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Electromagnetism and Multi-scale Structures

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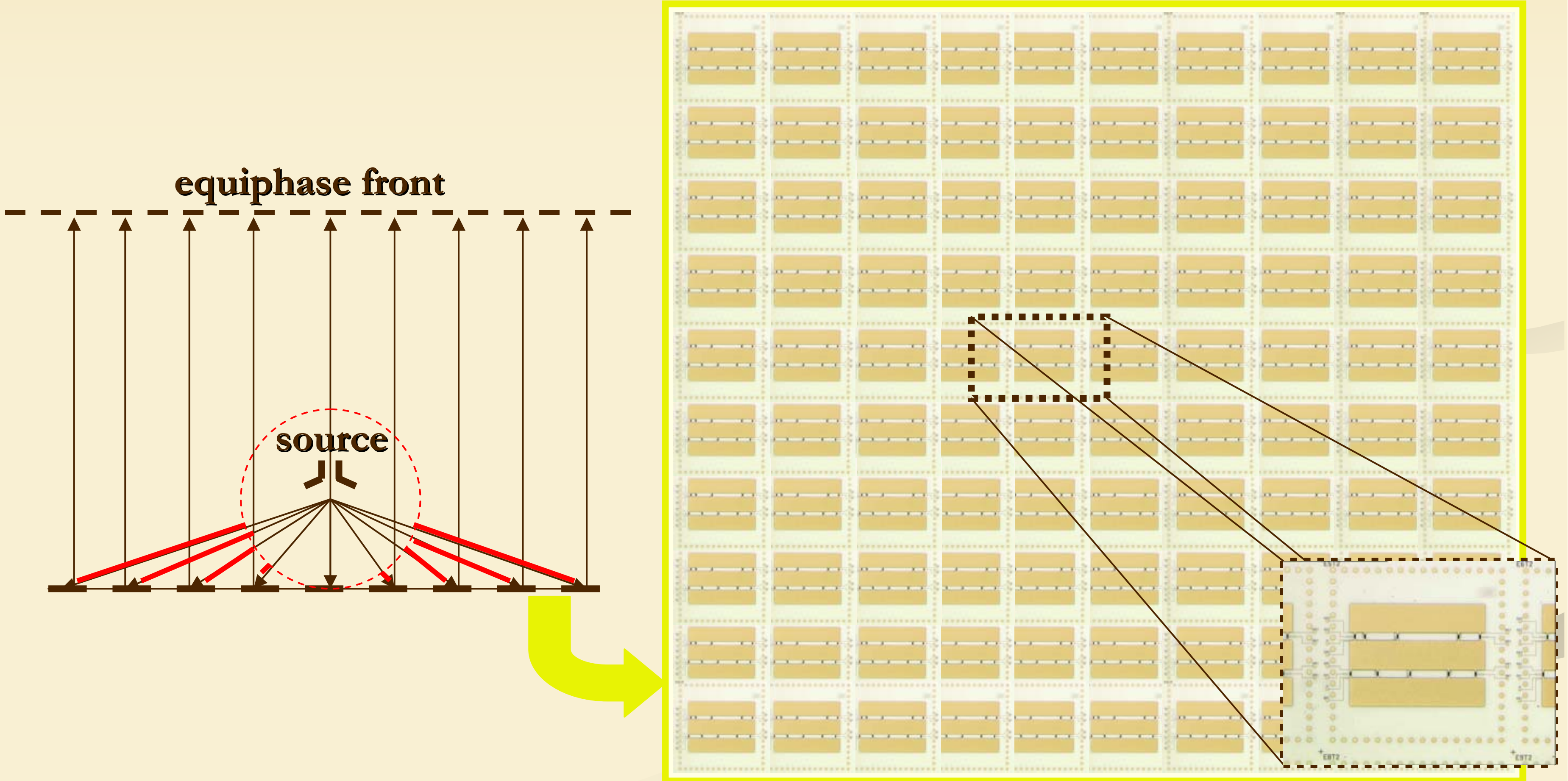
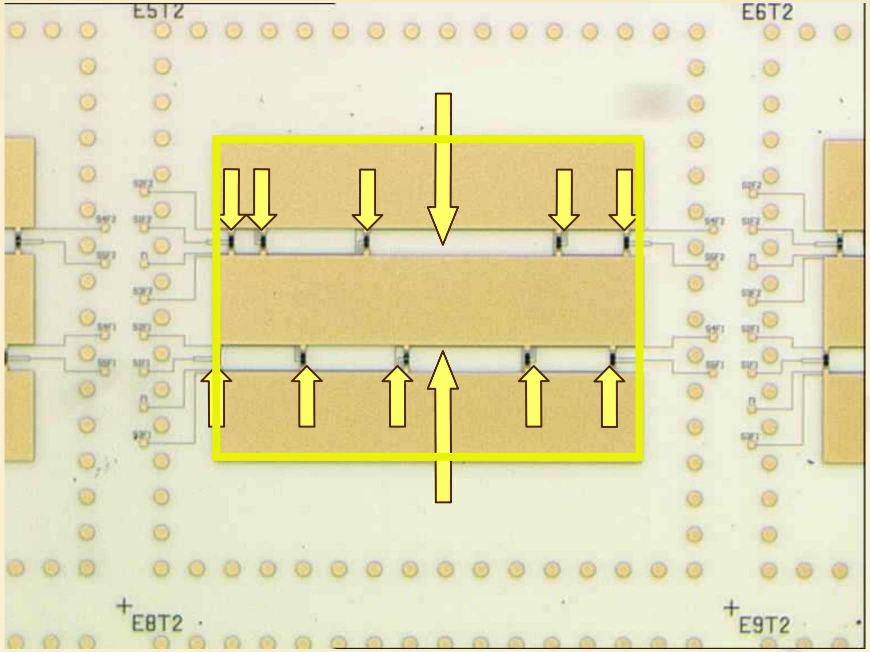
EXAMPLE :

RECONFIGURABLE REFLECTARRAY WITH NON-IDENTICAL CELLS



MEMS-Controlled Phase shifter Elements for a Linearly Polarised Reflectarray (*)

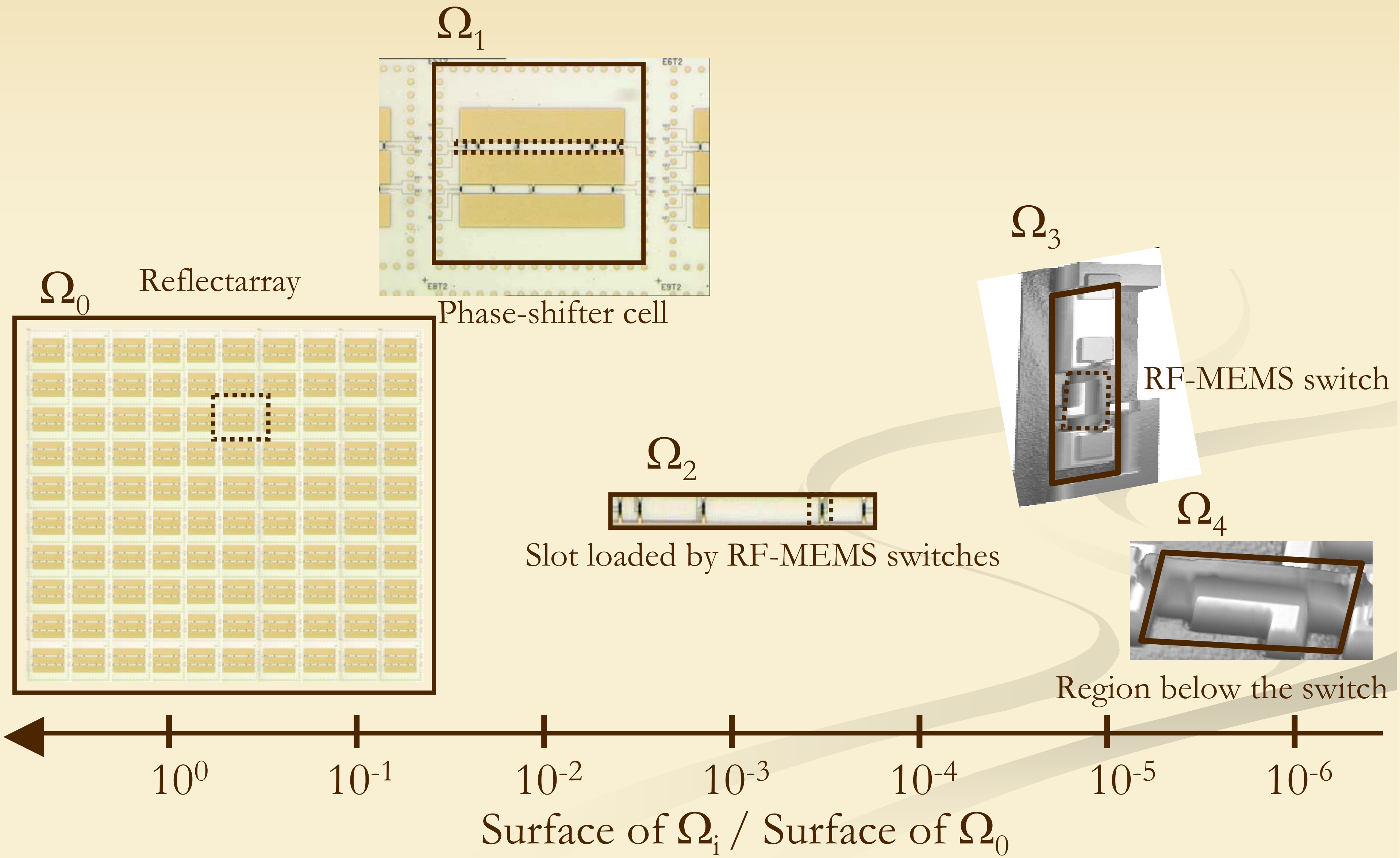
(*) Cadoret D., Laisne A., Gillard R. and Legay H., *Microwave and Optical Technological Letters* (2005)



Top view

2^{10} = 1024 ON/OFF states configurations for achieving the phase-shift range of 360°

Visualization of the muliple scale levels



Typical numerical problems when modeling multi-scale structures

⇨ **Classical meshing-based techniques :**

- ✓ Ill-conditioned matrices
- ✓ Numerical convergence problem and/or very time-consuming

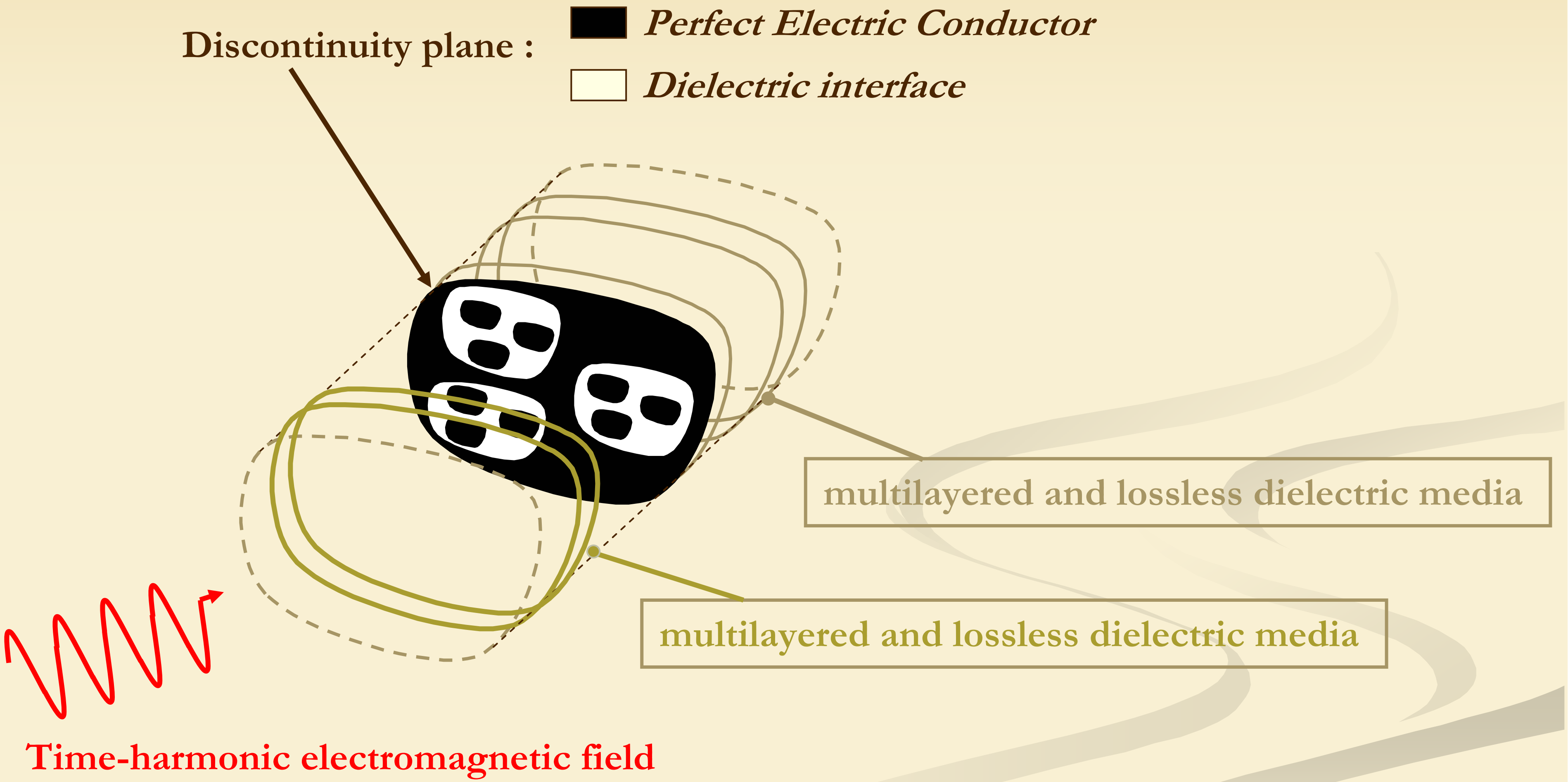
⇨ **Hybrid techniques** (Global modeling) :

- ✓ Connections may be delicate from a theoretical and practical points of view

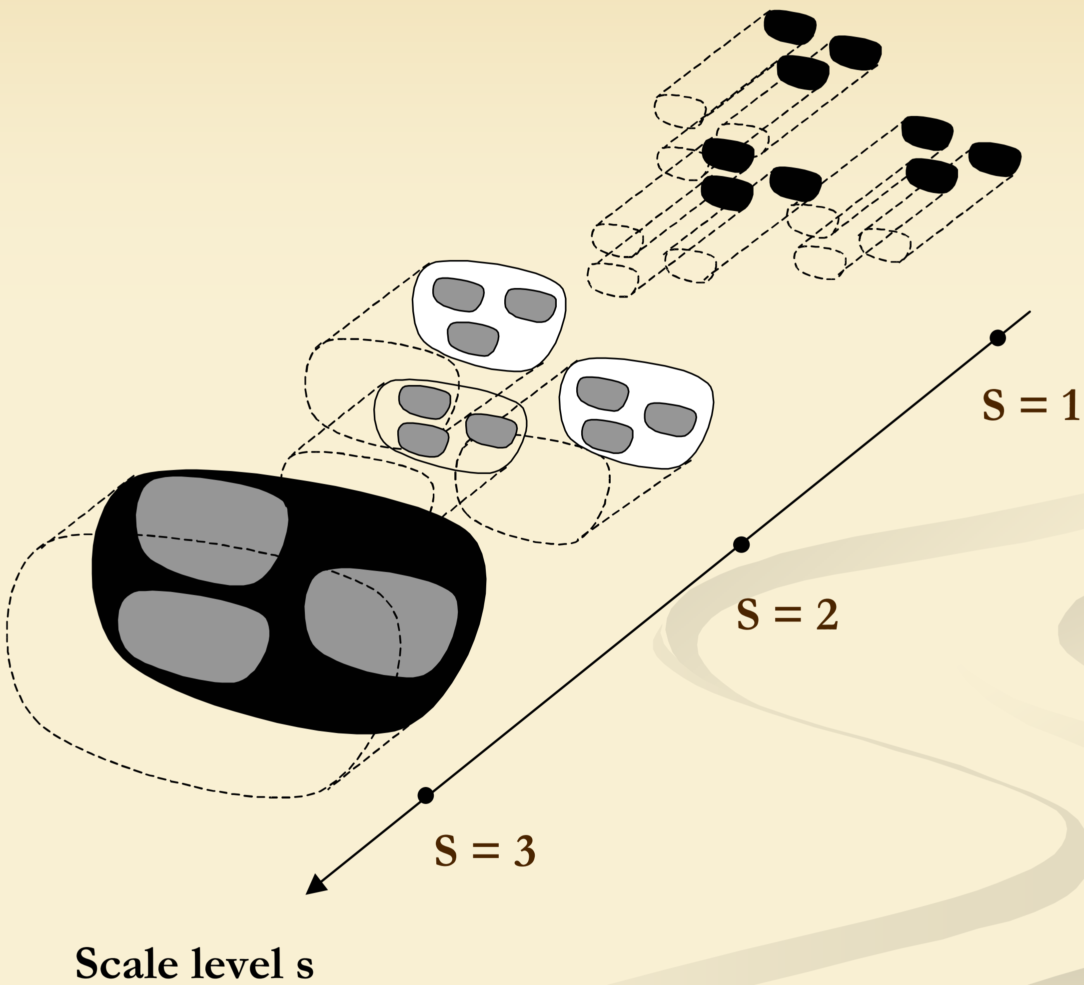
Need for new theoretical approaches for the modeling and design of multi-scale structures

⇨ **Scale Changing Technique (SCT) : monolithic (unique) formulation**

Scale Changing Technique (SCT)



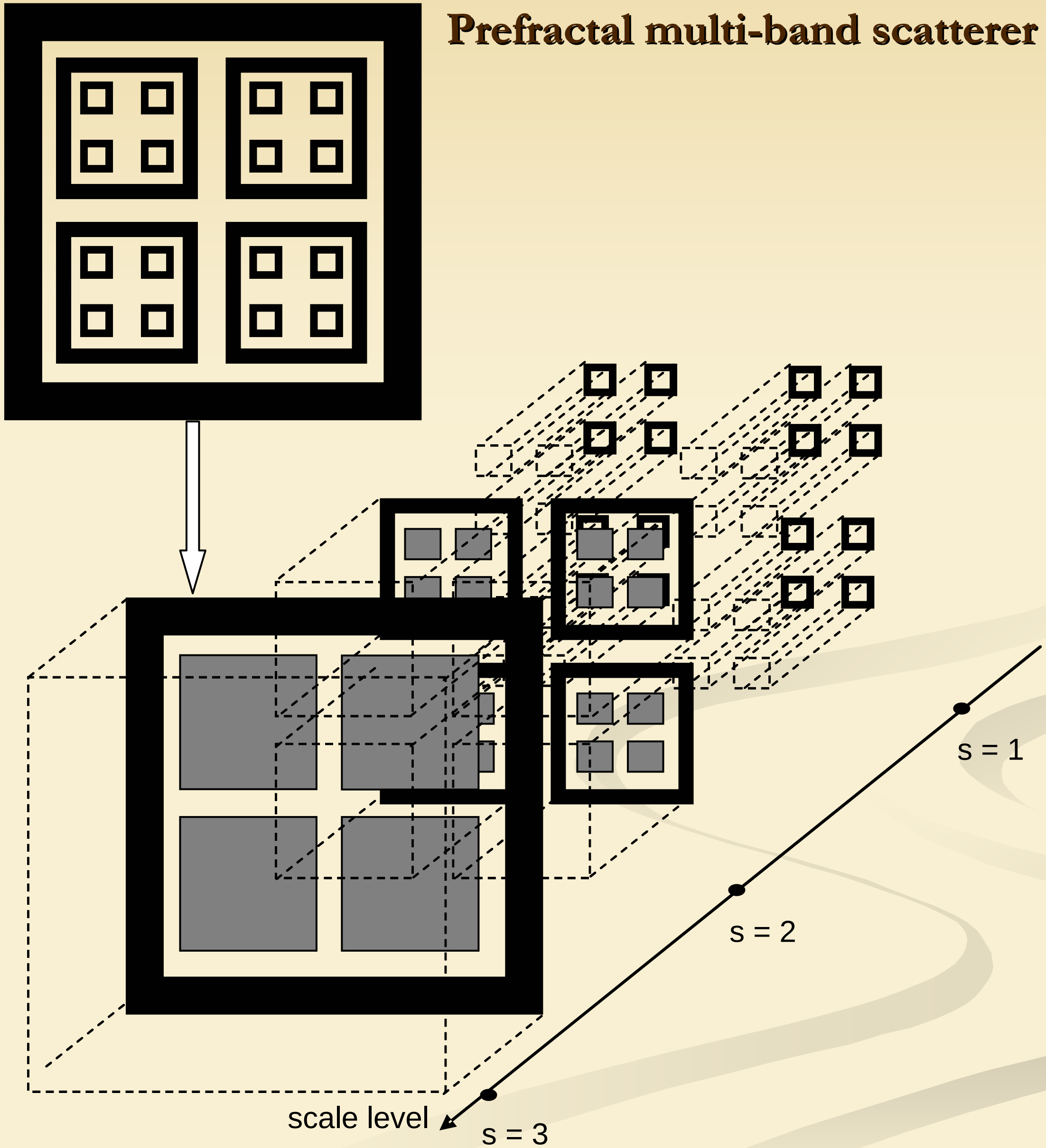
1. partitioning process



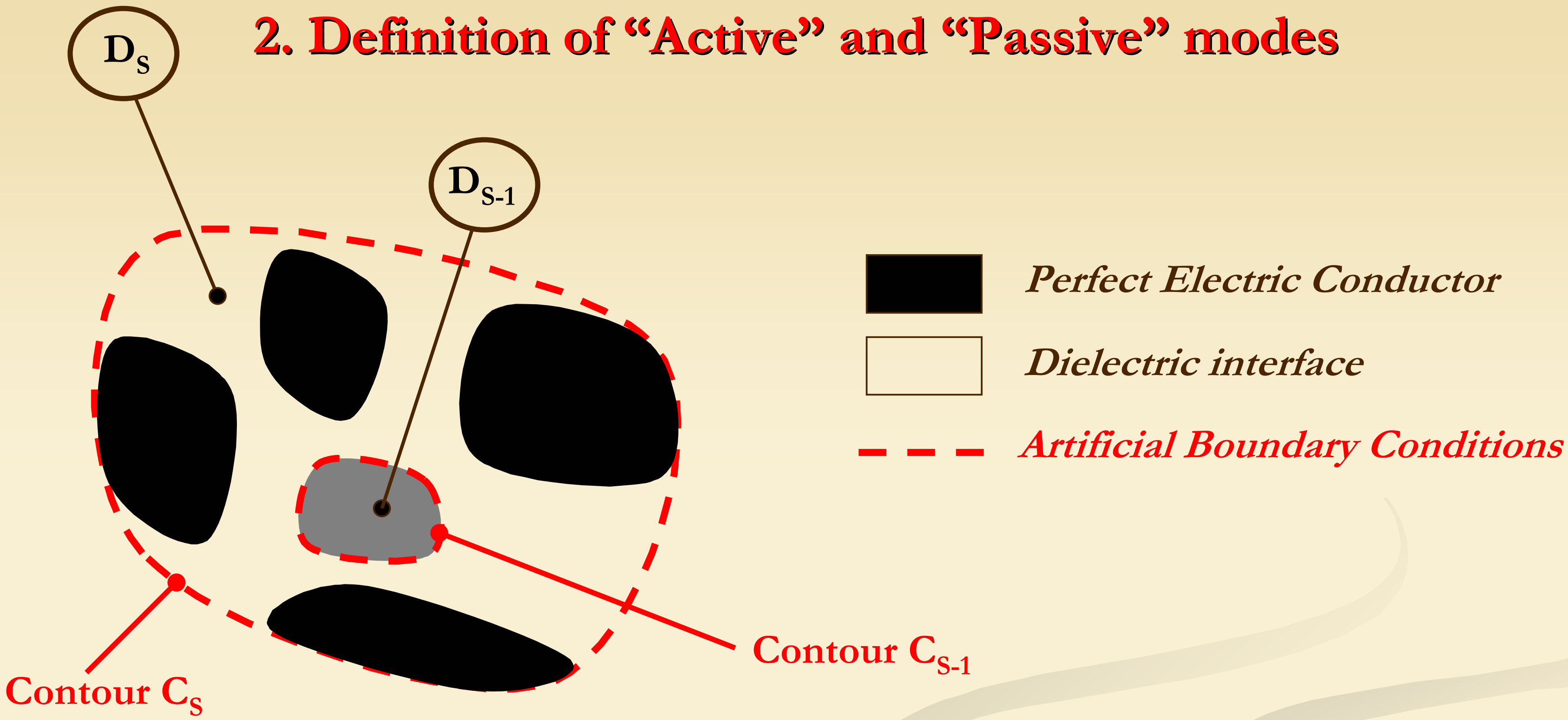
hierarchical domain-decomposition

Example :

Prefractal multi-band scatterer



2. Definition of "Active" and "Passive" modes



⇨ Derivation of the *modal basis* in D_S and D_{S-1} :

$$\begin{cases} \left[\nabla_T^2 + k_n^{(s)^2}\right] \vec{F}_n^{(s)} = \vec{0} \\ \text{B.C. along } C_S \end{cases}$$

and

$$\begin{cases} \left[\nabla_T^2 + k_n^{(s-1)^2}\right] \vec{F}_n^{(s-1)} = \vec{0} \\ \text{B.C. along } C_{S-1} \end{cases}$$

Tangential electric field in D_S : smooth variations & highly irregular fluctuations

$$\vec{E}^{(s)} = \sum_{n=1}^{\infty} V_n^{(s)} \vec{F}_n^{(s)} = \boxed{\sum_{n=1}^{N^{(s)}} V_n^{(s)} \vec{F}_n^{(s)}} + \boxed{\sum_{N^{(s)}+1}^{\infty} V_n^{(s)} \vec{F}_n^{(s)}}$$

Large-scale (spectrally localized)

Linear combination of few lower-order modes in D_S

Participate in the description of the coupling between smaller sub-domains in D_S

Fine-scale (spatially localized)

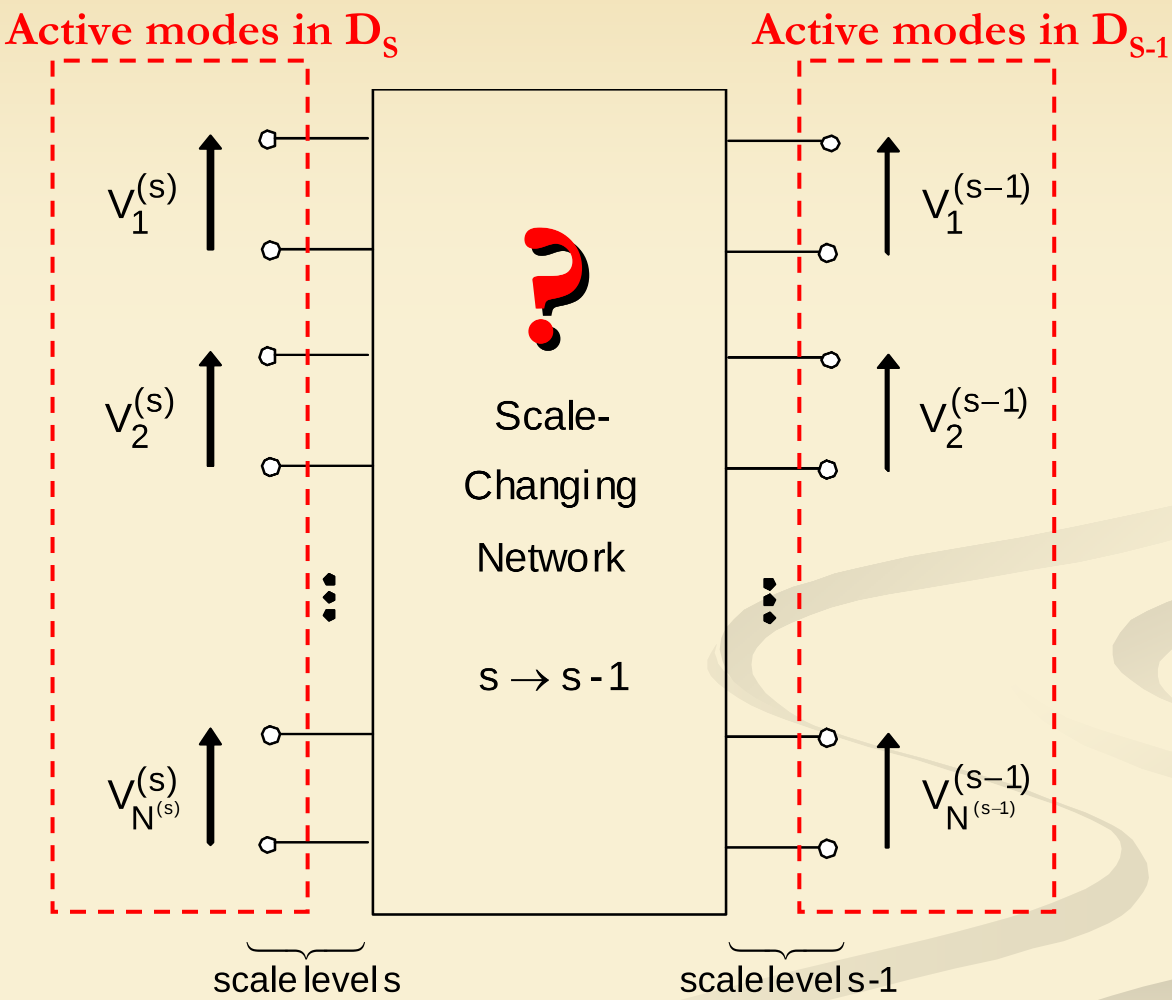
Linear combination of an infinite number of higher-order modes in D_S

Contributes significantly to the representation of the field only in the vicinity of discontinuities and sharp edges

« Active » modes

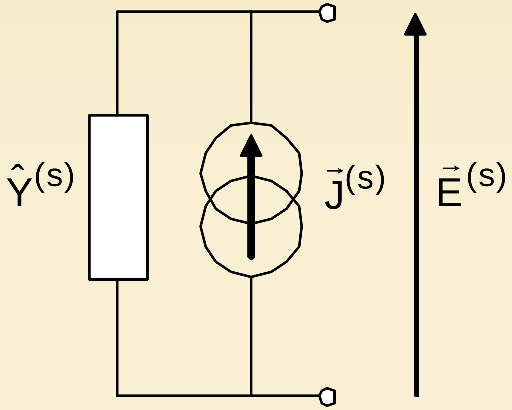
« Passive » modes

3. Derivation of the "Scale-Changing Network" *



⇨ Active modes in D_S and D_{s-1} are taken as field excitations:

- "Scale-Changing Sources" at the large scale D_S



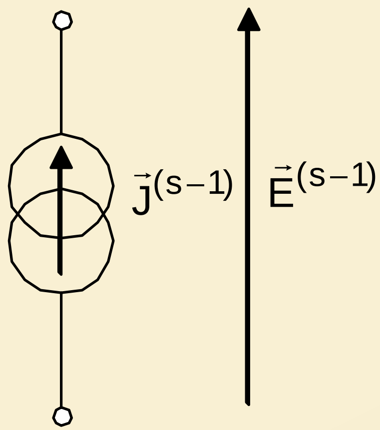
$$\vec{J}^{(s)} = \sum_{n=1}^{N^{(s)}} I_n^{(s)} \vec{F}_n^{(s)}$$

Known combination of active modes

$$\hat{Y}^{(s)} = \sum_{n=N^{(s)}+1}^{\infty} \left| \vec{F}_n^{(s)} \right\rangle Y_n^{(s)} \left\langle \vec{F}_n^{(s)} \right|$$

Passive mode are shunted by their modal admittance

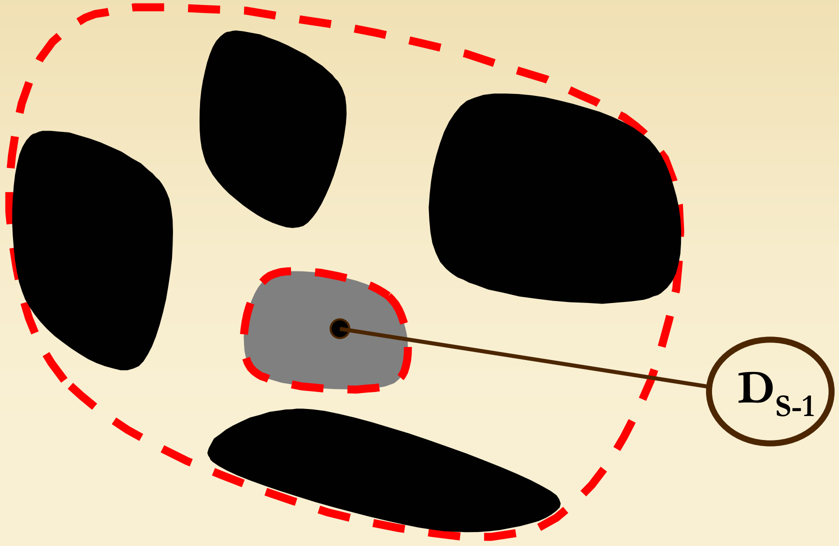
- "Scale-Changing Sources" at the smaller scale D_{S-1}



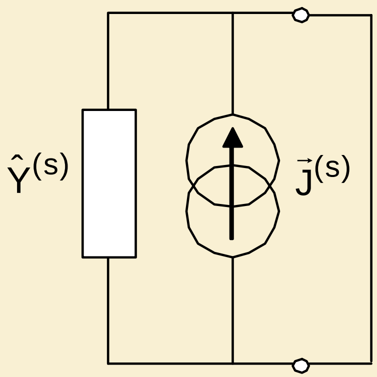
Known combination of active modes

$$\vec{J}^{(s-1)} = \sum_{n=1}^{N^{(s-1)}} I_n^{(s-1)} \vec{F}_n^{(s-1)}$$

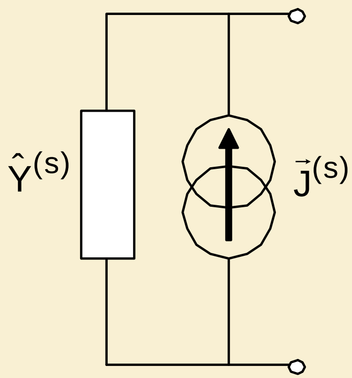
Formulation of the boundary value problem in D_S



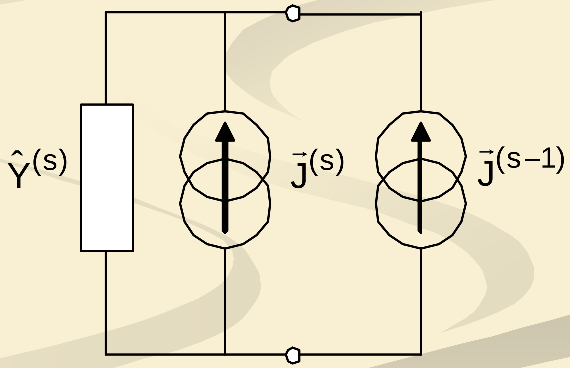
- ***Equivalent circuits that model the boundary conditions*:**



in the perfect electric conductors domain



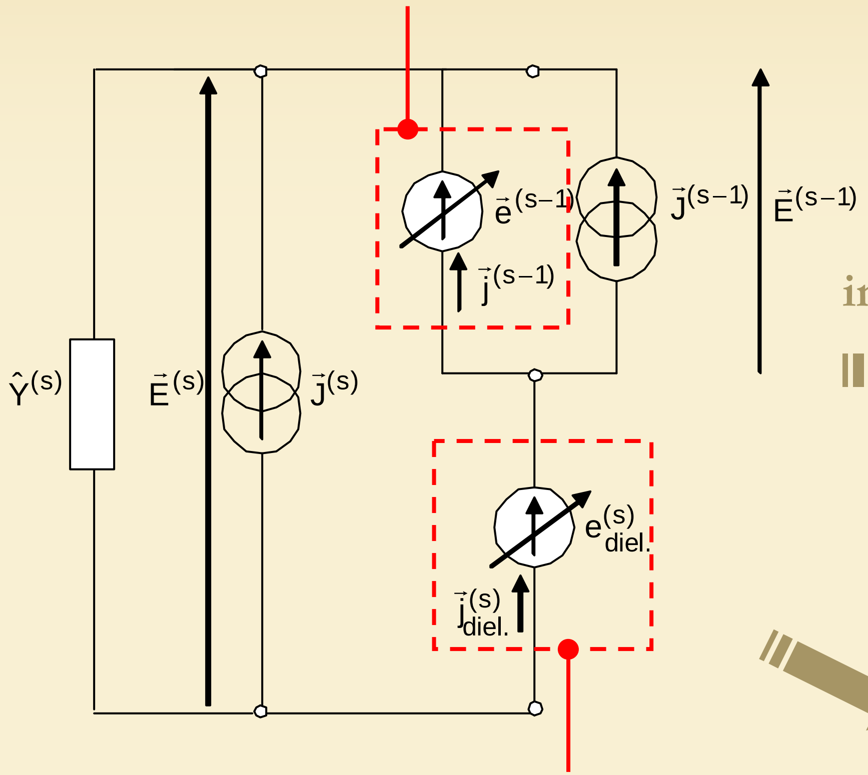
in the lossless dielectric domain



in the sub-domain D_{S-1}

● *Equivalent network representation of B.C. in the domain D_s*

virtual source in $D_{S\text{-}1}$

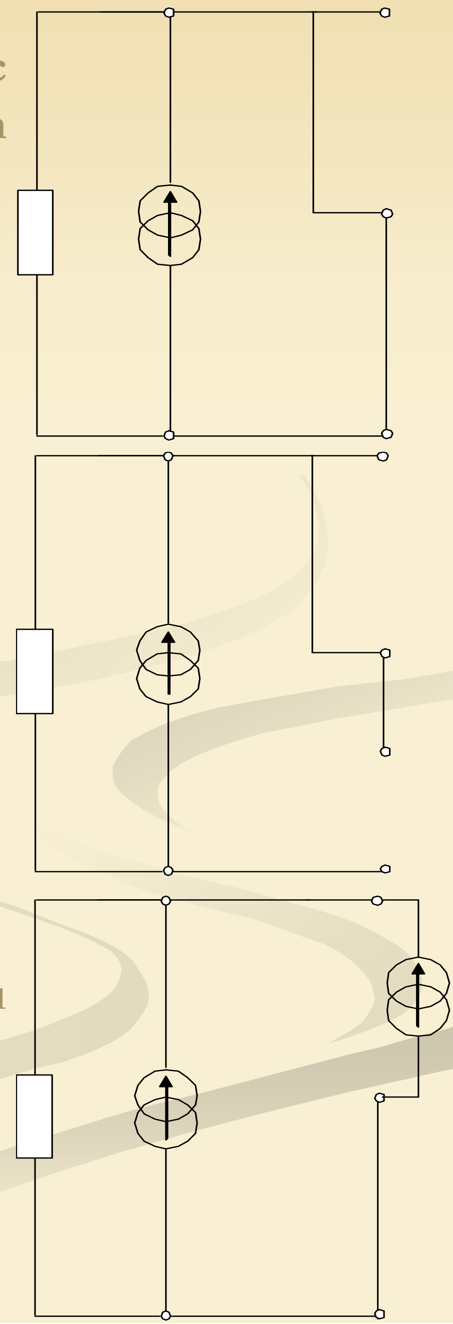


virtual source in dielectric domain

in the perfect electric conductors domain

in the lossless dielectric domain

in the sub-domain $D_{S\text{-}1}$



The concept of virtual sources has been introduced by Prof. H. Baudrand in the 80's

● *Derivation of the boundary value problem*

Kirchhoff's and Ohm's laws applied to the equivalent network :

$$\begin{bmatrix} \vec{E}^{(s)} \\ \vec{E}^{(s-1)} \\ \vec{j}^{(s-1)} \\ \vec{j}^{(s)}_{diel} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \hat{1} & \hat{1} \\ 0 & 0 & \hat{1} & 0 \\ -\hat{1} & -\hat{1} & \hat{Y}^{(s)} & \hat{Y}^{(s)} \\ -\hat{1} & 0 & \hat{Y}^{(s)} & \hat{Y}^{(s)} \end{bmatrix} \begin{bmatrix} \vec{J}^{(s)} \\ \vec{J}^{(s-1)} \\ \vec{e}^{(s-1)} \\ \vec{e}^{(s)}_{diel} \end{bmatrix}$$

dual quantities of the sources — sources

with $\vec{e}^{(s-1)}$ and $\vec{e}^{(s)}_{diel}$ virtual sources, i.e. :

$$\begin{cases} \vec{j}^{(s-1)} = \vec{0} & \text{in sub-domain } D^{(s-1)} \\ \vec{j}^{(s)}_{diel} = \vec{0} & \text{in the dielectric domain} \end{cases}$$

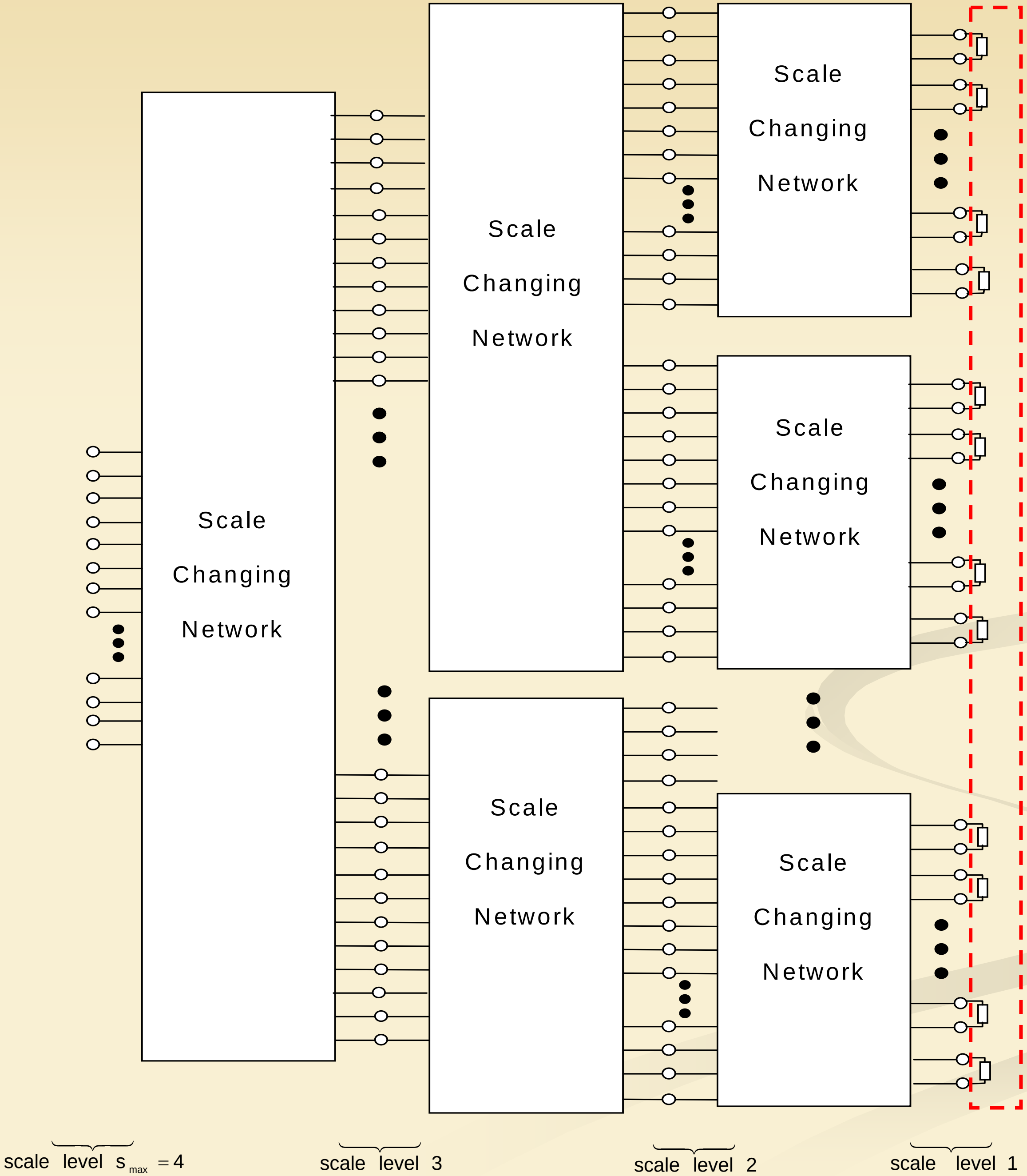
● *Numerical resolution by applying Galerkin's method*

Choice of two sets of entire-domain trial functions for the expansion of the two (unknown) virtual sources :

$$\begin{bmatrix} [V^{(s)}] \\ [V^{(s-1)}] \\ [0] \\ [0] \end{bmatrix} = \begin{bmatrix} [0] & [0] & [P] & [Q] \\ [0] & [0] & [R] & [0] \\ -[P]^{*T} & -[R]^{*T} & [\hat{Y}]_{11} & [\hat{Y}]_{12} \\ -[Q]^{*T} & [0] & [\hat{Y}]_{21} & [\hat{Y}]_{22} \end{bmatrix} \begin{bmatrix} [I^{(s)}] \\ [I^{(s-1)}] \\ [a^{(s-1)}] \\ [a^{(s)}] \end{bmatrix}$$

$$\begin{bmatrix} [V^{(s)}] \\ [V^{(s-1)}] \end{bmatrix} = \begin{bmatrix} \mathcal{Z}^{(s,s-1)} \end{bmatrix} \begin{bmatrix} [I^{(s)}] \\ [I^{(s-1)}] \end{bmatrix}$$

3. Global EM Simulation by cascading SCNs



At the smallest scale level (s = 0) :

Equivalent surface impedances

Key advantages of the Scale Changing Technique

- ✓ Judicious partitioning of the discontinuity plane avoids critical aspect ratios
- ✓ Fine description of the electromagnetic field at each scale may be reached
- ✓ Modifications of the geometry at a given scale does not require the recalculation of the overall structure (modular approach)
- ✓ Scale changing networks are computed separately : highly parallelizable

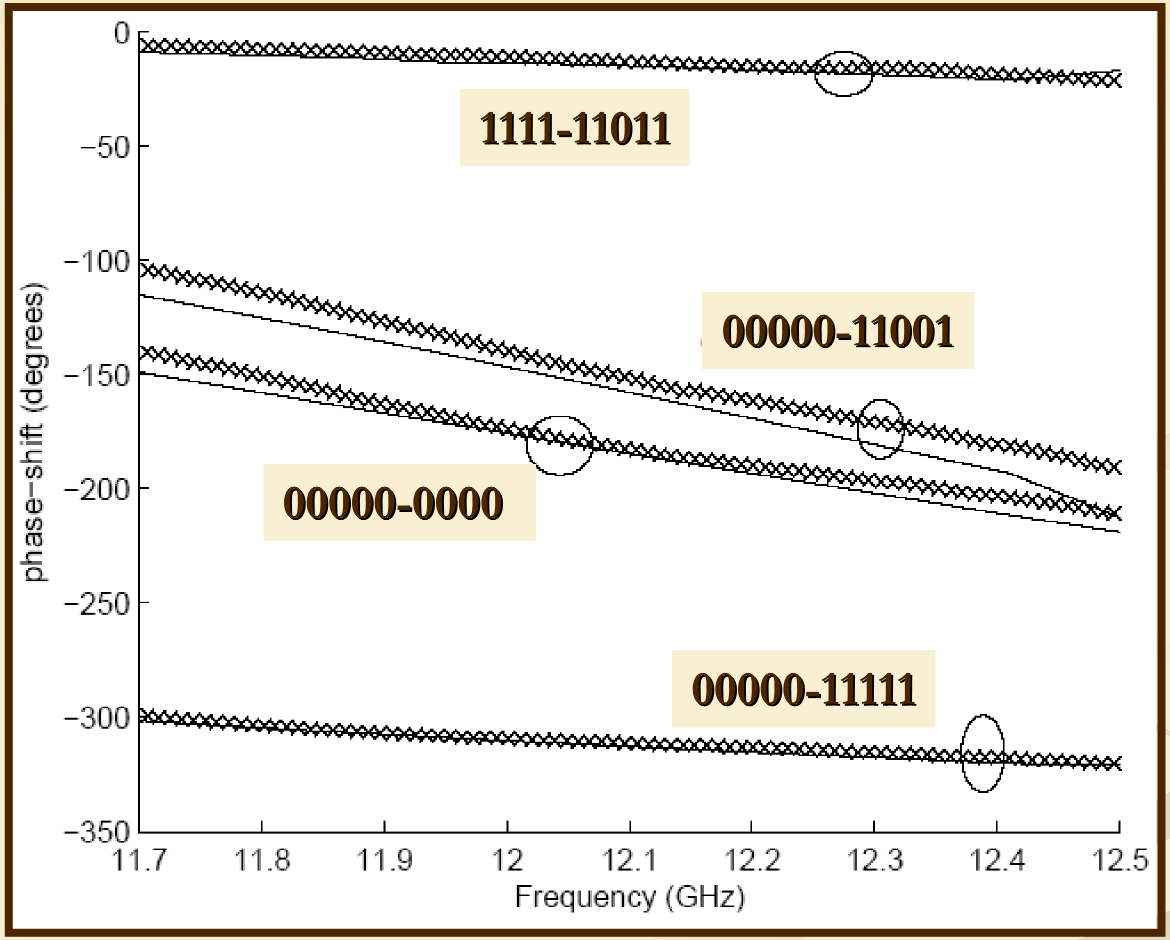
Difficulties

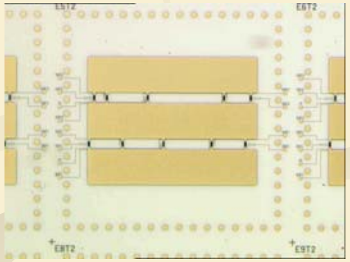
- ✓ Systematic convergence studies on the number of modes are required
- ✓ No systematic rules for the choice of the boundary conditions

Example No1 : MEMS-controlled planar Phase-shifter *

(——) Experimental data (waveguide simulator technique)

(xxxx) Scale-Changing Technique





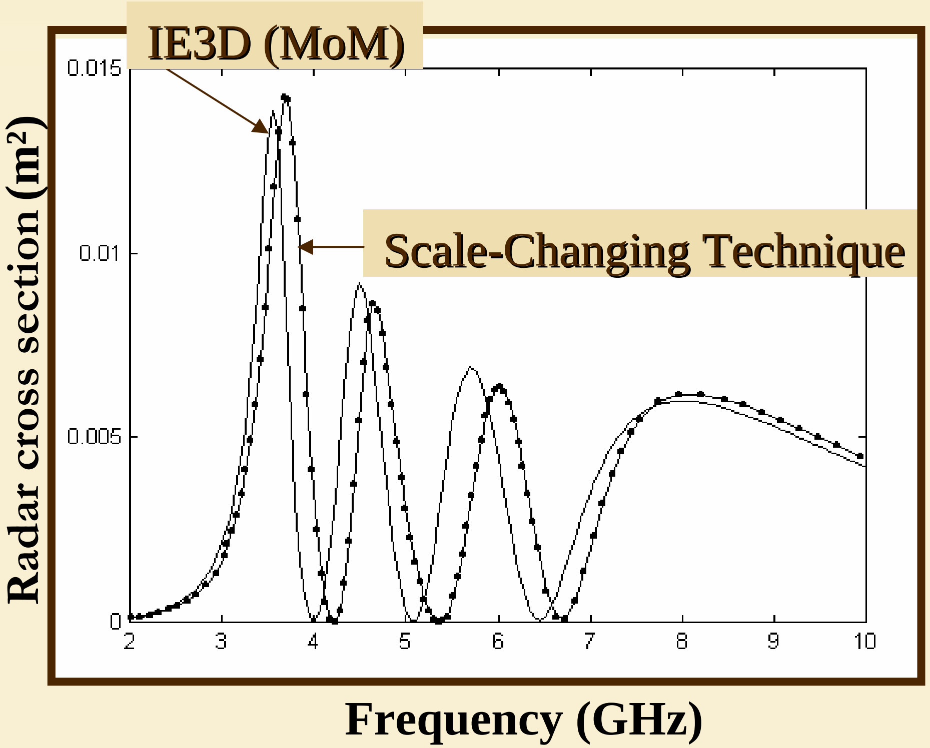
0 : switch is OFF

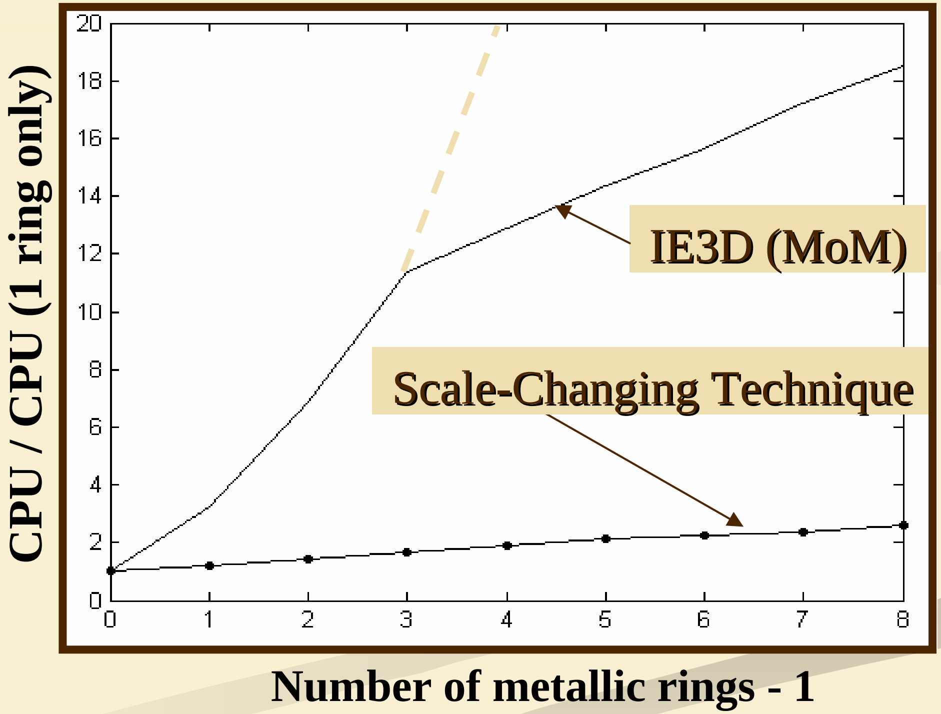
1 : switch is ON

* *From* E. Perret, H. Aubert, H. Legay, *IEEE Trans. On Microwave Theory and Tech.* (2006)

Example No2 : Multi-band scatterer *

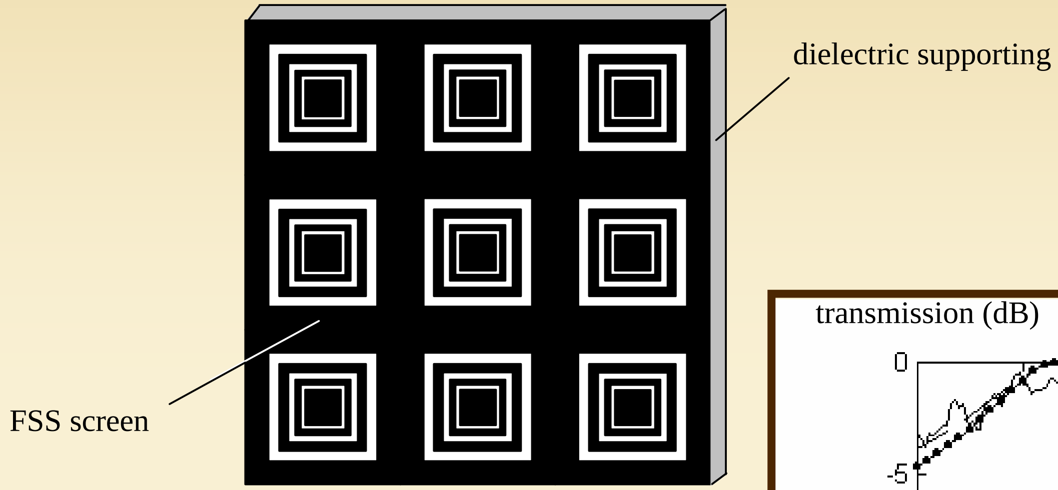
Concentric metallic rings

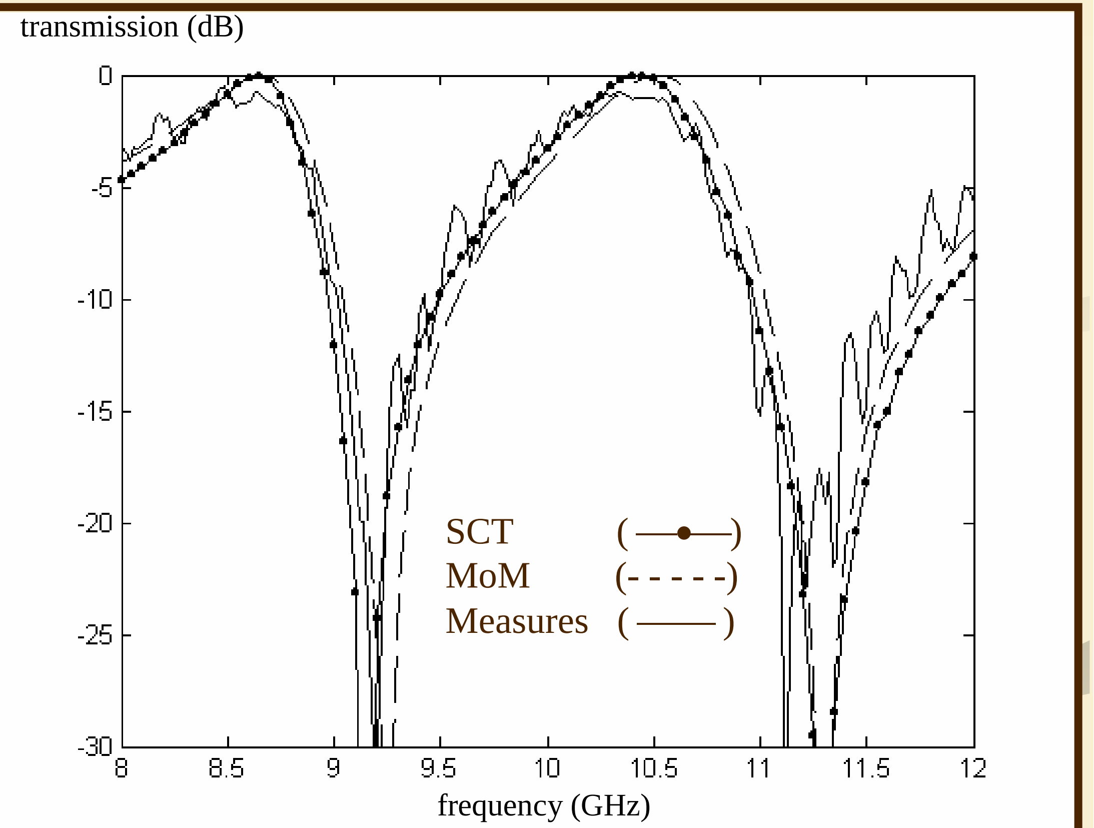




* *From* D. Voyer, H. Aubert, J. David, *Electronics Letters*, Feb. 2005

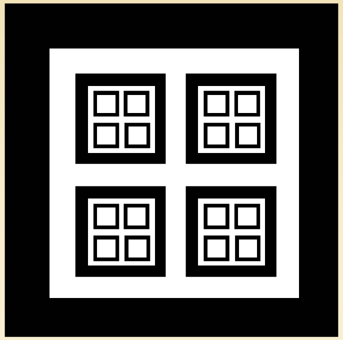
Exemple No3 : Multi-Frequency Selective Surface *



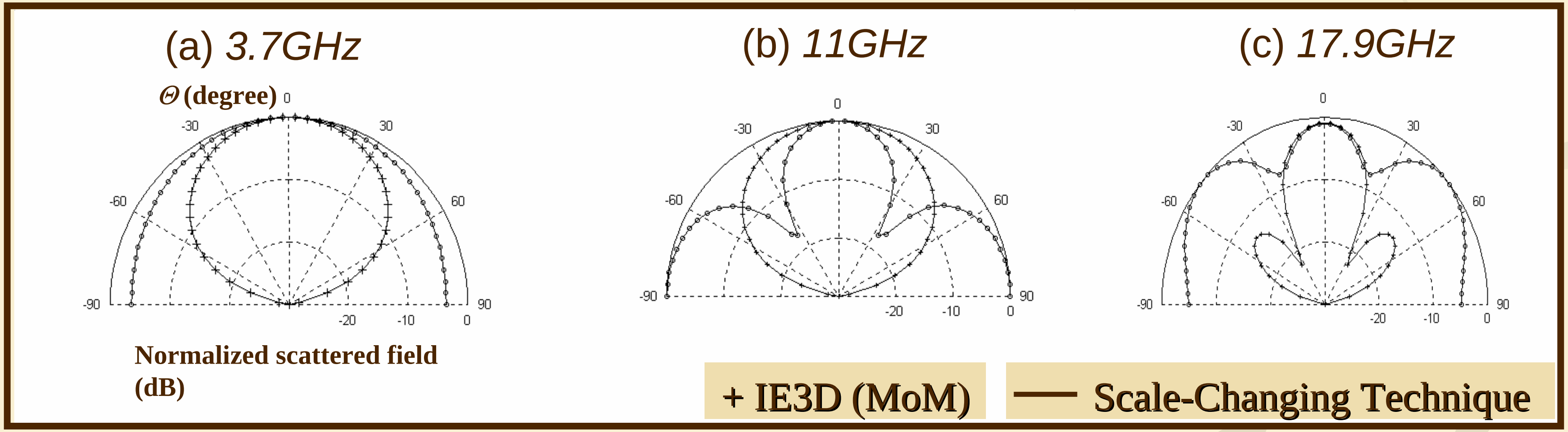


* *From* **D. Voyer, H. Aubert, J. David,** ***IEEE Trans. Antennas Propagat.*** **(Oct. 2006)**

Example No4 : Finite-size multi-frequency selective surface *



Sierpinski carpet



* *From* D. Voyer, H. Aubert, J. David, *IEEE Trans. Antennas Propagat.* (Oct. 2006)

The applications of SCT for the electromagnetic simulation of …

1. Active antennas in non linear regime

Hybridization of SCT with the Multi-domain approach
in collaboration with ONERA, PhD. Studies funded by Thalès (2005-2008)

2. Reflectarrays with coupled dissemblable cells

PhD. Studies funded by Thalès/Midi-Pyrénées Regional Council (2006-2009)

3. Very Large Structures

BQR PRES Toulouse in collaboration with IRIT (2009)

4. Multi-scale structures

Implementation of SCT in Grid Computing environment
ANR Project : Multi-scale modeling: from Electromagnetism to the GRID
in collaboration with ID Lab. Grenoble (2007-2010)

5. Periodical Frequency Selective surfaces

PhD. Studies funded by CNES (2007-2010)

The future of the Scale-Changing Technique (SCT)

1. Hybridization of SCT with full-wave 3D techniques (TLM, Multi-domain approach)
   Complex structures 3D

2. Implementation of SCT in Grid Computing environment
   "Scale-driven" scheduler