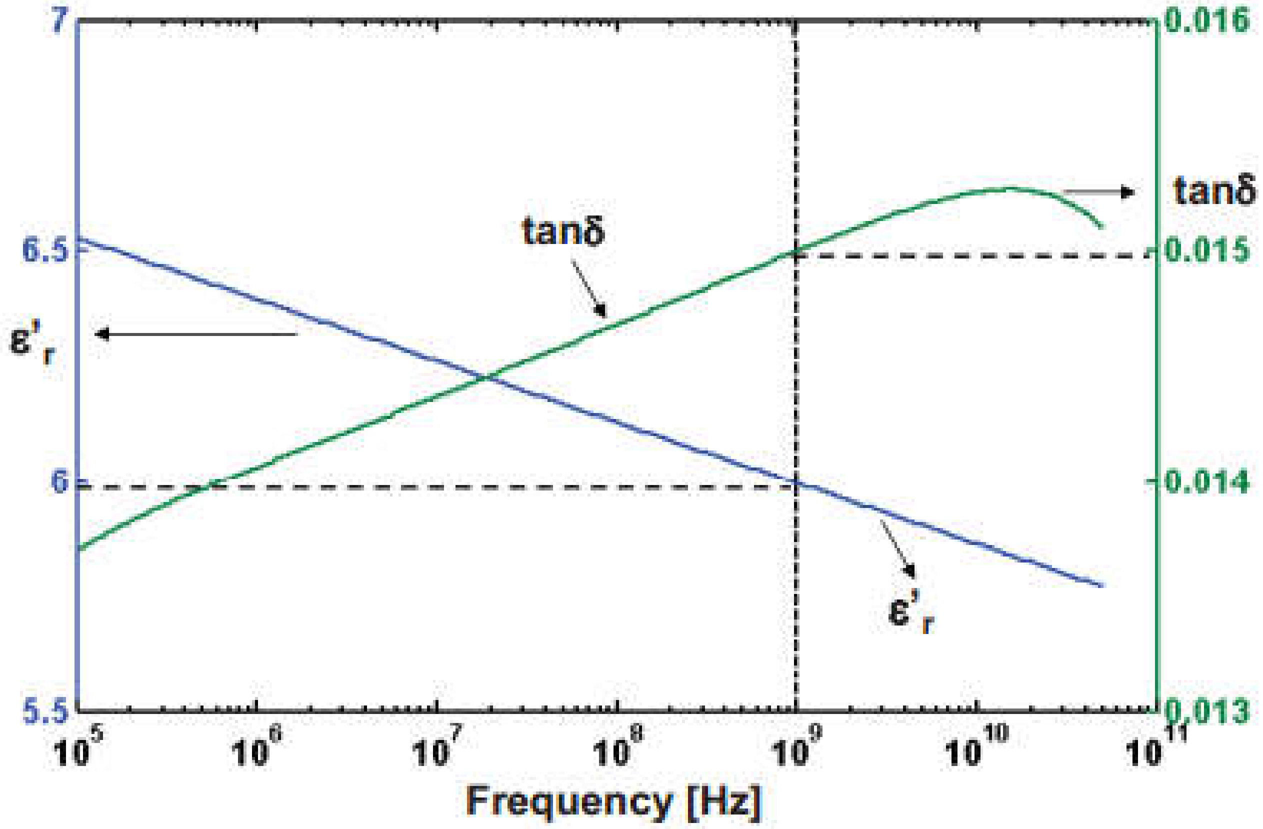
Fibre weave - discretisation (in CAD tool)



cross-section a

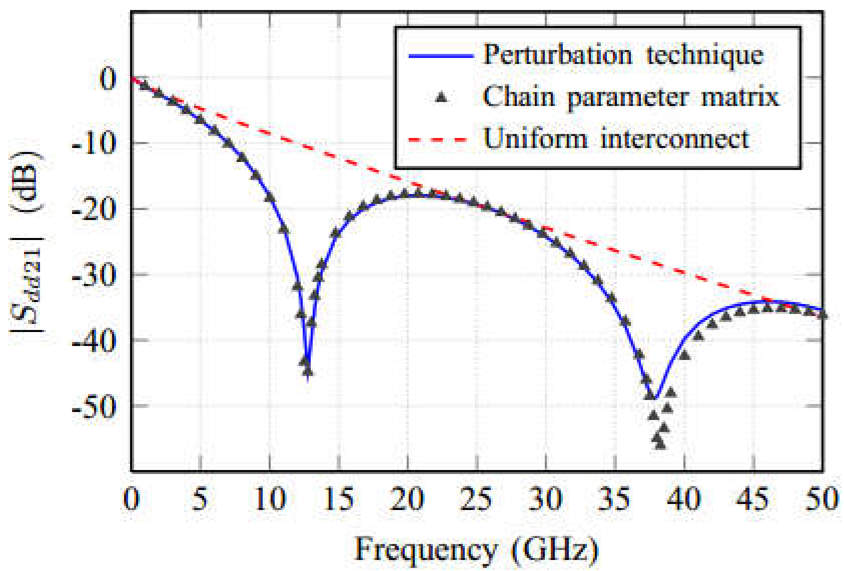
cross-section b

Fibre weave - material properties

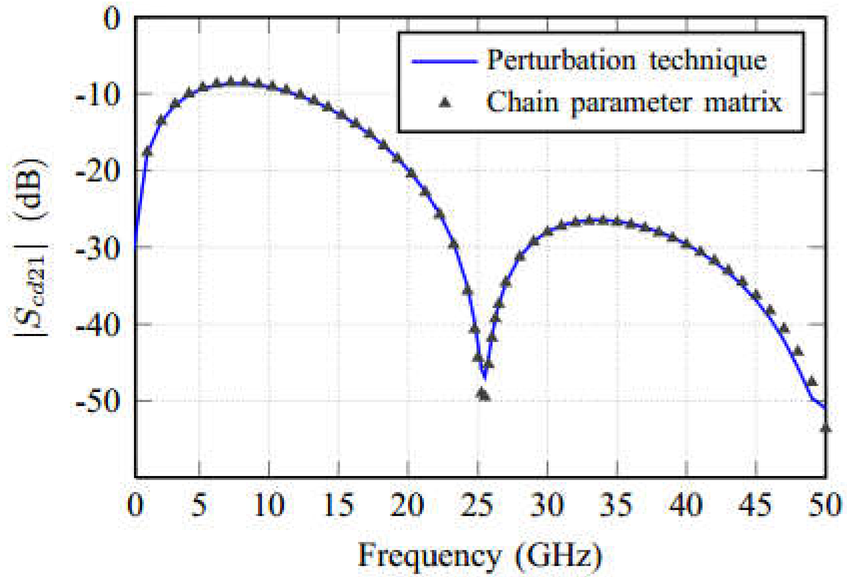


real part of dielectric permittivity ε'_r and $\tan\delta$ as a function of frequency

Propagation characteristics for a 10 inch line



differential mode transmission

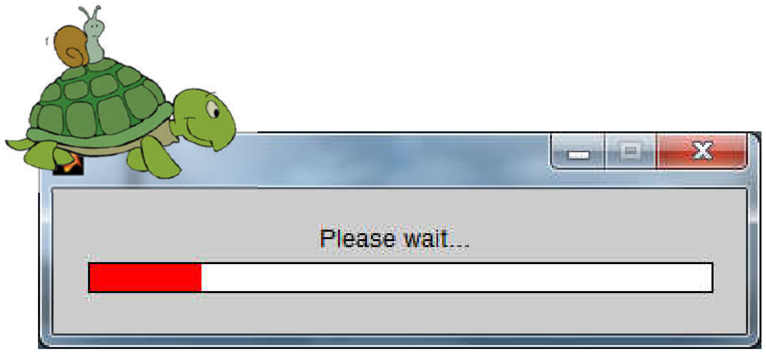


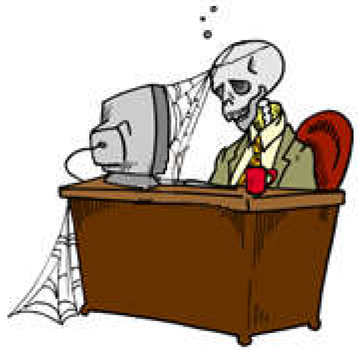
forward differential to common mode conversion

- *introduction*
- *RLGC-modelling of multiconductor lines*
- *variability analysis along the signal propagation direction*
- analysis of statistical signals resulting from random variations in geometry, material properties, component values, linear and non-linear drivers and loads

  - PART 1: MTL
- *brief conclusions*
- *questions & discussion*

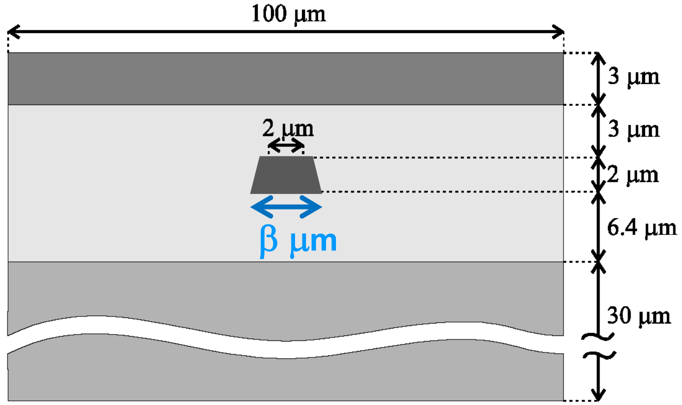
- Interconnect designers need to perform statistical simulations for variation-aware verifications
- Virtually all commercial simulators rely on the Monte Carlo method
  - Robust, easy to implement
  - Time consuming:
    slow convergence $\sim 1/\sqrt{N}$





Stochastic Telegrapher's eqns. (single line):

$$\frac{d}{dz}V(z,s,\beta) = -Z(s,\beta)\,I(z,s,\beta),$$
$$\frac{d}{dz}I(z,s,\beta) = -Y(s,\beta)\,V(z,s,\beta)$$



single IEM line

- *V* and *I* : unknown voltage and current along the line
  - function of position, frequency and of stochastic parameter β
- $s = j\omega$; $Z = R + sL$ and $Y = G + sC$ i.e. known p.u.l. TL parameters
- assume – *by way of example* - that β is a Gaussian random variable:

$$\beta = \mu_\beta(1 + \sigma_\beta \xi)$$

mean

standard deviation

normalized Gaussian random variable with zero mean and unit variance

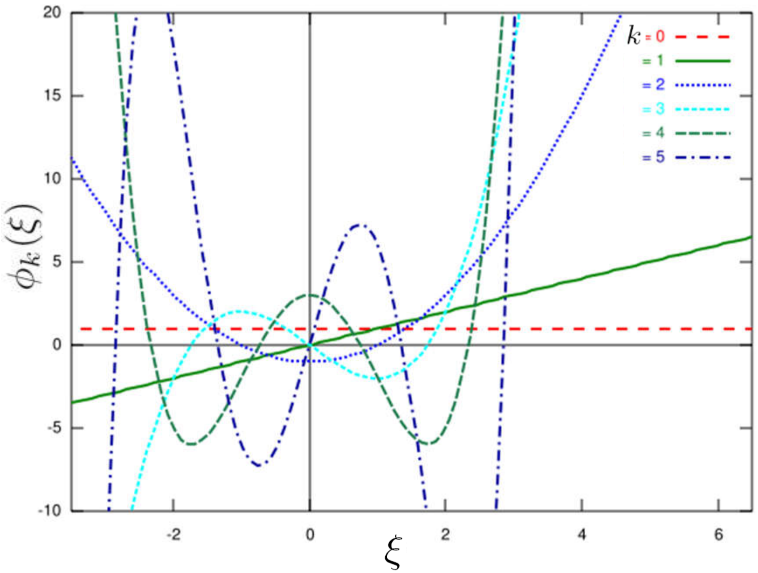
- **step 1: Hermite "Polynomial Chaos" expansion of Telegrapher's eqns.:**

$$\frac{d}{dz}V(z,s,\beta) = -Z(s,\beta)\, I(z,s,\beta)$$

$$V(z,s,\beta) = \sum_{k=0}^{K} V_k(z,s)\phi_k(\xi) \quad ?$$

$$I(z,s,\beta) = \sum_{k=0}^{K} I_k(z,s)\phi_k(\xi) \quad ?$$

$$Z(s,\beta) = \sum_{k=0}^{K} Z_k(s)\phi_k(\xi) \quad \& \quad Z_k(s) = \underbrace{< Z(s,\beta), \phi_k(\xi) >}_{\text{inner product}} / \; k!$$



Hermite polynomials

inner product:

$$< f(\xi), g(\xi) >= \int_{-\infty}^{+\infty} f(\xi)\, g(\xi) \, \frac{1}{\sqrt{2\pi}} \underbrace{e^{-\frac{1}{2}\xi^2}}_{\text{our Gaussian distribution}} d\xi$$

"judiciously" selected inner product

such that $< \phi_k(\xi), \phi_m(\xi) >= k!\, \delta_{km}$

- **expanded TL equations**

$$\frac{d}{dz}\sum_{k=0}^{K} V_k(z,s)\phi_k(\xi) = -\sum_{k=0}^{K}\sum_{l=0}^{K} Z_k(s) I_l(z,s)\phi_k(\xi)\phi_l(\xi)$$

$$\frac{d}{dz}\sum_{k=0}^{K} I_k(z,s)\phi_k(\xi) = -\sum_{k=0}^{K}\sum_{l=0}^{K} Y_k(s) V_l(z,s)\phi_k(\xi)\phi_l(\xi)$$

- **step 2: Galerkin projection on the Hermite polynomials $\phi_m(\xi)$, $m = 0,\ldots,K$**

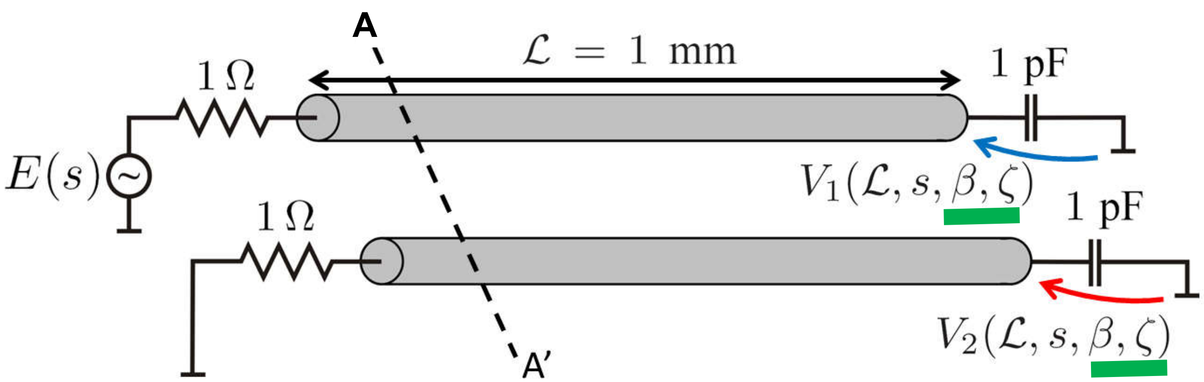
$$\left.\begin{aligned}
&\forall m = 0,\ldots,K,\\
&\frac{d}{dz}V_m(z,s) = -\sum_{k=0}^{K}\sum_{l=0}^{K}\alpha_{klm} Z_k(s) I_l(z,s)\\
&\frac{d}{dz}I_m(z,s) = -\sum_{k=0}^{K}\sum_{l=0}^{K}\alpha_{klm} Y_k(s) V_l(z,s)
\end{aligned}\right\}$$

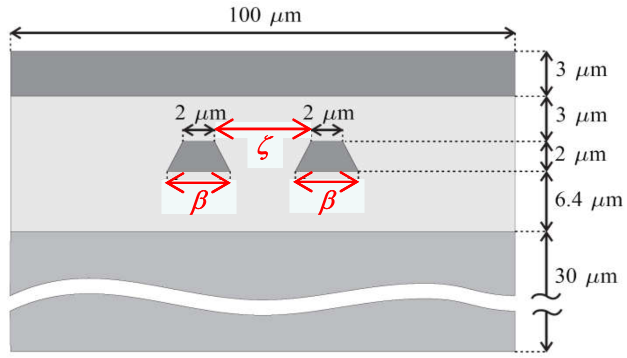
$$\alpha_{klm} = <\phi_k(\xi)\phi_l(\xi), \phi_m(\xi)> / \, m!$$

"augmented" set of deterministic TL eqns.
(β has been eliminated)

- + 🙂 deterministic
- + 🙂 solution yields complete statistics, i.e. mean, standard dev., skew, …, PDF
- + 🙂 again (coupled) TL- equations
- + ☹ larger set (K times the original)
- + 🙂 still much faster than Monte Carlo

Example



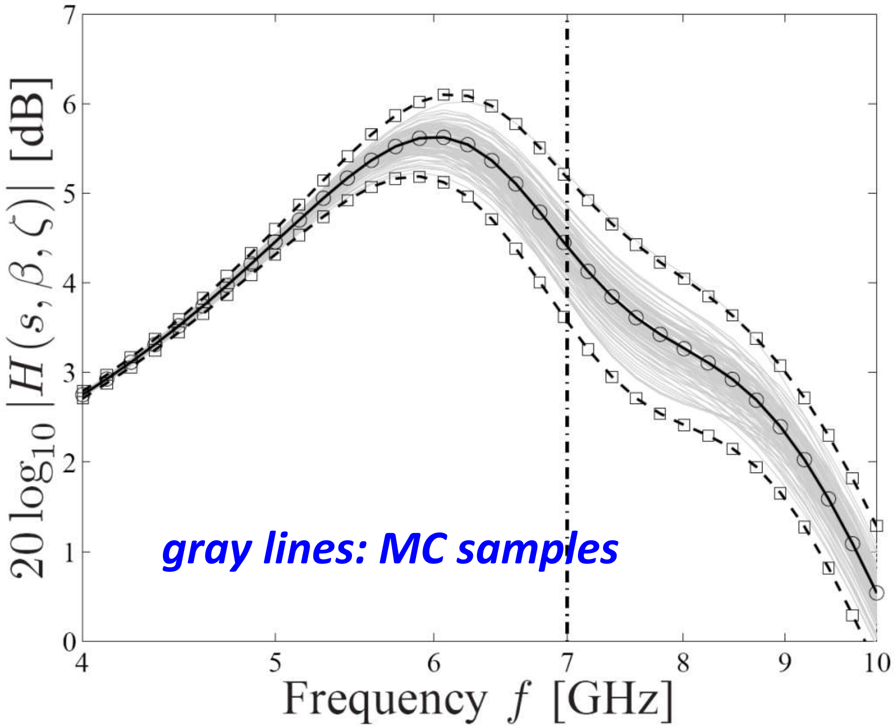


cross-section AA'

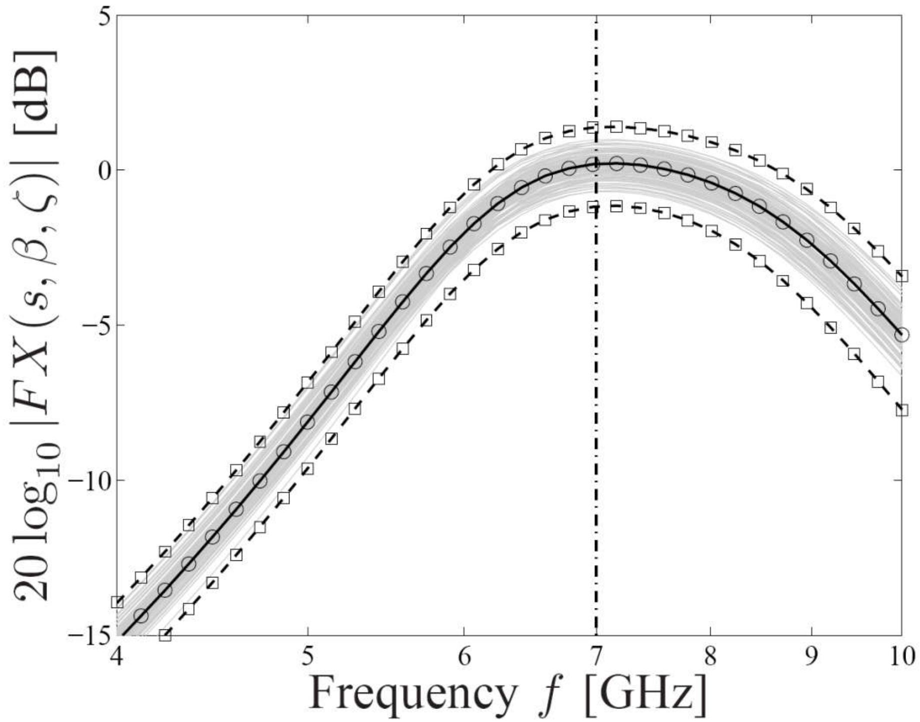
- β : Gaussian RV: μ_β = 2 mm and σ_β = 10% ζ : Gaussian RV: μ_ζ = 3 mm and σ_ζ = 8%
- transfer function: $H(s) = V_1(s)/E(s)$ (ii) forward crosstalk $FX(s) = V_2(s)/E(s)$
- compare with Monte Carlo run (50000 samples)
- efficiency of the Galerkin Polynomial Chaos

Technique	CPU time [s]			Speed-up factor
	setup	solve	total	
Novel approach	0.23	8.09	8.31	228
Monte Carlo			1895.72	

Transfer function $H(s,\beta,\zeta)$



Forward crosstalk $FX(s,\beta,\zeta)$



full-lines: mean values μ using SGM

circles: mean values μ using MC

dashed lines: ±3σ-variations using SGM

squares: ±3σ-variations using MC

- *introduction*
- *RLGC-modelling of multiconductor lines*
- *variability analysis along the signal propagation direction*
- analysis of statistical signals resulting from random variations in geometry, material properties, component values, linear and non-linear drivers and loads
  - **PART 2: the overall approach**
- *brief conclusions*
- *questions & discussion*

So far:

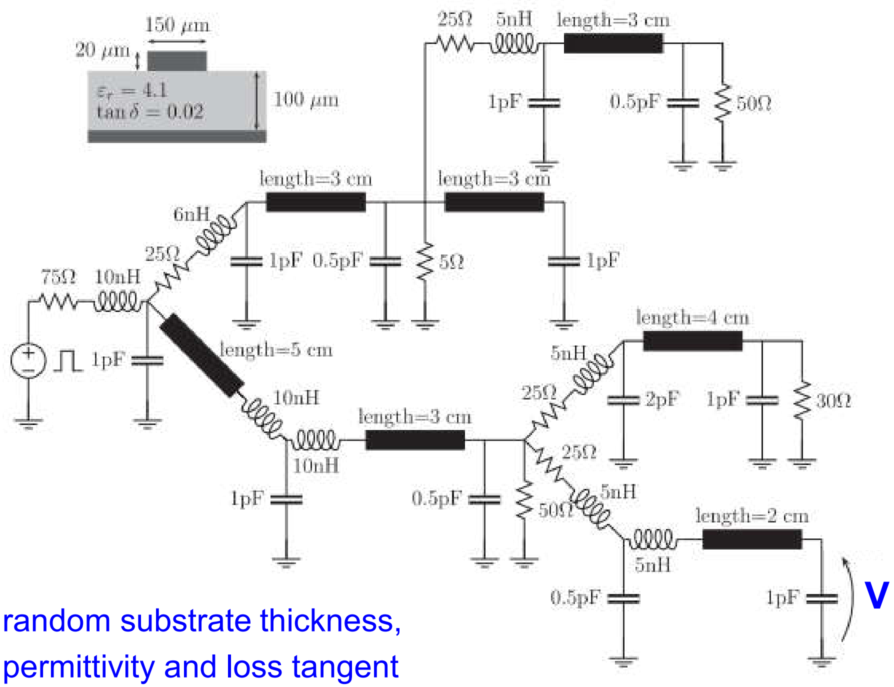
- 🙂 tractable variability analysis of (on-chip) interconnects
  (*and passive multiports*) outperforming Monte Carlo analysis
- ☹ relies on Matlab implementations of the presented techniques
- ☹ only relatively small passive circuits with few random variables

Next:

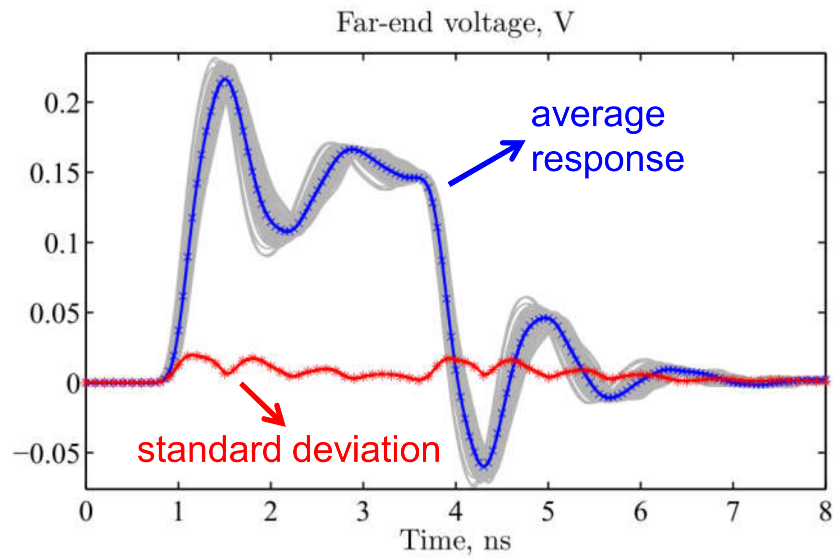
- 🙂 extension of techniques to include nonlinear and active devices
- 🙂 extension to many randomly varying parameters
- 🙂 integration into SPICE-like design environments
  - perform transient analyses
  - simulate complex circuit topologies including connectors, via’s, packages, drivers, receivers

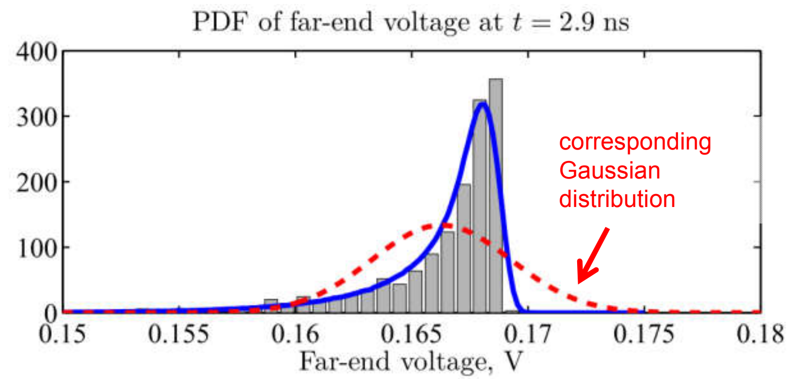
remember – slide 35 - PC projection and testing results in:

"augmented" set of deterministic TL eqns. $\rightarrow$ can be directly imported in SPICE



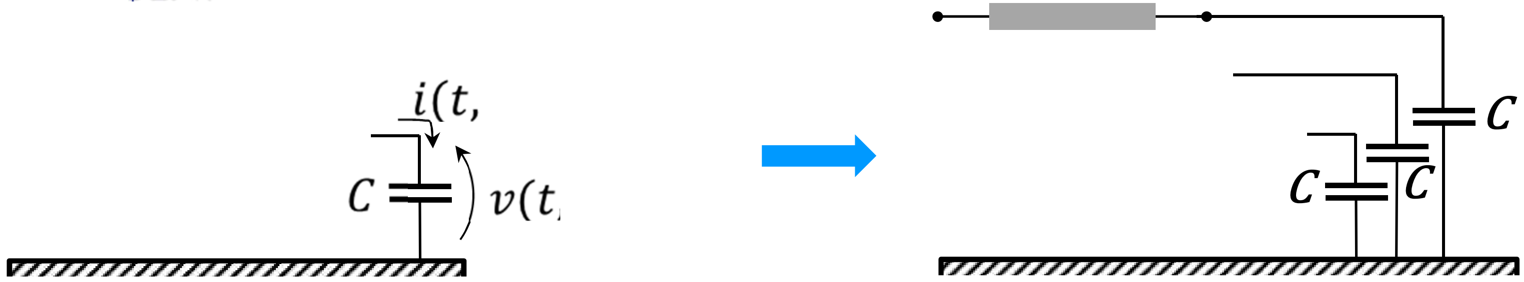
random substrate thickness,
permittivity and loss tangent





HSPICE Monte Carlo (1000 runs): … 38 min
HSPICE polynomial chaos: ……………… 7 s
Speed-up: …………………………………. **310 x**

Linear terminations



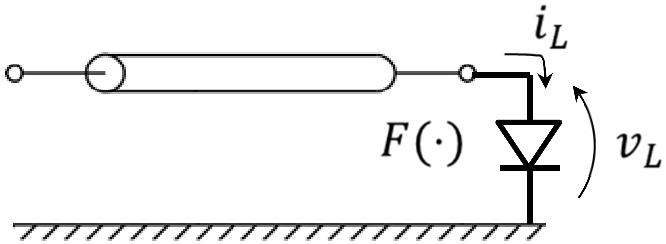
the deterministic augmented lines share the same termination:

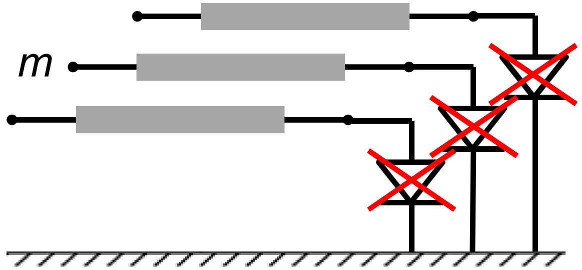
$$i(t,\xi) = C\frac{d}{dt}v(t,\xi)$$ $\rightarrow$ random variable ξ

$$i_0\varphi_0 + i_1\varphi_1 + \cdots = C\left(\frac{d}{dt}v_0\varphi_0 + \frac{d}{dt}v_1\varphi_1 + \cdots\right)$$ $\rightarrow$ PC expansion

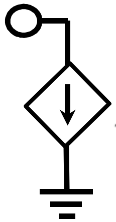
$$\boxed{i_m(t) = C\frac{d}{dt}v_m(t)}$$ $\rightarrow$ decoupled equations after projection

Non-linear terminations





the deterministic line m now has
the following termination:

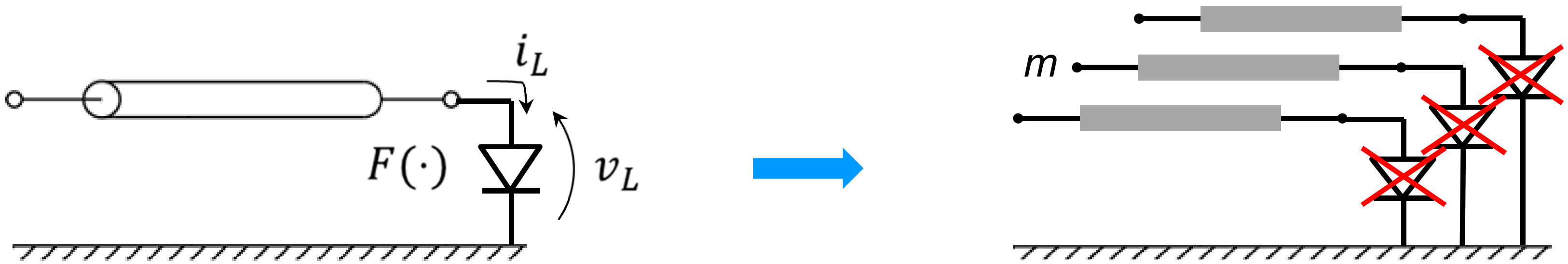

$j_1 a_{m1} w_1 + j_2 a_{m2} w_2 + \cdots$

voltage controlled (v_{L0}, v_{L1}, ..)
current source

applicable to

- arbitrary device models
- transistor-level descriptions
- behavioral macromodels
- encrypted library models

Non-linear terminations



$$i_{Lm} = \langle F(v_{L0}\varphi_0 + v_{L1}\varphi_1 + \cdots), \varphi_m \rangle \cancel{=} F(v_{Lm})$$

but $$i_{Lm} = \int F(v_{L0}\varphi_0(\xi) + v_{L1}\varphi_1(\xi) + \cdots)\, \varphi_m(\xi) w(\xi) d\xi$$

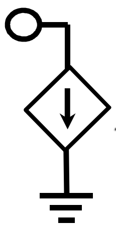
$$\approx \sum_{q=1}^{Q} \underbrace{F(v_{L0}a_{0q} + v_{L1}a_{1q} + \cdots)}_{= j_q} a_{mq} w_q$$

$a_{mq} \triangleq \varphi_m(\xi_q)$

ξ_q: quadrature nodes

w_q: quadrature weights

the deterministic line m now has the following termination:



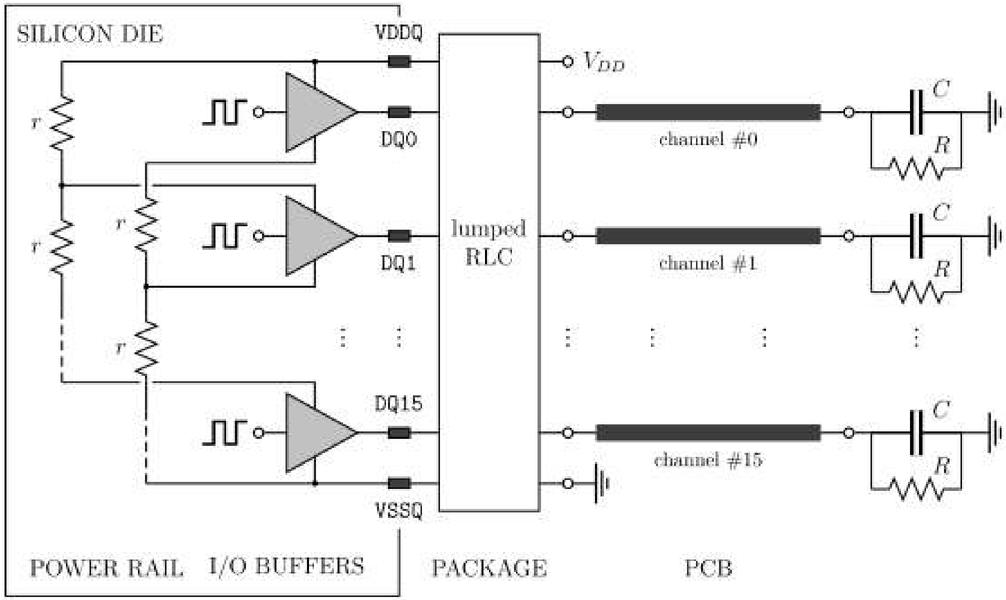
$$j_1 a_{m1} w_1 + j_2 a_{m2} w_2 + \cdots$$

voltage controlled (v_{L0}, v_{L1}, ..) current source

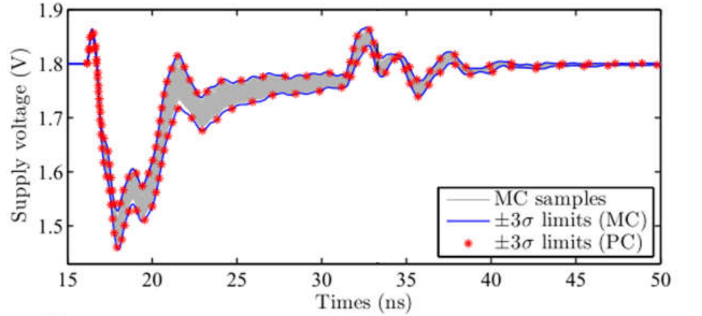
applicable to

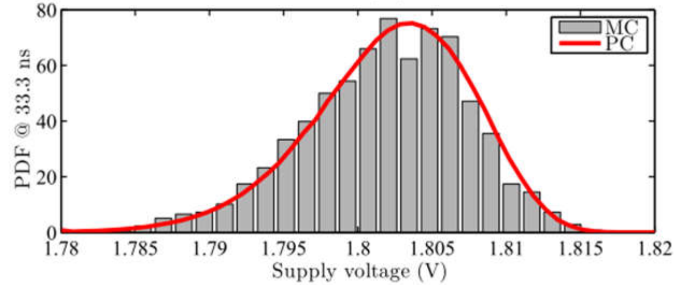
- arbitrary device models
- transistor-level descriptions
- behavioral macromodels
- encrypted library models

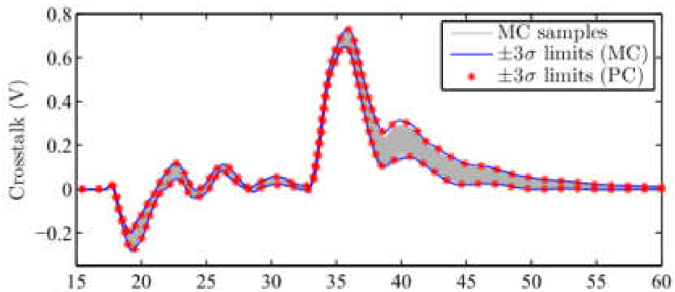
16-bit digital transmission channel

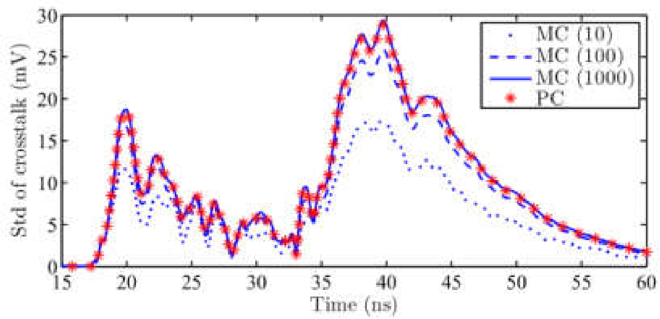


random power rail resistance and package parasitics

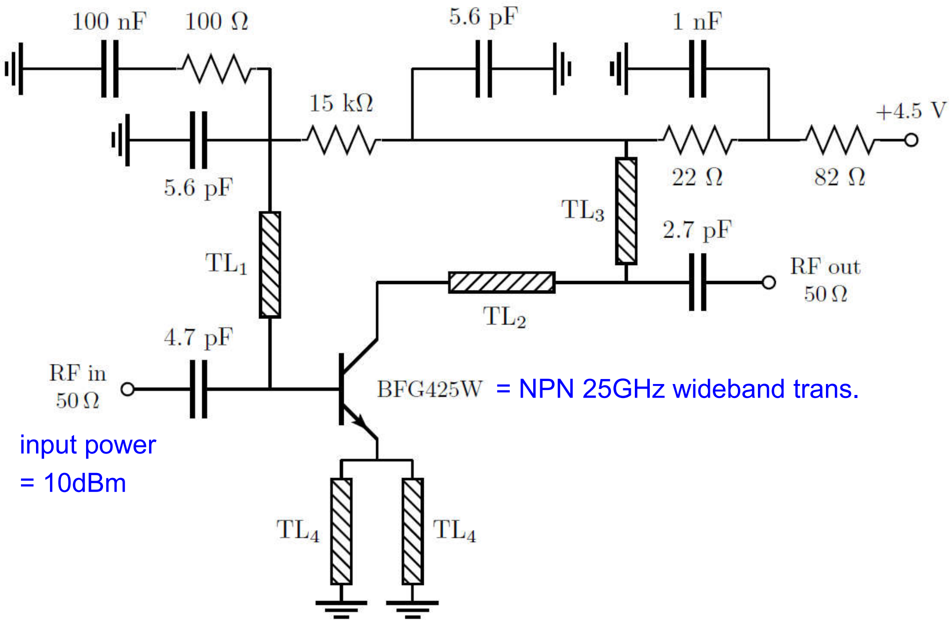


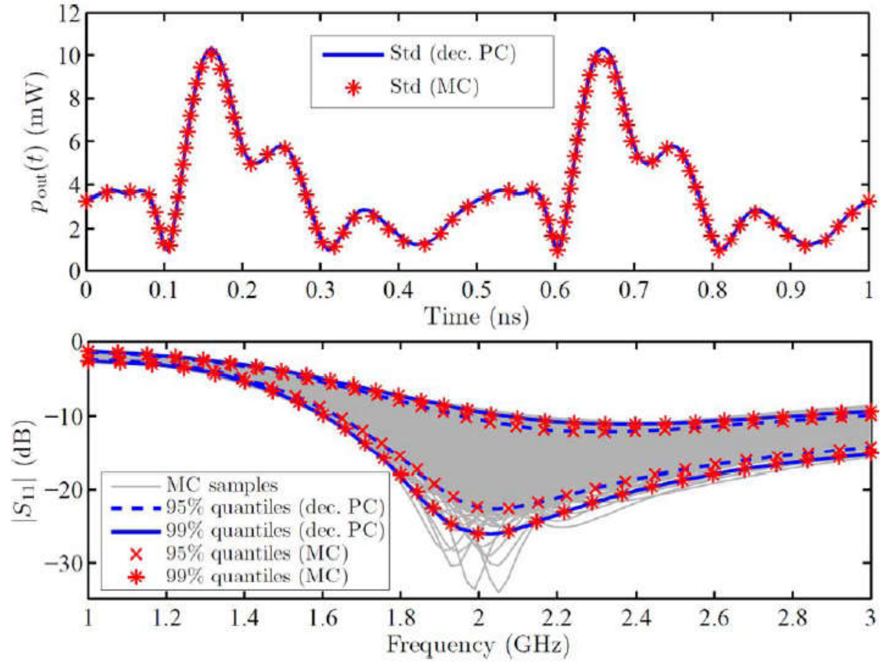






Monte Carlo (1k runs) .... ~ 2.3 days
Polyn. chaos (Galerkin-based) .... ~ 9 h
Polyn. chaos (**stochastic testing-based**) ... ~ 1 h
Overall speed-up .... **47 x**





25 random variables using a point-matching technique: ♫

- parasitic R's, L's and C's of BJT (10%)
- forward current gain (10%)
- ∀ lumped components in LNA schematic (10%)
- widths of 4 transmission lines (5%)

for the same accuracy 10^5 Monte Carlo single circuit simulations are needed versus only 351 for the new technique
speed-up factor: 285

Conclusions

- broad classes of coupled multiconductor transmission lines (MTLs) can be handled;
- efficient and accurate RLGC modelling of MTLs from DC to skin-effect regime is possible thanks to the differential surface current concept;
- MTL variations along the signal propagation direction can be efficiently dealt with thanks to a 2-step perturbation technique;
- all frequency and time-domain statistical signal data can be efficiently collected for *many* random variations both in MTL characteristics and in linear and non-linear drivers, loads, amplifiers, … thanks to advanced Polynomial Chaos approaches – by far outperforming Monte Carlo methods;
- for *very many* random variables the curse of dimensionality remains cfr. roughness analysis or scattering problems → ongoing research;
- initial statistics can be very hard to get e.g. a multipins connector → ongoing research.

Acknowledgement

Thanks to all PhD students and colleagues of the EM group I have been working with on these topics over very many years:

- Niels Faché (now with Keysight Technologies - USA)
- Jan Van Hese (now with Keysight Technologies - Belgium)
- F. Olyslager (full professor at INTEC, UGent – deceased)
- Thomas Demeester (post-doc at INTEC, UGent)
- Luc Knockaert (assistant professor at INTEC, UGent)
- Tom Dhaene (full professor at INTEC, UGent)
- Dries Vande Ginste (full professor at INTEC, UGent)
- Hendrik Rogier (full professor at INTEC, UGent)
- Paolo Manfredi (post-doc at INTEC; assistant professor Politecnico di Torino)

Close collaboration on statistical topics with

Prof. Flavio Canavero (EMC Group, Dipartimento di Elettronica,
Politecnico di Torino (POLITO), Italy)

Thank you for your attention!!

- additional reading material: see included list *restricted* to our own work

Questions and

Discussion?

- additional questions: right now or at daniel.dezutter@ugent.be

Bibliographic references D. De Zutter et al.

Differential admittance R,L,G,C- modelling

1. De Zutter D and Knockaert L (2005), *"Skin effect modeling based on a differential surface admittance operator"*, IEEE Transactions on Microwave Theory and Techniques. Vol. 53(8), pp. 2526–2538.
2. De Zutter D, Rogier H, Knockaert L and Sercu J (2007), *"Surface current modelling of the skin effect for on-chip interconnections"*, IEEE Transactions on Advanced Packaging,. Vol. 30(2), pp. 342–349.
3. Rogier H, De Zutter D and Knockaert L (2007), *"Two-dimensional transverse magnetic scattering using an exact surface admittance operator"*, Radio Science. Vol. 42(3)
4. Demeester T and De Zutter D (2008), *"Modeling the broadband inductive and resistive behavior of composite conductors"*, IEEE Microwave and Wireless Components Letters. Vol. 18(4), pp. 230-232.
5. Demeester T and De Zutter D (2008), *"Quasi-TM transmission line parameters of coupled lossy lines based on the Dirichlet to Neumann boundary operator"*, IEEE Transactions on Microwave Theory and Techniques. Vol. 56(7), pp. 1649-1660.
6. Demeester T and De Zutter D (2009), *"Internal impedance of composite conductors with arbitrary cross section"*, IEEE Transactions on Electromagnetic Compatibility. Vol. 51(1), pp. 101-107.
7. Demeester T and De Zutter D (2009), *"Construction and applications of the Dirichlet-to-Neumann operator in transmission line modeling"*, Turkish Journal of Electrical Engineering and Computer Sciences. Vol. 17(3), pp. 205-216.
8. Demeester T and De Zutter D (2010), *"Fields at a finite conducting wedge and applications in interconnect modeling"*, IEEE Transactions on Microwave Theory and Techniques. Vol. 58(8), pp. 2158–2165.
9. Demeester T and De Zutter D (2011), *"Eigenmode-based capacitance calculations with applications in passivation layer design"*, IEEE Transactions on Components Packaging and Manufacturing Technology. Vol. 1(6), pp. 912-919.

10. De Zutter D (2014), "*Accurate broadband modeling of multiconductor line RLGC-parameters in the presence of good conductors and semiconducting substrates*", IEEE Electromagnetic Compatibility Magazine. Vol. 3, Quarter 2, pp. 76-84.
11. Huynen M, Gossye M, De Zutter D and Vande Ginste D (2017), *"A 3-D differential surface admittance operator for lossy dipole antenna analysis"*, IEEE Antennas and Wireless Propagation Letters., December, 2017. Vol. 16(1), pp. 1052-1055.

Multiconductor Transmission Line perturbation technique

12. Chernobryvko M, Vande Ginste D and De Zutter D (2013), *"A two-step perturbation technique for nonuniform single and differential lines"*, IEEE Transactions on Microwave Theory and Techniques. Vol. 61(5), pp. 1758-1767.
13. Chernobryvko M, De Zutter D and Vande Ginste D (2014), *"Non-uniform multiconductor transmission line analysis by a two-step perturbation technique"*, IEEE Transactions on Components Packaging and Manufacturing Technology., November, 2014. Vol. 4(11), pp. 1838-1846.
14. Manfredi P, De Zutter D and Vande Ginste D (2016), *"Analysis of nonuniform transmission lines with an iterative and adaptive perturbation technique"*, IEEE Transactions on Electromagnetic Compatibility,., June, 2016. Vol. 58(3), pp. 859-867.

UNIVERSITEIT GENT

Variablility analysis of interconnects

1. Vande Ginste D, De Zutter D, Deschrijver D, Dhaene T, Manfredi P and Canavero F (2012), *"Stochastic modeling-based variability analysis of on-chip interconnects"*, IEEE Trans. on Components Packaging and Manufacturing Technology. Vol. 2(7), pp. 1182-1192.
2. Biondi A, Vande Ginste D, De Zutter D, Manfredi P and Canavero F (2013), *"Variability analysis of interconnects terminated by general nonlinear loads"*, IEEE Transactions on Components Packaging and Manufacturing Technology. Vol. 3(7), pp. 1244-1251.
3. Manfredi P, Vande Ginste D, De Zutter D and Canavero F (2013), *"Improved polynomial chaos discretization schemes to integrate interconnects into design environments"*, IEEE Microwave and Wireless Components Letters. Vol. 23(3), pp. 116-118.
4. Manfredi P, Vande Ginste D, De Zutter D and Canavero F (2013), *"Uncertainty assessment of lossy and dispersive lines in SPICE-type environments"*, IEEE Transactions on Components Packaging and Manufacturing Technology. Vol. 3(7), pp. 1252-1258.
5. Manfredi P, Vande Ginste D, De Zutter D and Canavero F (2013), *"On the passivity of polynomial chaos-based augmented models for stochastic circuits"*, IEEE Transactions on Circuits and Systems I-Regular Papers. Vol. 60(11), pp. 2998-3007.
6. Biondi A, Manfredi P, Vande Ginste D, De Zutter D and Canavero F (2014), *"Variability analysis of interconnect structures including general nonlinear elements in SPICE-type framework"*, Electronics Letters. Vol. 50(4), pp. 263-265.
7. Manfredi P, Vande Ginste D, De Zutter D and Canavero F (2014), *"Stochastic modeling of nonlinear circuits via SPICE-compatible spectral equivalents"*, IEEE Transactions On Circuits And Systems I-Regular Papers. Vol. 61(7), pp. 2057-2065.
8. Manfredi P, Vande Ginste D and De Zutter D (2015), *"An effective modeling framework for the analysis of interconnects subject to line-edge roughness"*, IEEE Microwave and Wireless Components Letters., August, 2015. Vol. 25(8), pp. 502-504.
9. Manfredi P, Vande Ginste D, De Zutter D and Canavero F (2015), *"Generalized decoupled polynomial chaos for nonlinear circuits with many random parameters"*, IEEE Microwave and Wireless Components Letters., August, 2015. Vol. 25(8), pp. 505-507.
10. Manfredi P, De Zutter D and Vande Ginste D (2017), *"On the relationship between the stochastic Galerkin method and the pseudo-spectral collocation method for linear differential algebraic equations"*, Journal of Engineering Mathematics., May, 2017. , pp. online, DOI 10.1007/s10665-017-9909-7.
11. De Ridder S, Manfredi P, De Geest J, Deschrijver D, De Zutter D, Dhaene T, and Vande Ginste D, *"A generative modeling framework for statistical link assessment based on sparse data"*, submitted to the IEEE Transactions on Components, Packaging and Manufacturing Technology.