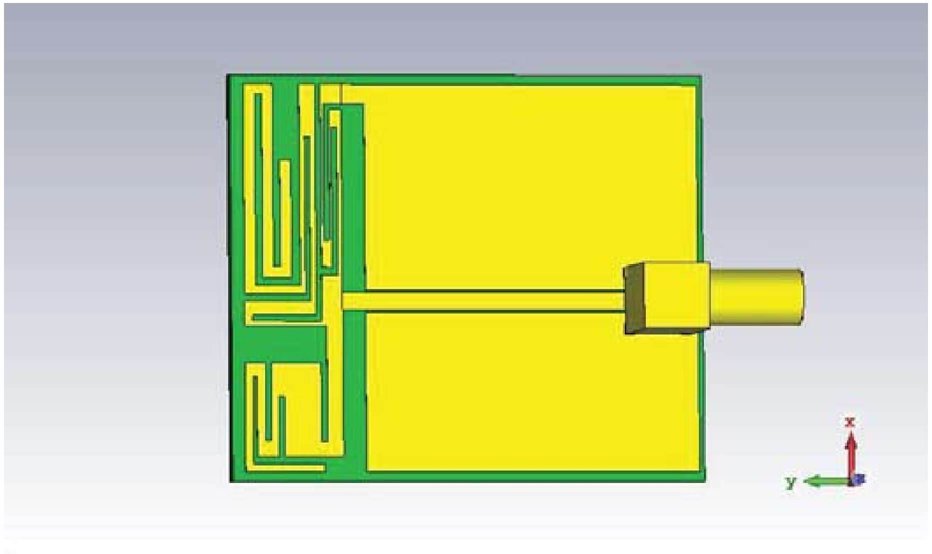
Some simulation issues (full wave simulations)

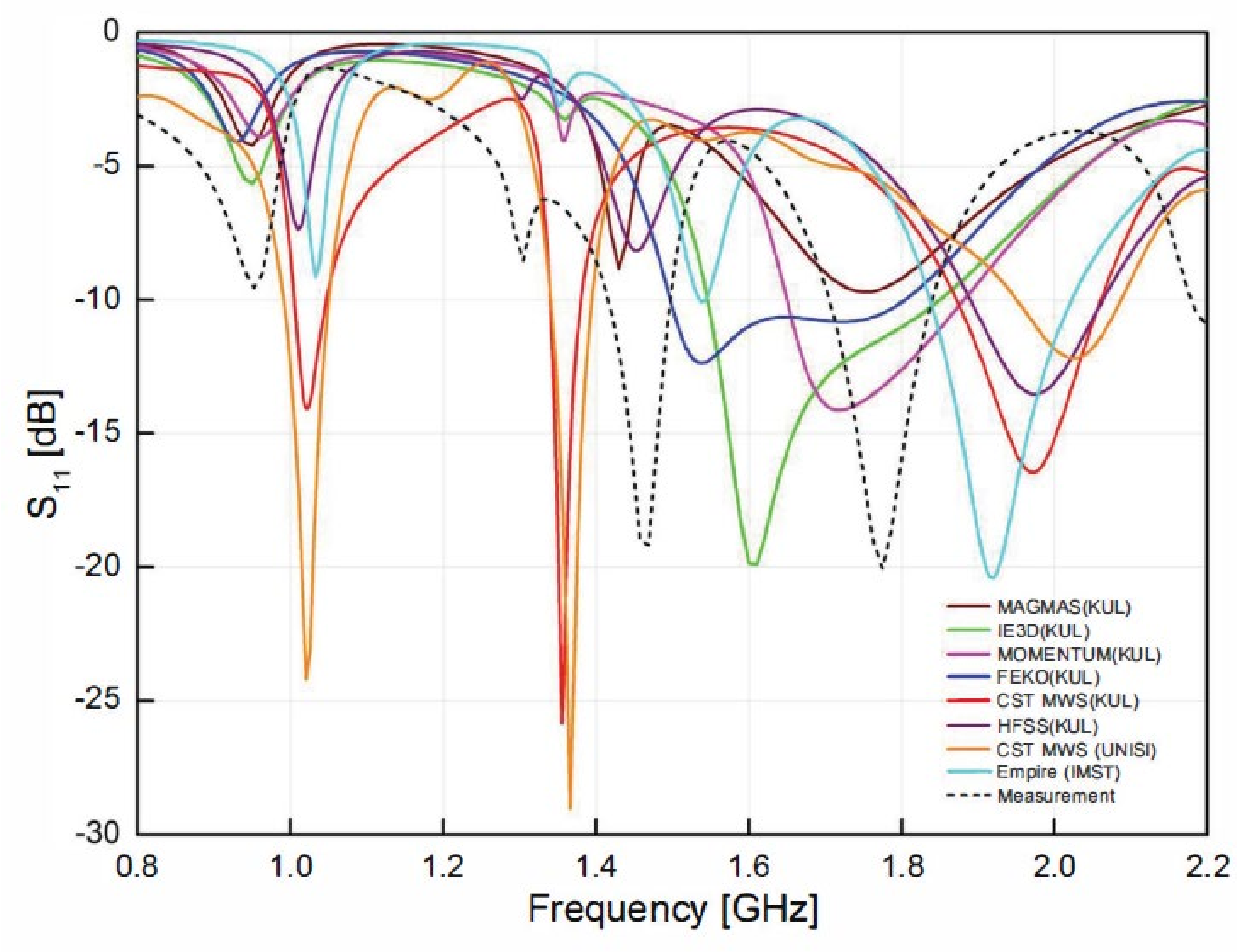
Advanced microwaves

What is the problem: an old benchmark



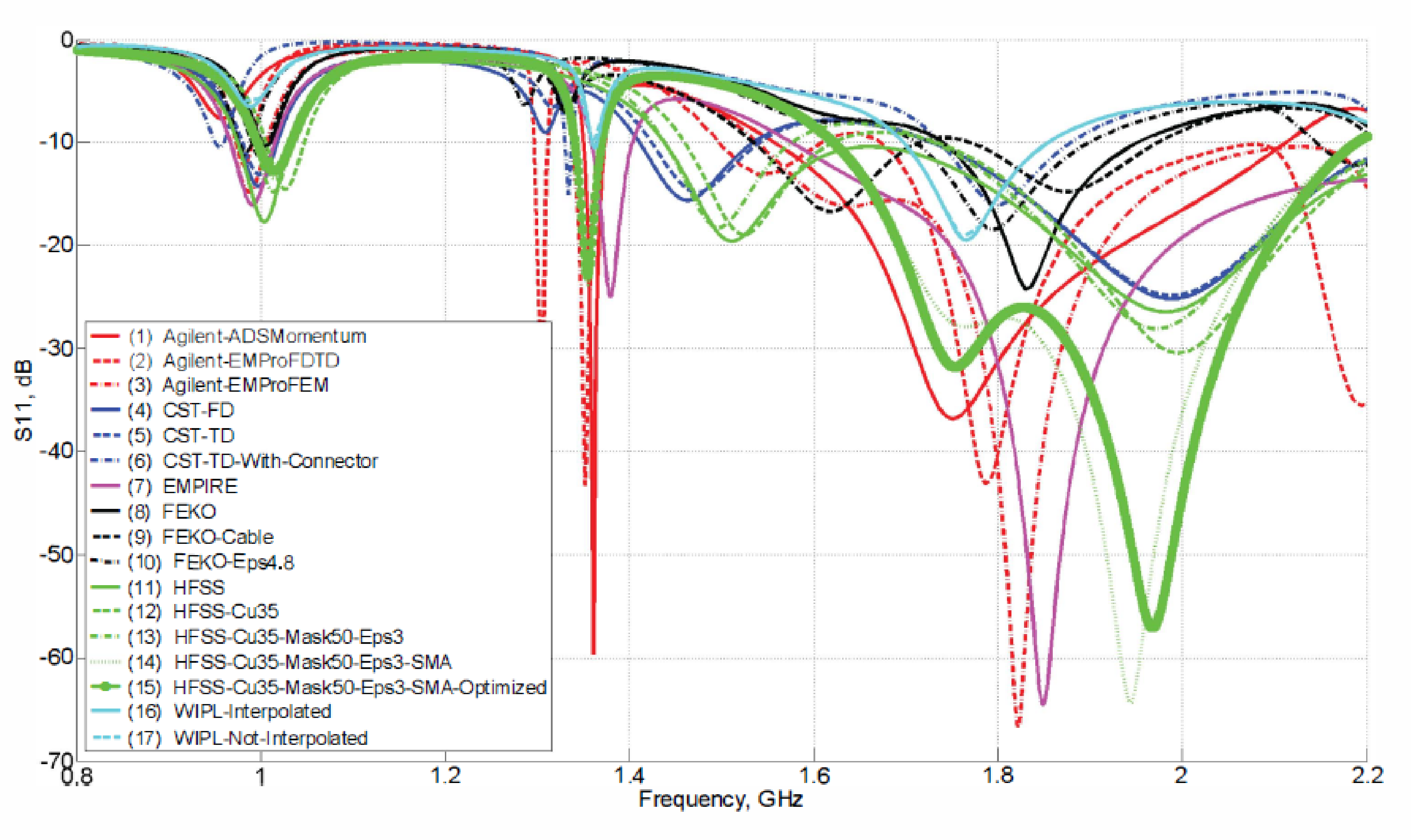
G. A. E. Vandenbosch, “State-of-the-art in antenna software benchmarking—‘Are we there, yet?’” *IEEE Antennas Propag. Mag.*, vol. 56, no. 4, pp. 300–308, Aug. 2014.

Results in 2009

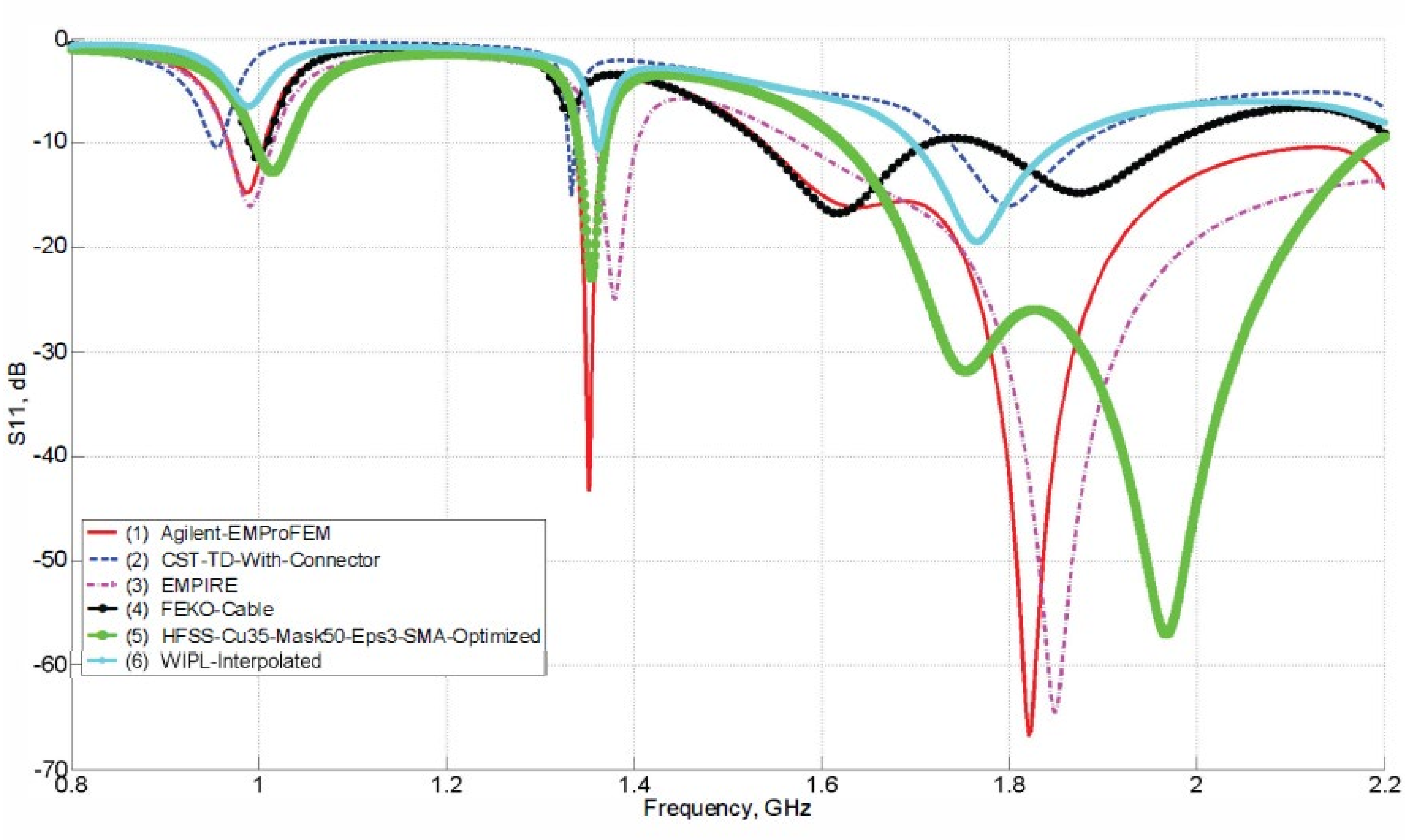


G. A. E. Vandenbosch, “State-of-the-art in antenna software benchmarking—‘Are we there, yet?’” *IEEE Antennas Propag. Mag.*, vol. 56, no. 4, pp. 300–308, Aug. 2014.

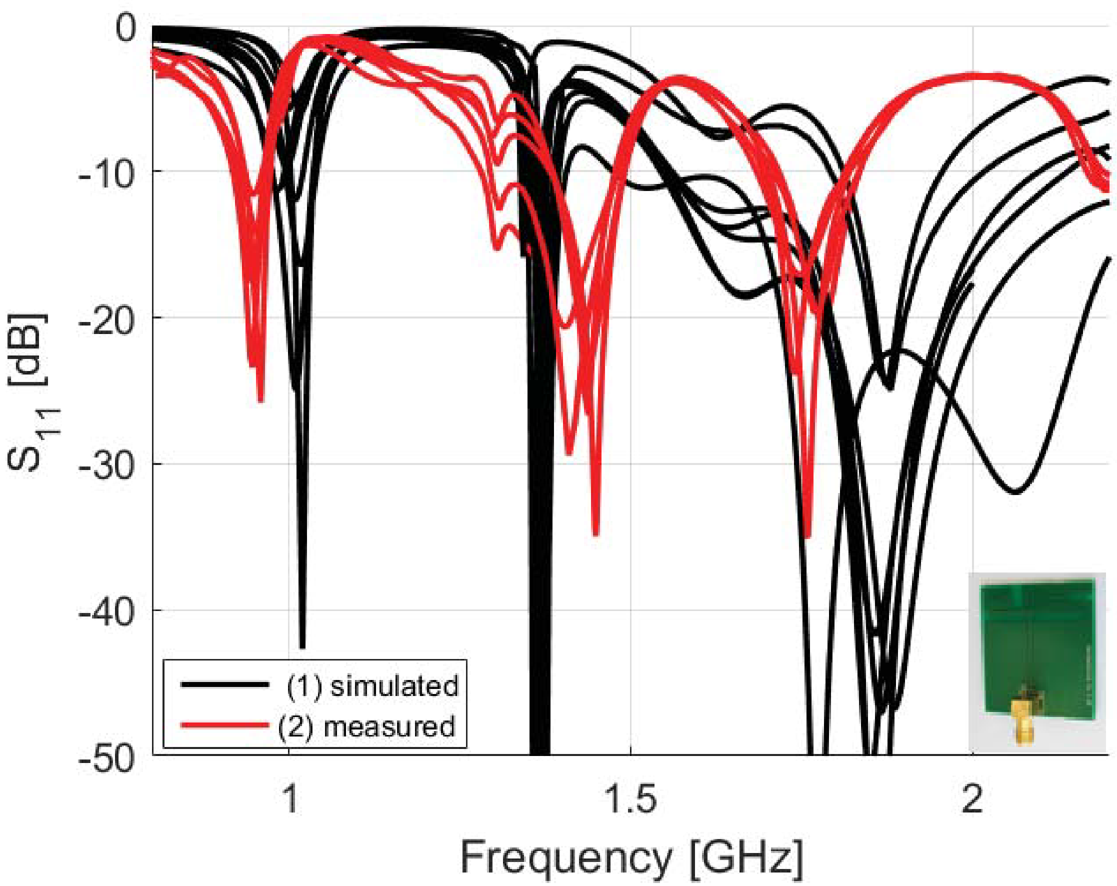
Results in 2013



Best results in 2013



Results in 2018



Guy A.E. Vandenbosch, Modeling and Design Tools for Small Antennas: State of the Art and Future Perspectives
IEEE Antennas and Propagation Magazine
Year: 2018 , Volume: 60 , Issue: 4
Pages: 18 - 20

An overview on methods

Selection of solution domain

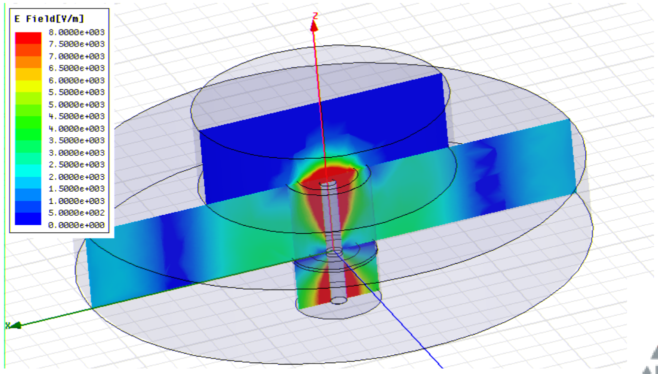
- Time domain
- Frequency domain

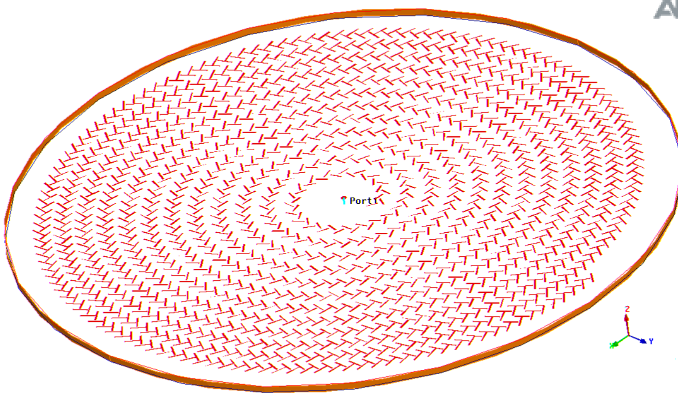
Selection of the Field Propagator

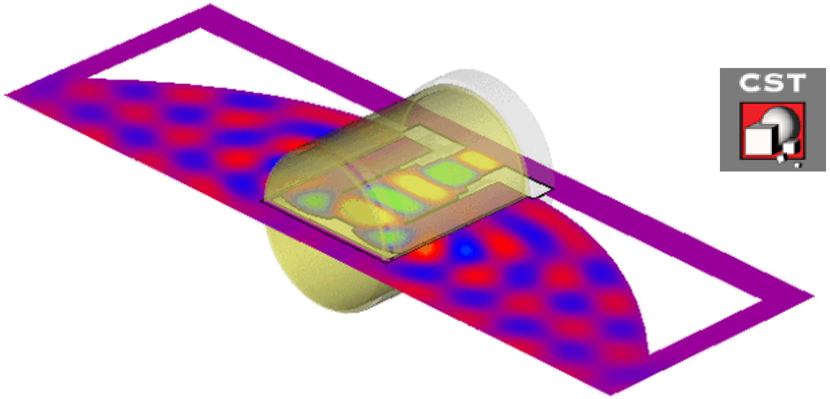
- Integral Equation (IE) model
    - Global field propagator
- Differential Equation (DE) model
    - Local field propagator

Selection of the Sampling Functions

- entire-domain functions
- sub-domain functions







Solution domain

Time domain

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = \mathbf{0}$$

Frequency domain

$$\nabla \times \mathbf{E} = -j\omega\mathbf{B}$$

$$\nabla \times \mathbf{H} = j\omega\mathbf{D} + \mathbf{J}$$

$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \cdot \mathbf{B} = \mathbf{0}$$

Field Propagator

Local

- An unknown (usually E and H) interacts only with its closest neighbours

Global

- All unknowns interact with each other

Example of local field propagator: 1-D FDTD

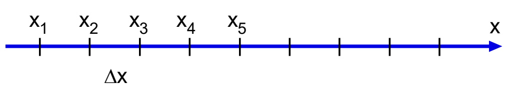
Consider the 1-d wave equation

$$\frac{\partial^2 u(x,t)}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 u(x,t)}{\partial t^2}$$

For the simulation domain

$$0 \le x \le d$$

And the following grid



with

$$x_m = (m-1)\Delta x$$

$$\Delta x = \frac{d}{M-1}$$

$$t_n = (n-1)\Delta t$$

$$u_m^n = u(x_m, t_n) = u\left[(m-1)\Delta x, (n-t)\Delta t\right]$$

Example of local field propagator: 1-D FDTD

We need to find the numerical expression for the derivatives:

$$\frac{\partial^2 u(x,t)}{\partial x^2} \simeq \frac{\partial}{x}\left[\frac{u(x+\Delta x/2,t)-u(x-\Delta x/2,t)}{\Delta x}\right]$$

$$\simeq \frac{u(x+\Delta x,t)-2u(x,t)+u(x-\Delta x,t)}{(\Delta x)^2}$$

$$\frac{\partial^2 u(x,t)}{\partial t^2} \simeq \frac{\partial}{t}\left[\frac{u(x,t+\Delta t/2)-u(x,t-\Delta t/2)}{\Delta t}\right]$$

$$\simeq \frac{u(x,t+\Delta t)-2u(x,t)+u(x,t-\Delta t)}{(\Delta t)^2}$$

Example of local field propagator: 1-D FDTD

With: $r = \dfrac{c\Delta t}{\Delta x}$ we write

$$r^2\left[u\left(x+\Delta x,t\right)-2u\left(x,t\right)+u\left(x-\Delta x,t\right)\right]=$$
$$\left[u\left(x,t+\Delta t\right)-2u\left(x,t\right)+u\left(x,t-\Delta t\right)\right]$$

Which can be written as

$$r^2\left(u_{m+1}^{n}-2u_{m}^{n}+u_{m-1}^{n}\right)=u_{m}^{n+1}-2u_{m}^{n}+u_{m}^{n-1}$$
$$u_{m}^{n+1}=r^2\left(u_{m+1}^{n}-2u_{m}^{n}+u_{m-1}^{n}\right)+2u_{m}^{n}-u_{m}^{n-1}$$

Each unknown interacts only
With its neighbours

Initial and boundary conditions

Initial condition in time: required for two time steps u_m^1 and u_m^2

Often, we take $u_m^1 = 0,\ u_m^2 = 0$

Boundary conditions in space, required at x_1 and x_M

Dirichlet BC: $u(0,t) = u_1^n = 0$

$$u(d,t) = u_M^n = 0$$

Neumann BC: $u_1^n = u_2^n$

$$u_M^n = u_{M-1}^n$$

Sources: hard sources

A hard source sets the value of a field at one or more grid points equal to a specific function of time and is thus a type of Dirichlet BC.

An issue with hard sources is that wave propagating towards them are reflected by them, which can cause modeling errors. A solution is to remove the source after launching the incident wave but before reflections arrive at the source location.

Sources: soft sources

A soft source corresponds to a forcing solution added to the wave equations, for EM problems an impressed electric current. The equation is thus modified as follows:

$$\nabla^2 \mathbf{E} - \frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} = \mu \frac{\partial \mathbf{J}}{\partial t}$$

In 1D it becomes

$$\frac{\partial^2 u(x,t)}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 u(x,t)}{\partial t^2} = \mu \frac{\partial J(x,t)}{\partial t}$$

Which can be written as

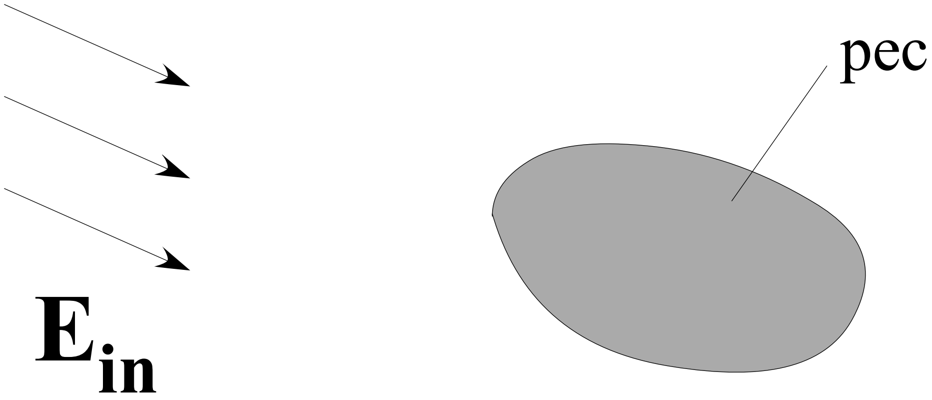
$$u_m^{n+1} = r^2\left(u_{m+1}^n - 2u_m^n + u_{m-1}^n\right) + 2u_m^n - u_m^{n-1} - c^2(\Delta t)^2 \mu \left.\frac{\partial J(x_m,t)}{\partial t}\right|_{t=t_n}$$

Finite element methods

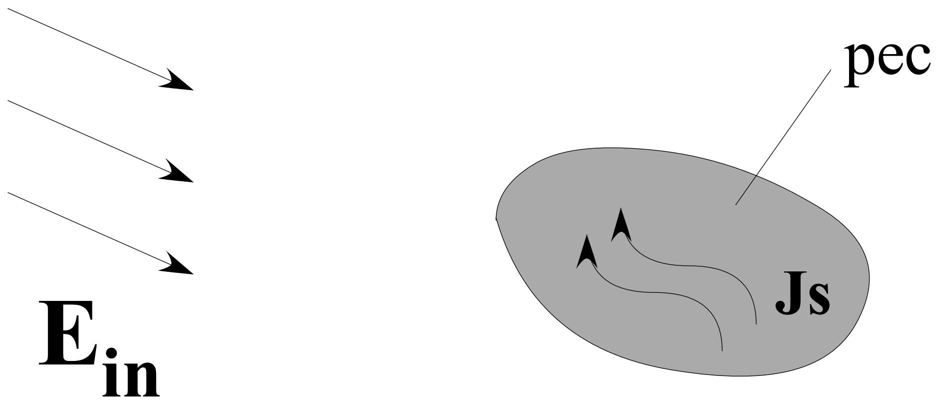
- Very rigorous, as based on function and functional analysis
- More rigorous than FDTD
- Can be used to solve any Partial differential equations
- Can take many forms
- Can be applied in time or frequency domain

Example of global field propagator: Electric Field Integral equation + Method of Moments

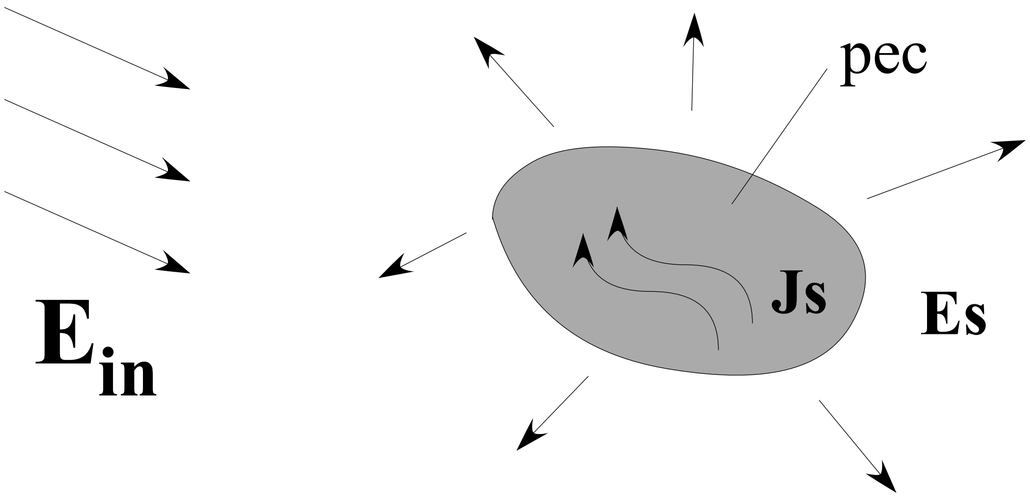
Electric field integral equation : principle



Electric field integral equation : principle



Electric field integral equation : principle



The electric field has to be normal to the body in pec:

$$\boldsymbol{n}\times\boldsymbol{E}_{in}+\boldsymbol{n}\times\boldsymbol{E}_{s}=0\Big|\text{on the pec}$$

Electric field integral equation

$$\boldsymbol{E}_s = \overline{\overline{\boldsymbol{G}}}_{EJ} \otimes \boldsymbol{J}_s$$

where $\overline{\overline{\boldsymbol{G}}}_{EJ}$ is the Green's function (field of point sources) for the electric field and

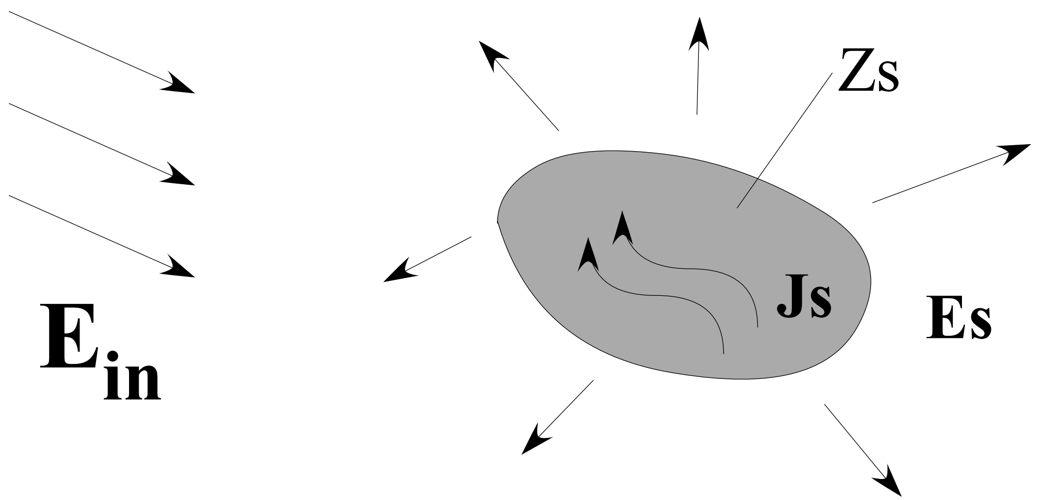
$$G \otimes f = \int_{sources} G(\mathbf{r}|\mathbf{r}')f(\mathbf{r}')dv'$$

and finally :

$$\boldsymbol{n} \times \boldsymbol{E}_{in} - \boldsymbol{n} \times \overline{\overline{\boldsymbol{G}}}_{EJ} \otimes \boldsymbol{J}_s = \boldsymbol{0}$$

EFIE

Electric field integral equation

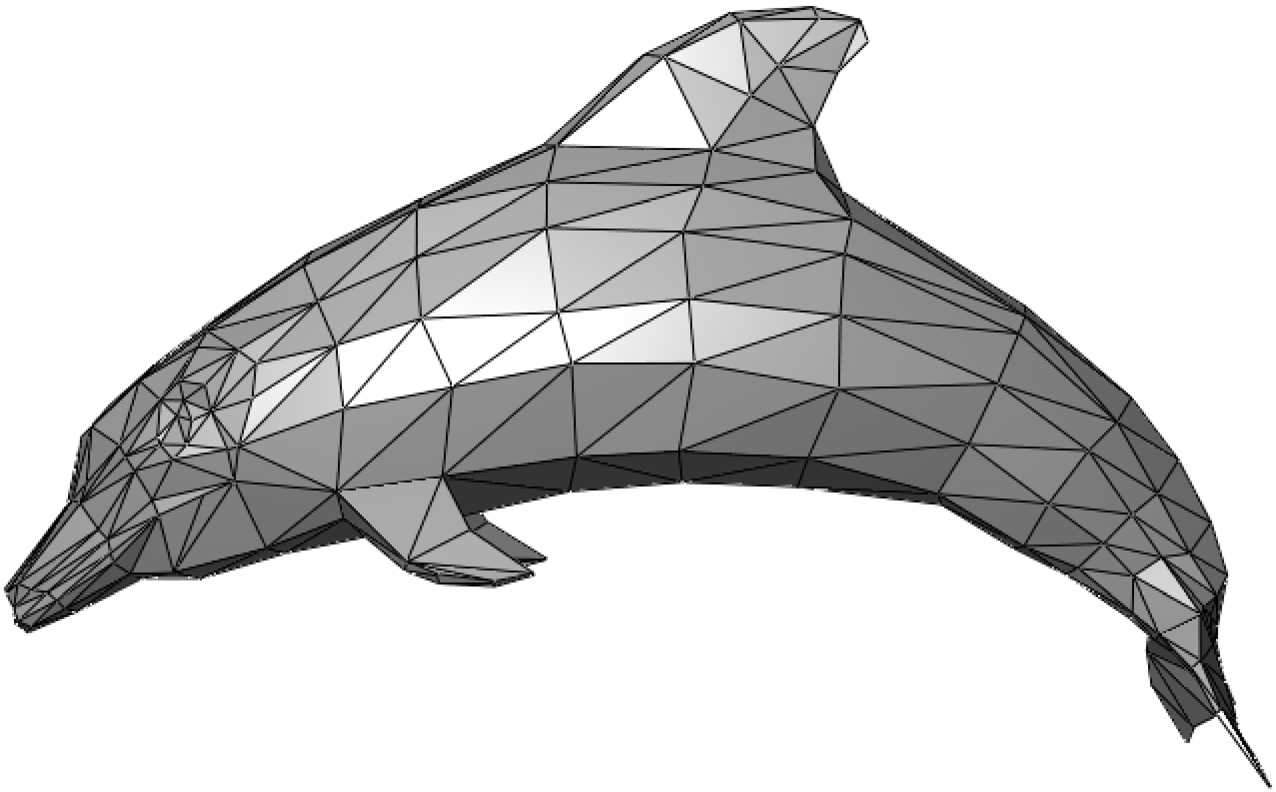


$$n \times E_{in} - n \times \overline{\overline{G}}_{EJ} \otimes J_s = Zs J_s$$

Leontovich impedance condition

Method of Moments

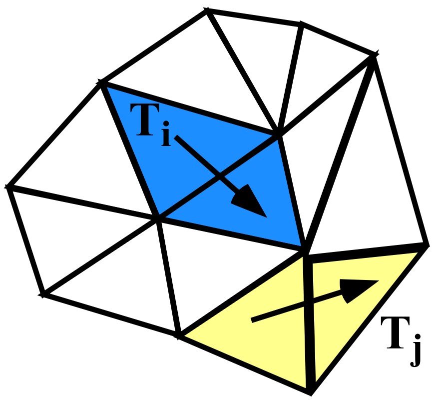
Let us consider a MoM using subsectionnal basis functions and a Galerkin testing procedure



The unknown current is expressed as a sum of basis functions

Method of Moments

The unknown current is expressed as a sum of basis functions



$$\mathbf{J_s} = \sum_{i=1}^{N} \alpha_i \mathbf{T}_i$$

$$\boldsymbol{n} \times \boldsymbol{E}_{in} - \boldsymbol{n} \times \overline{\overline{\boldsymbol{G}}}_{EJ} \otimes \boldsymbol{J}_s = 0$$

$$\boldsymbol{n} \times \boldsymbol{E}_{in} = \boldsymbol{n} \times \overline{\overline{\boldsymbol{G}}}_{EJ} \otimes \sum_{i=1}^{N} i_i \boldsymbol{J}_s$$

Galerkin testing procedure

$$Z_{ij} = \int_{s_i} \boldsymbol{T}_i(\boldsymbol{\rho})\, ds_i \int_{s'_j} \overline{\overline{\boldsymbol{G}}}_{EJ}(\boldsymbol{\rho} \mid \boldsymbol{\rho}') \cdot \boldsymbol{T}_j(\boldsymbol{\rho}')\, ds'_i \qquad [i] = [Z]^{-1}[U]$$

$$u_i = \int_{s_i} \boldsymbol{T}_i(\boldsymbol{\rho})(\boldsymbol{n} \times \boldsymbol{E}_{in})\, ds_i$$

Popular Commercial softwares

- Time domain
  - Finite Difference Time Domain (FDTD)
    - Discretization of space (3-D) and time
    - Requests absorbing boundary conditions
    - Local field propagator
    - Unknowns E and H fields
    - Mathematical excitation is a time pulse in a specific cell.
    - Physical feeds are defined as special functions (for instance transmission line modes in waveguides or cables)

Popular Commercial softwares

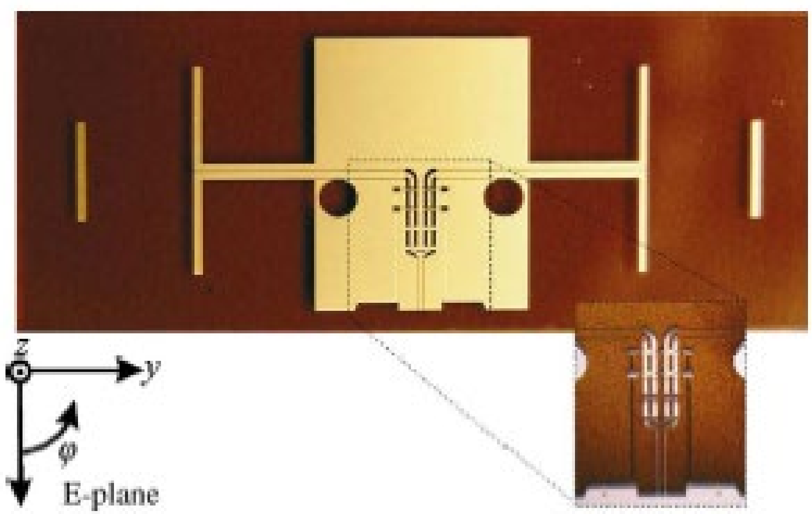
- Frequency domain
  - Finite Element Method (FEM)
    - Volume discretization of space (3-D)
    - Requests absorbing boundary conditions
    - Local field propagator
    - Unknowns E and H fields
    - Mathematical excitation is a field in a cell.
    - Physical feeds are defined as special functions (for instance as transmission line modes)

Popular Commercial softwares

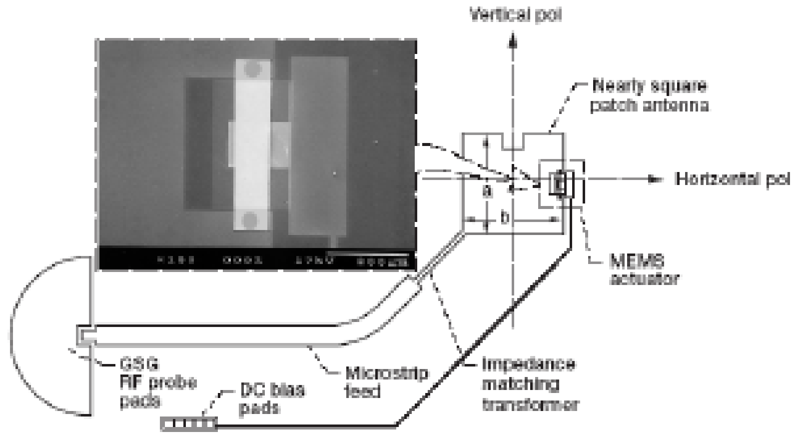
– Integral Equation + Method of Moment (MoM)
  - Surface discretization of conducting surfaces (2-D)
  - Global field propagator
  - Unknowns are surface currents
  - Mathematical excitation is a current or voltage in a cell
  - Great flexibility in the feed definition
  - Good compatibility with circuit simulators
  - Limited treatment of inhomogeneous problems

Example of simulation problems: MEMS in antennas

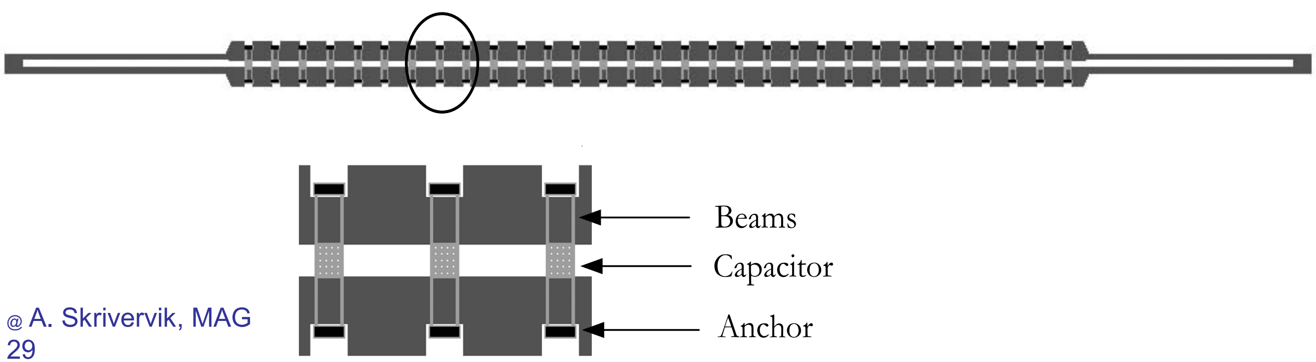
examples

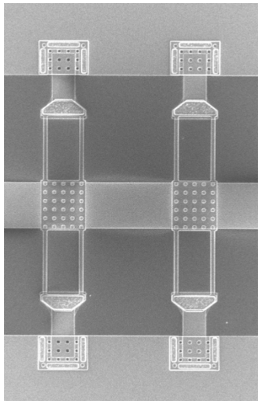


Shi Cheng, *et al.*, "Switched Beam Antenna Based on RF MEMS SPDT Switch on Quartz Substrate", IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, VOL. 8, 2009



Simons R. N. , Chun D., Katehi L. "POLARIZATION RECONFIGURABLE PATCH ANTENNA USING MICROELECTROMECHANICAL SYSTEMS (MEMS) ACTUATORS", AP-S International Symposium, San Antonio, Texas, June 16–21, 2002





Characteristics of MEMS-in antenna analysis

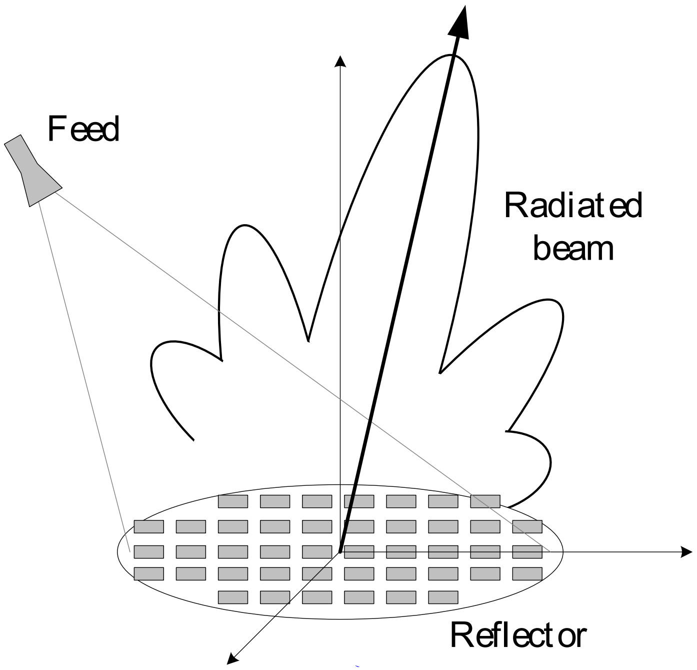
- Complex shapes
  - 3-D inhomogeneous regions
  - 3-D conducting surfaces (might be curved)
- Potentially Small ground planes
- Ill defined interfaces with feeds, mostly not properly modeled by transmission line modes
- Lumped circuit elements may be included in the radiation aperture (typically the MEMS)
- Different scales between the MEMS and the radiating aperture

EM- Modeling challenges

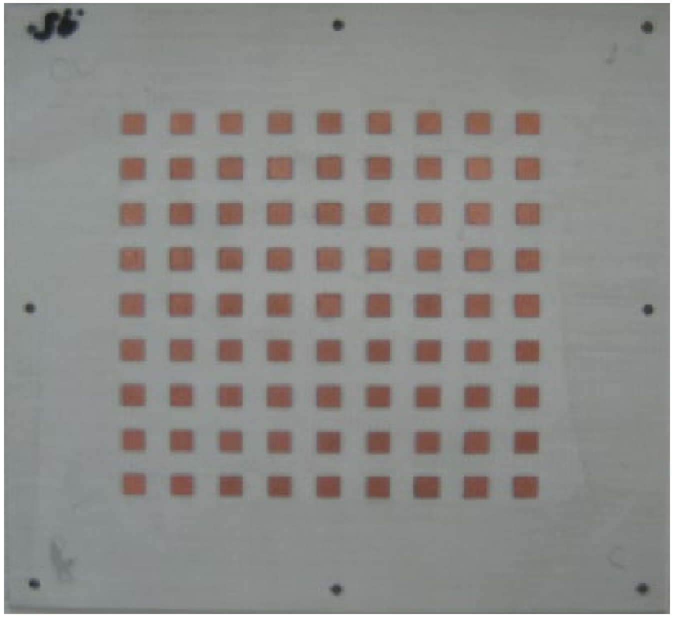
- Examples : 3 different reflectarrays
- Issues
- Possible solutions
- Requirements

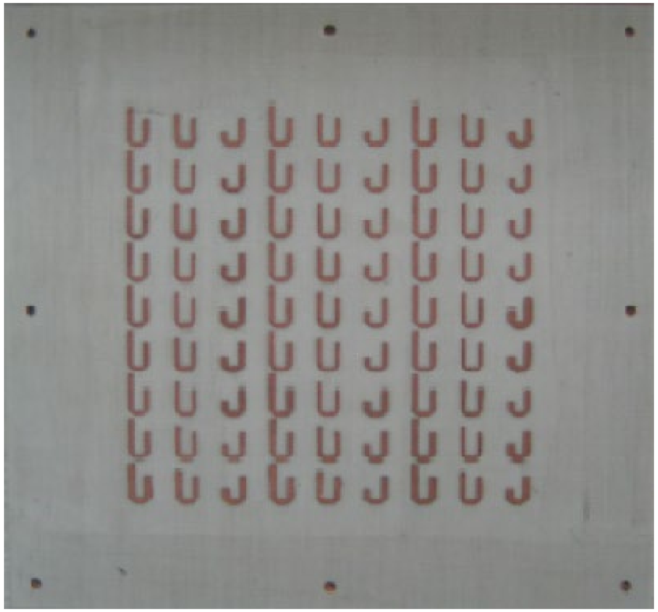
Tunable reflectarray

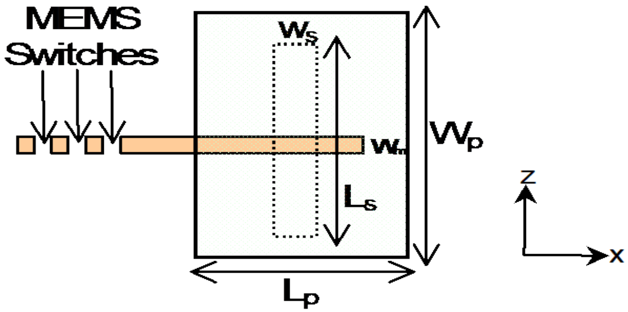
- Reflectarray (RA) principle
- Main interest in RA
  - Performances, cost, weight, etc.
  - Possibility of electronic scanning
- Reconfigurable RA cells technologies:
  - PIN diodes
  - ferroelectric thin films
  - liquid-crystal
  - Photonically-controlled semiconductor
  - MEMS

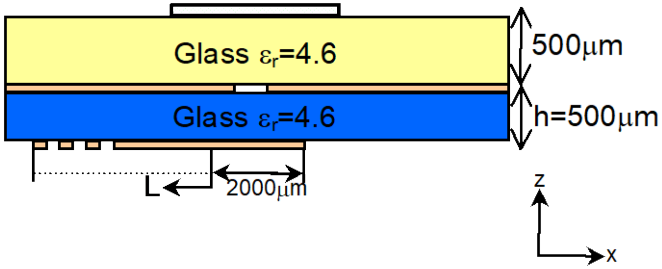


Tuneable reflectarray: MEMS in the circuit



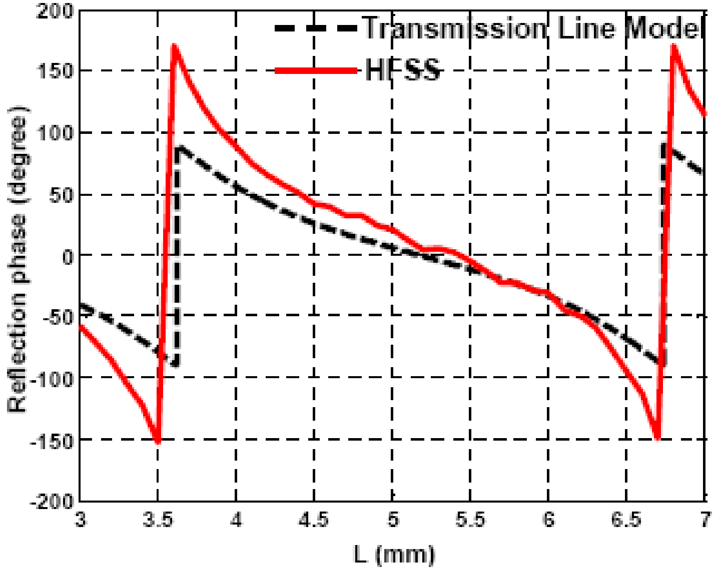




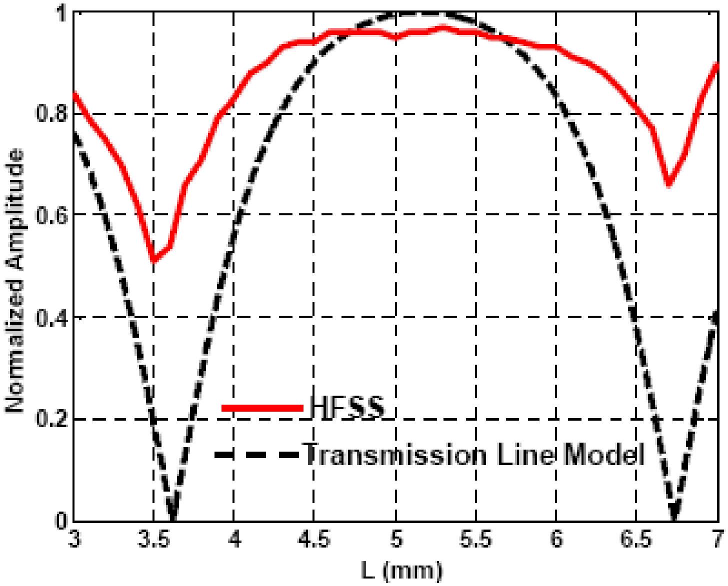


Done by the METU in Ankara in the frame of AMICOM Network

Tuneable reflectarray: MEMS in the circuit



Phase versus length

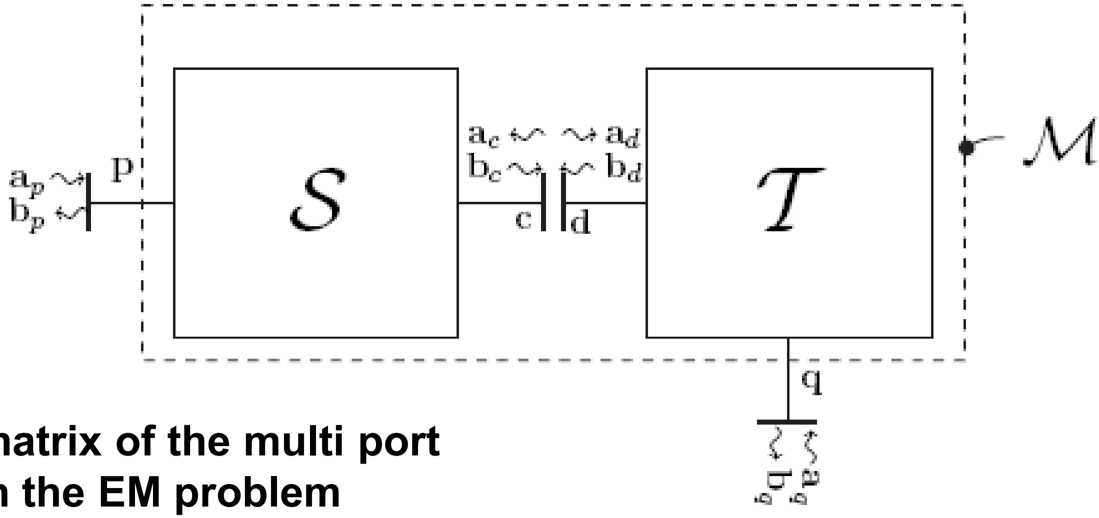


Amplitude versus length

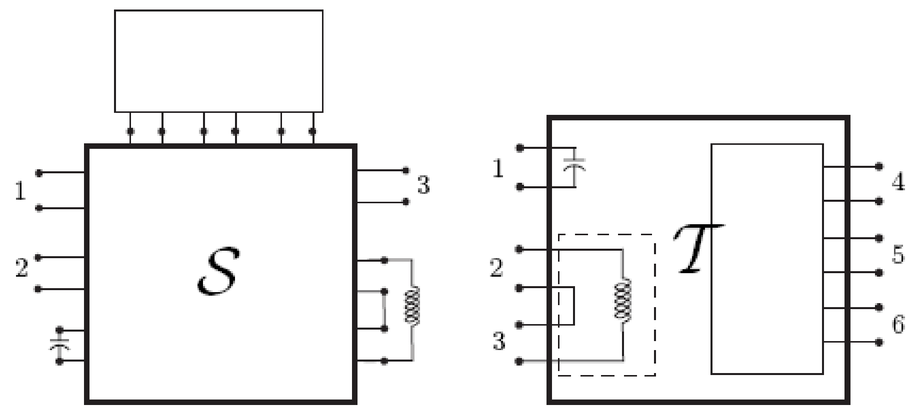
MEMS in circuit : Electromagnetic modeling

- The radiating element has to be modeled using a full wave EM simulator (IE, FEM, FDTD, ...)
- A good circuit model is needed for the MEMS, usually doing a full wave simulations, from which an usually simple equivalent circuit can be extracted
- The MEMS and the antenna are combined at a circuit level
- The packaging can easily be taken into account in the simulation of the MEMS

MEMS in circuit : Electromagnetic modeling



S : scattering matrix of the multi port associated with the EM problem
T: external circuits (MEMS for instance)



$$\begin{bmatrix} b_p \\ \hline b_c \end{bmatrix} = \left[\begin{array}{c|c} \mathcal{S}_{pp} & \mathcal{S}_{pc} \\ \hline \mathcal{S}_{pc}^{t} & \mathcal{S}_{cc} \end{array}\right] \cdot \begin{bmatrix} a_p \\ \hline a_c \end{bmatrix}$$

$$\begin{bmatrix} b_q \\ \hline b_d \end{bmatrix} = \left[\begin{array}{c|c} \mathcal{T}_{qq} & \mathcal{T}_{qd} \\ \hline \mathcal{T}_{qd}^{t} & \mathcal{T}_{dd} \end{array}\right] \cdot \begin{bmatrix} a_q \\ \hline a_d \end{bmatrix}$$

$$\mathcal{M} = \left[\begin{array}{c|c} \mathcal{S}_{pp} & 0 \\ \hline 0 & \mathcal{T}_{qq} \end{array}\right] + \left[\begin{array}{c|c} \mathcal{S}_{pc} & 0 \\ \hline 0 & \mathcal{T}_{qd} \end{array}\right] \cdot \left[\begin{array}{c|c} -\mathcal{S}_{cc} & \mathbf{I} \\ \hline \mathbf{I} & -\mathcal{T}_{dd} \end{array}\right]^{-1} \cdot \left[\begin{array}{c|c} \mathcal{S}_{pc}^{t} & 0 \\ \hline 0 & \mathcal{T}_{qd}^{t} \end{array}\right]$$

Modeling issues

- The ports need to be well defined, which is not always trivial
- Parasitic reactances result from the way the ports are defined in the different methods used (FDTD, FEM, IE). They need to be taken into account
- In solvers based on Maxwell's equation in differential form, the actual size and precise location of the component cannot easily be taken into account, and cumbersome distributing procedures may be required, but it can bee done. [See for instance C. H. Durney, W. Sui, D. A. Christensen, and J. Zhu, "A general formulation for connecting sources and passive lumped-circuits elements across multiple 3-D FDTD cells," *IEEE Microwave Guided Wave Lett.,* vol. 6, pp. 85–87, Feb. 1996.]
- EM solvers based on the resolution of Integral Equation are better suited to the introduction of lumped ports, but they need pre-processing (Green's functions, ...) which can quite involved

Modeling issues : Example of FDTD cell

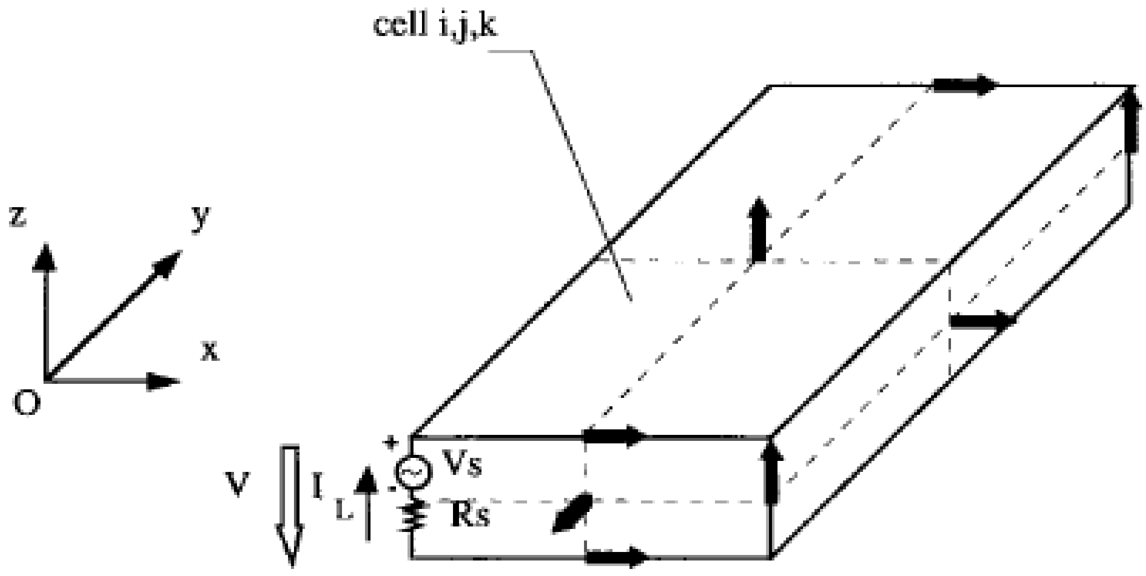
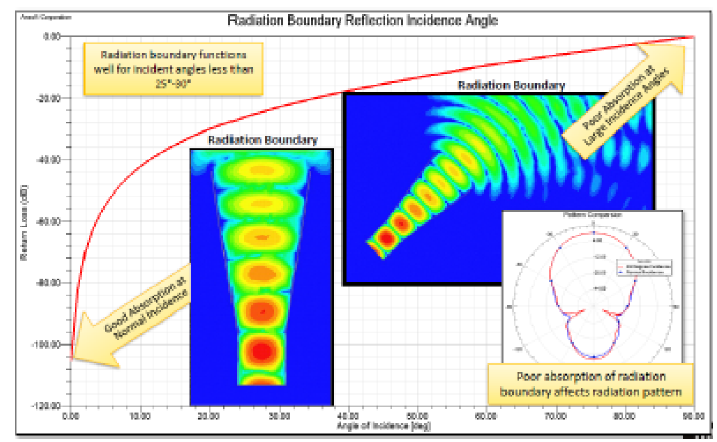


Fig. 1. Standard Yee cell with a lumped resistive voltage generator.

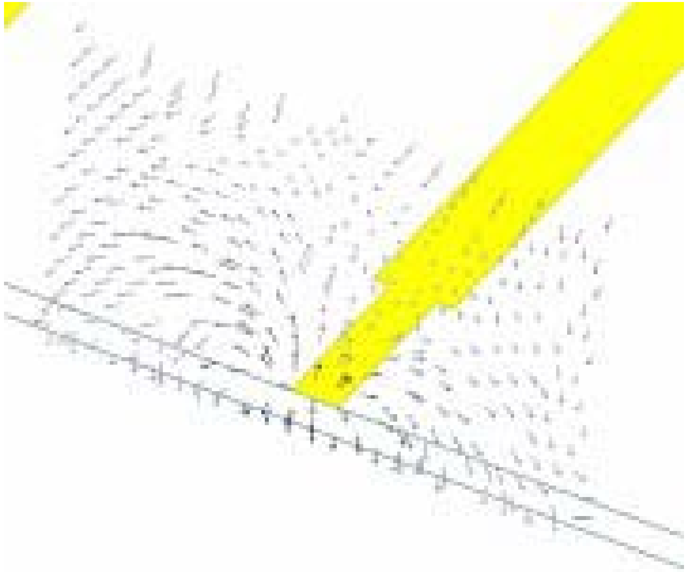
Lumped elements in FDTD or FEM

- Used to simplify geometry or make meshing more efficient
- Material properties for surfaces
  - Finite conductivity (imperfect conductor)
  - Perfect electric or magnetic conductor
- Surface approximations for components
  - Lumped RLC
  - Layered impedance
- Radiation
  - Absorbing boundary condition
  - Perfectly matched layers (PML)
- Any object surface that touches the background is automatically defined as Perfect E boundary



EPFL

Wave ports example: a micorwave line



Wave port: the modes are solved
In the plane transverse to the port
Wave ports solve for characteristic impedance and propagation constants at the port cross-section

Lumped ports

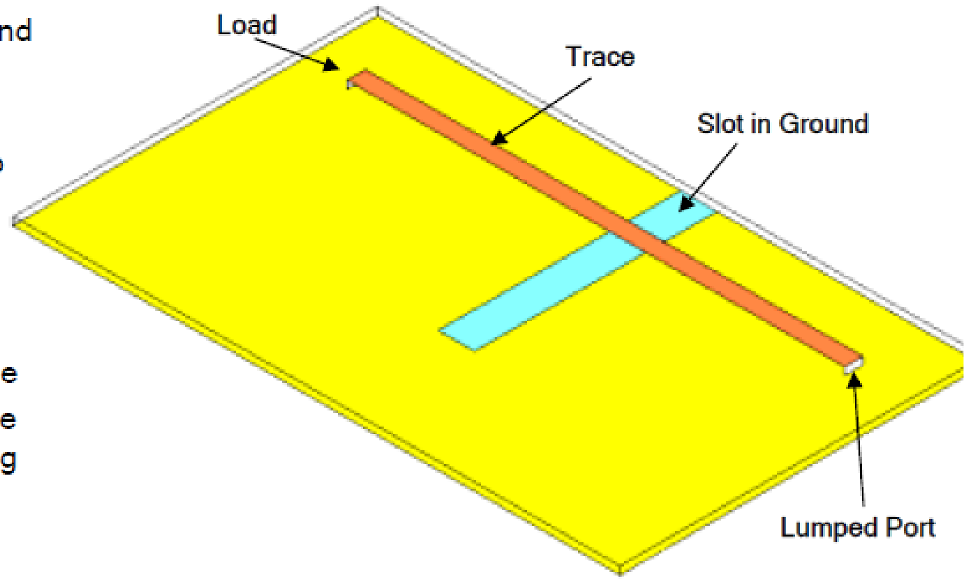
- Lumped ports excite a simplified, single-mode field excitation assuming a user-supplied Zo for S-parameter referencing
- A Terminal line may still be defined, but only one per port.
- Impedance and Propagation constants are not computed
- Port boundaries are simplified to support simple uniform field distributions.
- Edges touching perfect_E or finite conductivity faces, such as ground planes and traces, take on the same definition for the port computation
- Edges not touching conductors become perfect_H edges for the port computation
- This is different than the assumption made by Wave ports!!
- Impedance and Calibration line assignments are required for Lumped port assignments

Wave ports versus lumped ports

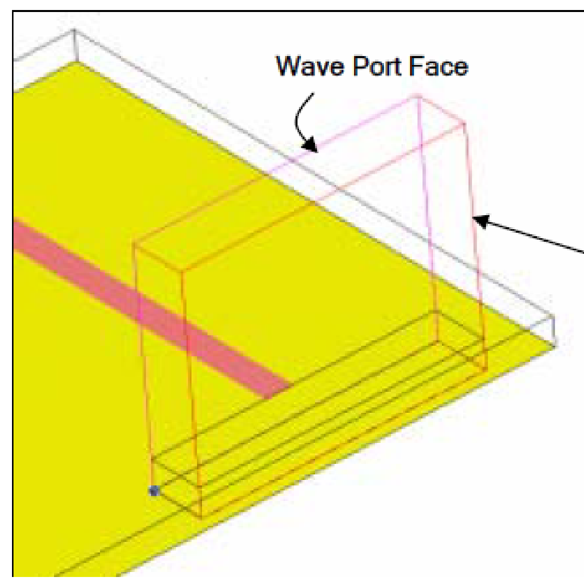
- Wave Ports are more Rigorous
  - True modal field distribution solution
  - Multiple mode, multiple terminal support
  - Use Wave ports by preference if there are no specific reasons their usage would be discouraged
- Port Spacing may force Selection
  - Widely spaced individual excitations usually permit Wave ports
  - Closer-spaced, yet still individual excitations may require Lumped ports
  - Closely-spaced, coupled excitations require Wave ports
    - Only Wave Ports handle multiple modes, multiple terminals.
- Port Location may force Selection
  - Wave ports are best on model exterior surface; interior use requires cap
  - Lumped ports are best for internal excitations, where caps would provide undue disruption to modeled geometry and fields
  - Wave Ports permit de-embedding to remove excess uniform input transmission lengths
  - Lumped Ports cannot be de-embedded to remove or add uniform input transmission lengths
- Transmission Line and Solution Frequency may force Selection
  - Lumped Ports support only uniform field distributions
  - Only Wave Ports solve for TE mode distributions, TM mode distributions, or multiple modes in same location
  - Most non-TEM excitations will require Wave Ports

Microstrip Port on RF Board

- Circuit board modeled inside air volume for ground slot excitation and EMI analysis
- Trace does not extend to end of board
  - For above reasons, port must be interior to modeled volume
- Wave port would require cap embedded in substrate [see bottom]
  - Port face extends from ground surface beneath substrate to well above trace plane
  - Cannot have intersecting cap and substrate solids, therefore Boolean subtraction during model construction is required

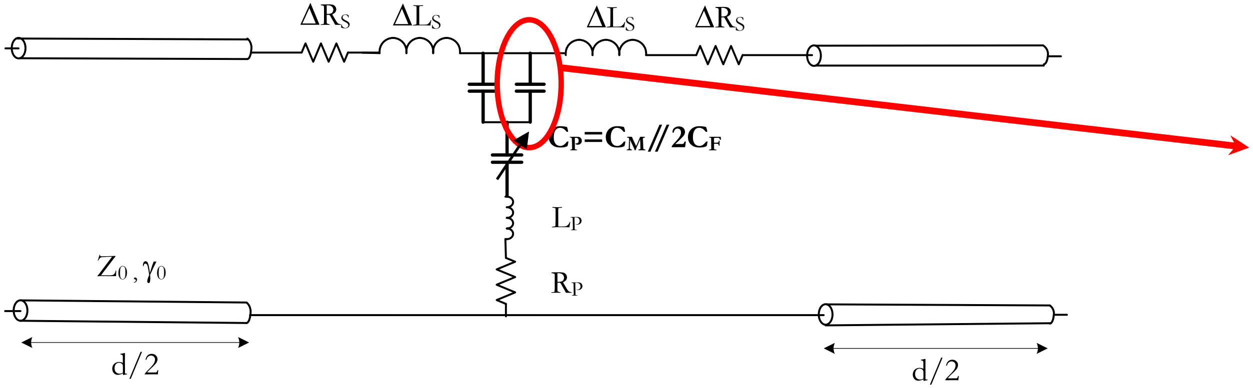


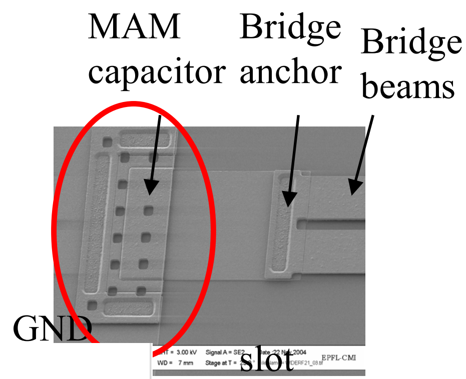
- Use Lumped Port for simplicity
  - Easier to draw
  - Sufficiently accurate solution for isolated line input (no coupled behavior to be neglected)
  - No large metal cap object present to perturb solution of ground plane resonance or radiation effects

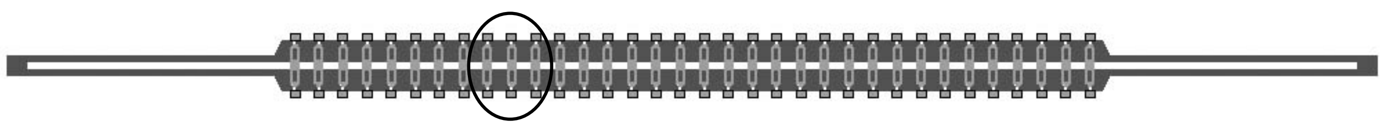


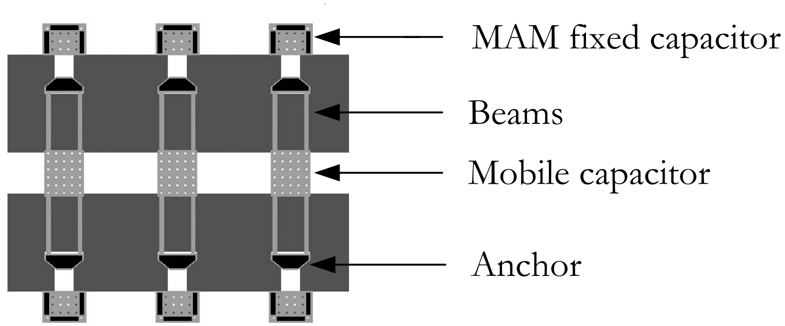
Application to MEMS : a digital TTDL

A fixed capacitor is added in series with the mobile capacitance of the bridge



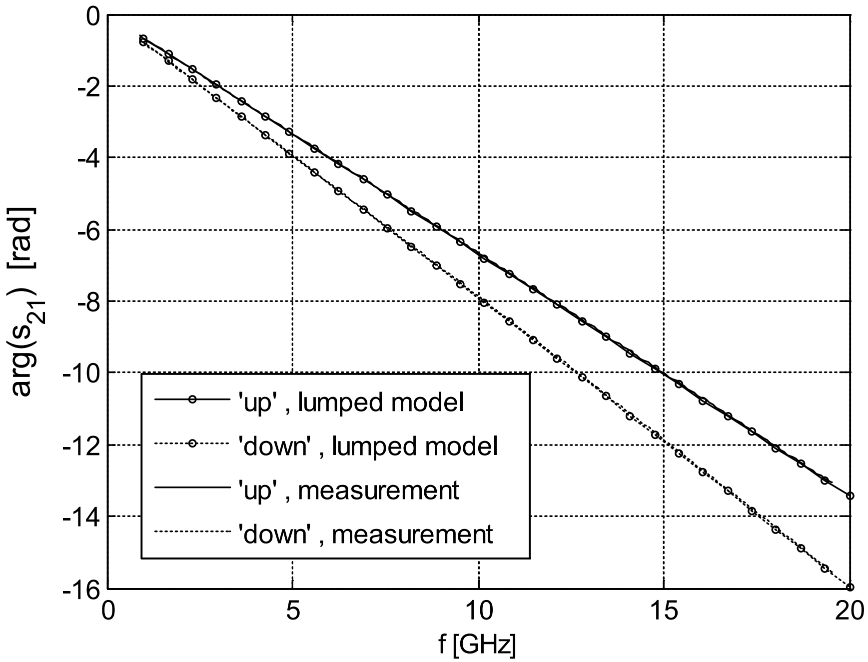


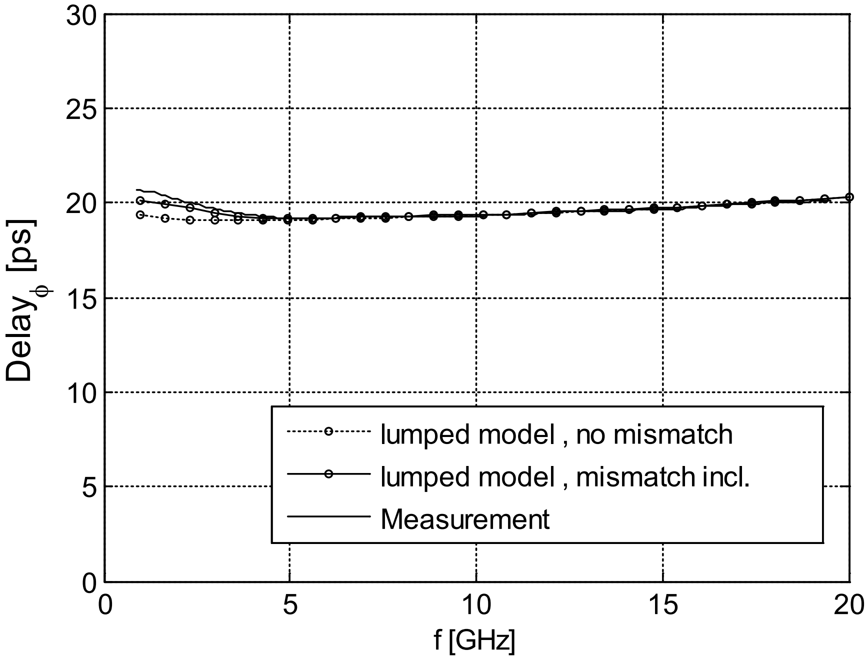




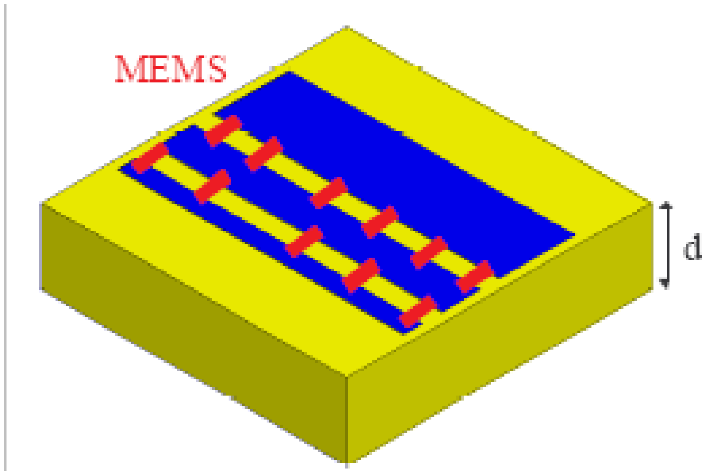
Application to MEMS : a digital TTDL

Results : DELAY

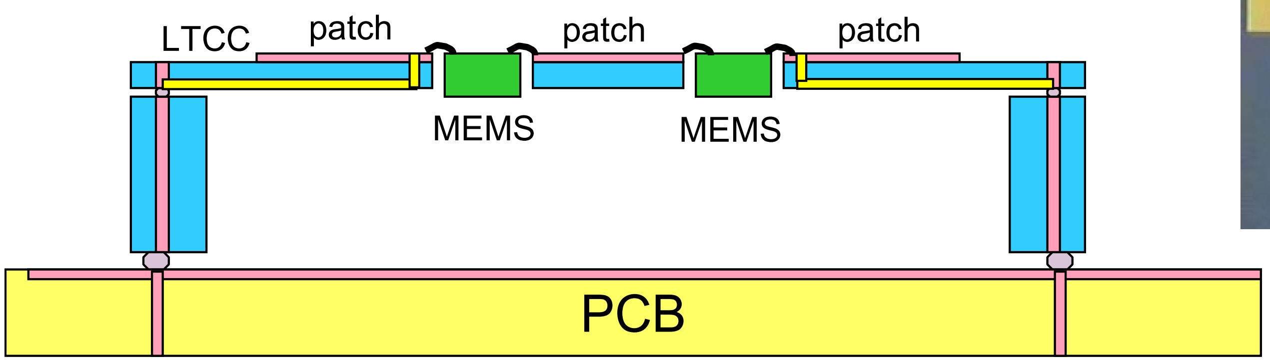


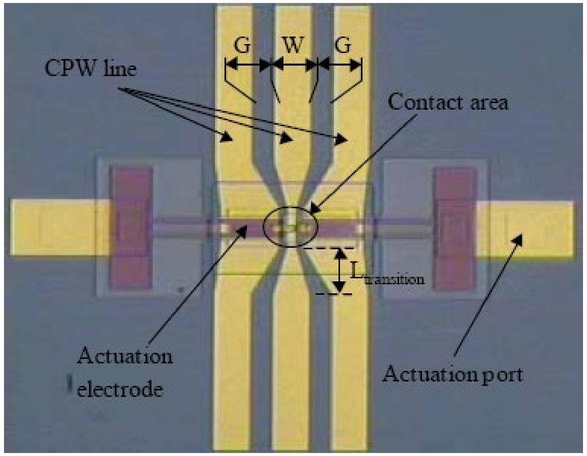


Tunable reflectarrays : MEMS in the radiating elements



RARPA NSP in NoE Amicom
(EPFL, AAS, LETI, IZT, VTT)





MEMS switch
(LETI)

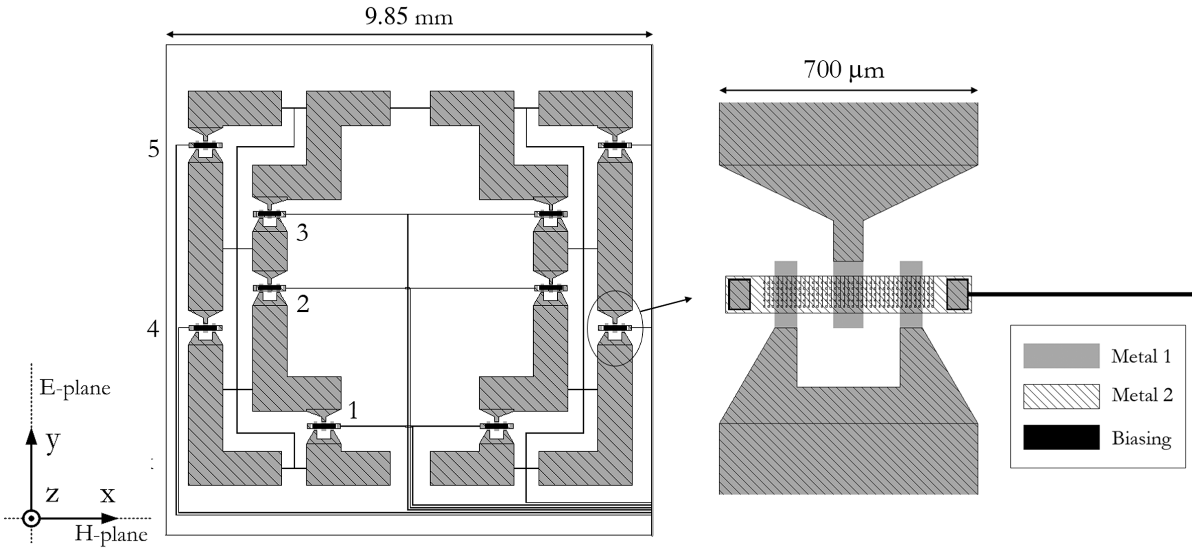
Modeling issues

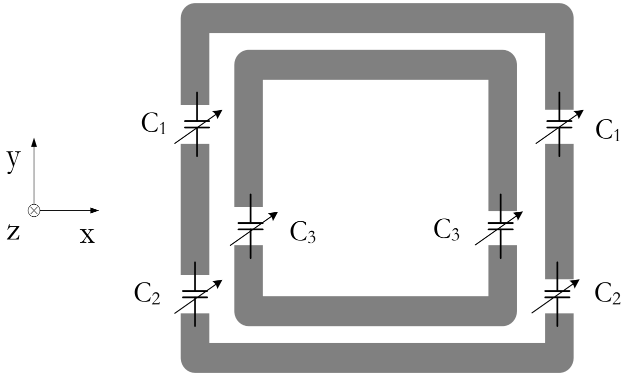
- The radiating element has to be modeled using a full wave EM solver
- The MEMS are much smaller than the radiating element
- The MEMS switches are small compared to the wavelength =>
  - They are modeled using a full wave EM simulator
  - Once characterized, they can be represented by a simple lumped equivalent circuit, which is connected to the antenna. But this connection cannot be done on a circuit level, it has to be done on the field level

Modeling issues

- The full wave EM solver needs to be able to handle lumped loaded ports located anywhere in the structure, (not only defined in transmission lines).
- We would like not to resolve the entire full wave problem each time we change the loads
- This can be done in a very natural way in IE based solvers, as the unknowns of the problem are currents rather than fields

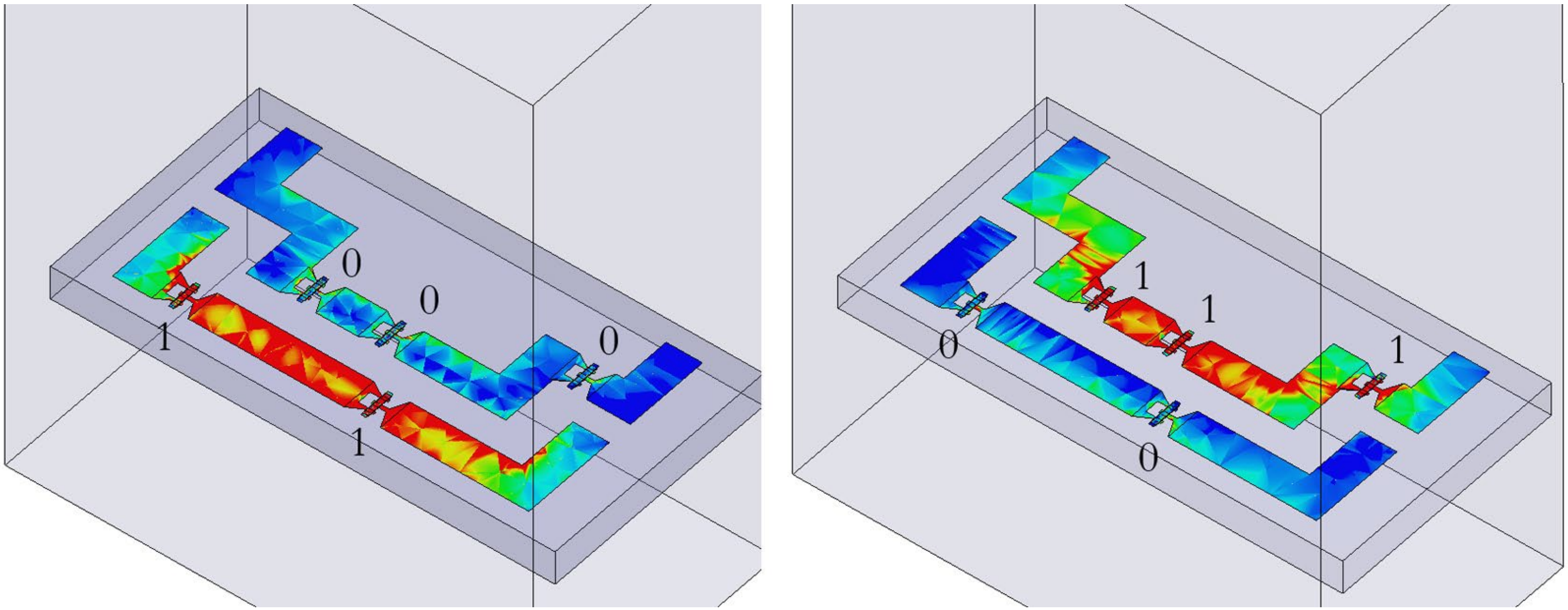
Tunable reflectarrays : MEMS in the radiating elements





Design by LEMA EPFL

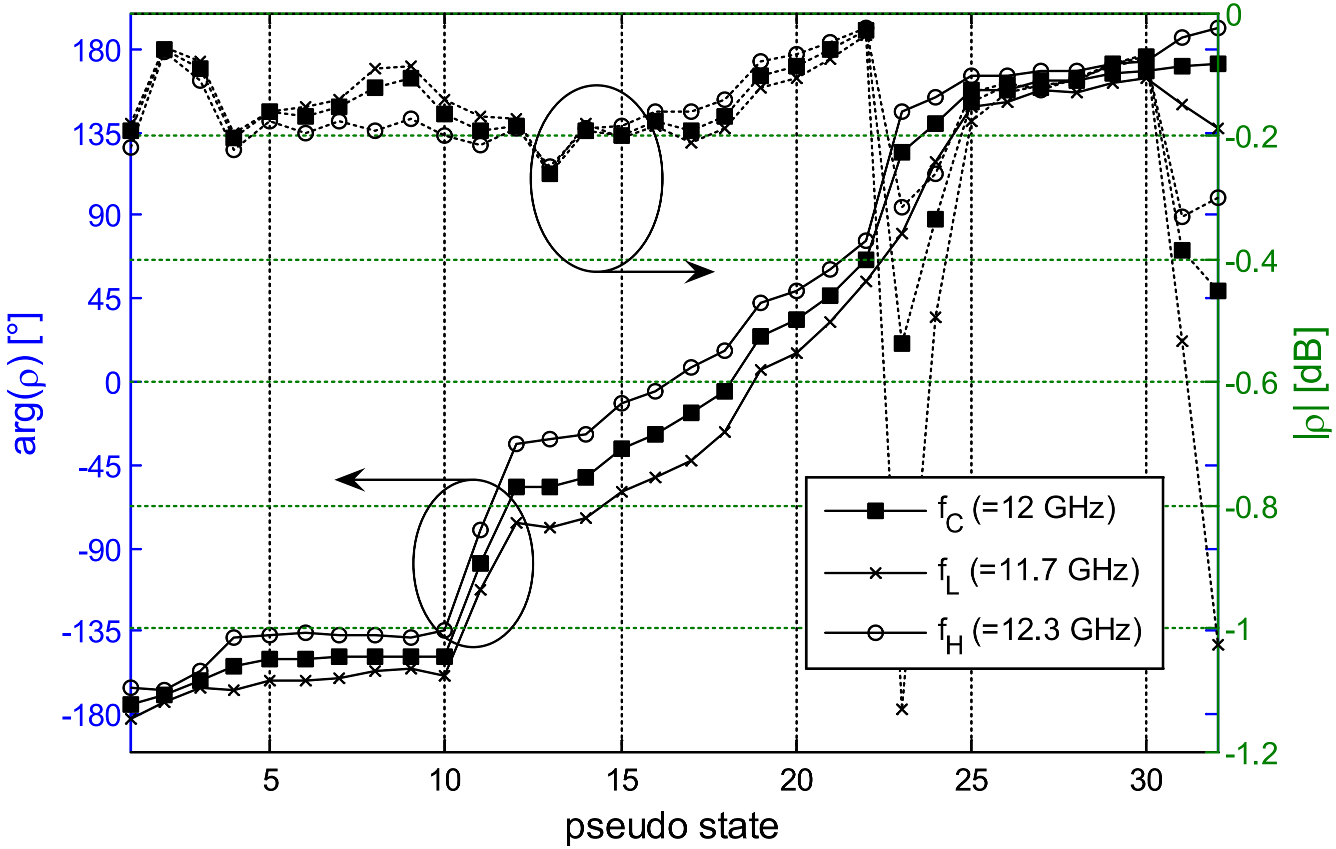
Effect of loading an antenna



Current distribution for two different MEMS states

The surface currents are affected, and need to be recomputed

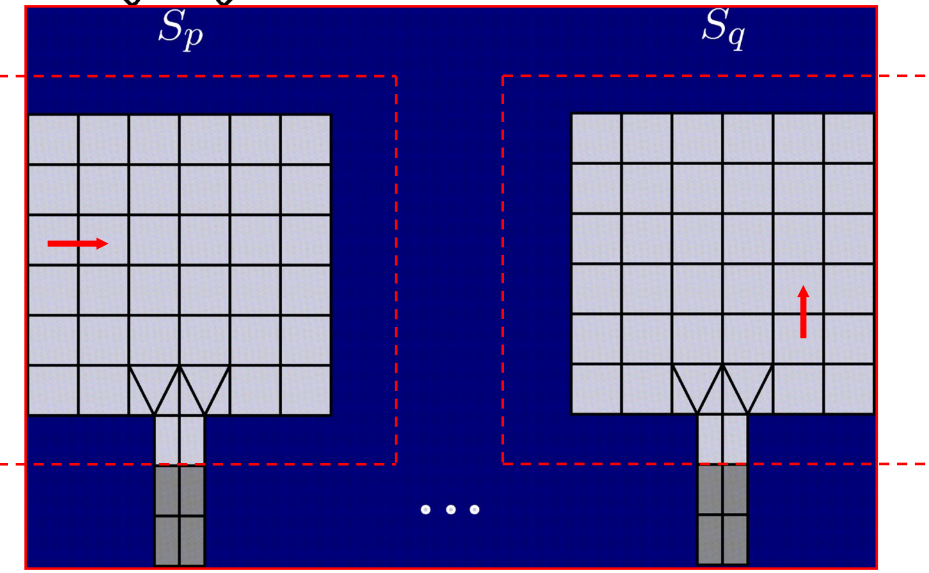
Effect of loading an antenna



EM modelling

- Using FEM or FDTD, a new full wave simulation has to be done for each new state of the MEMS, in order to obtain the new current distribution of the antenna. A lumped element model is sufficient for the MEMS
- Using IE and MoM, only one full wave simulation is needed. As the unknowns of the problem are currents, the MoM matrix can be computed only once (for each frequency), and the current distribution for each state of the MEMS is obtained by changing only the excitation vector

Example



$$\bar{\mathbf{G}}_{\mathbf{A}} = \begin{bmatrix} G_{\mathbf{A}}^{xx} & 0 & 0 \\ 0 & G_{\mathbf{A}}^{xx} & 0 \\ G_{\mathbf{A}}^{zx} & G_{\mathbf{A}}^{zy} & G_{\mathbf{A}}^{zz} \end{bmatrix}$$

$$\bar{\mathbf{G}}_{V} = \begin{bmatrix} G_{V}^{t} & 0 & 0 \\ 0 & G_{V}^{t} & 0 \\ 0 & 0 & G_{V}^{z} \end{bmatrix}$$

$$\hat{\mathbf{n}} \times \mathbf{E} = \hat{\mathbf{n}} \times \Big\{ -j \int_{S'} \bar{\mathbf{G}}_{\mathbf{A}} \cdot \mathbf{J}\, dS'$$

$$-j\,\mathrm{grad} \int_{S'} \bar{\mathbf{G}}_{V} : \mathrm{grad}'\,\mathbf{J}\, dS' + j\,\mathrm{grad} \int_{\partial S'} [\bar{\mathbf{G}}_{V} \cdot \mathbf{J}] \cdot \hat{\mathbf{u}}\, dl'$$

$$\int_{S'} \bar{\mathbf{G}}_{\mathbf{EM}} \cdot \mathbf{M}\, dS' \Big\} = -\hat{\mathbf{n}} \times \mathbf{E}_{\mathrm{exc}}$$

Example

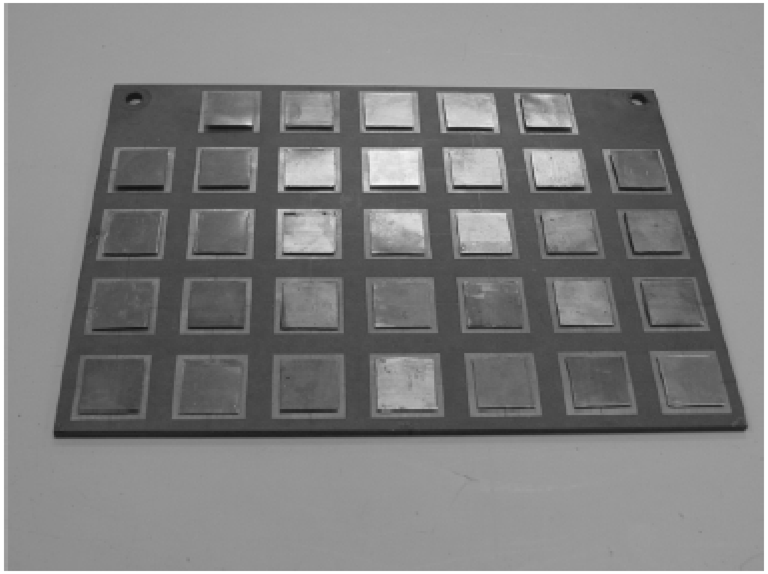
After discretization of the integral equation and projection on the test function, we obtain :

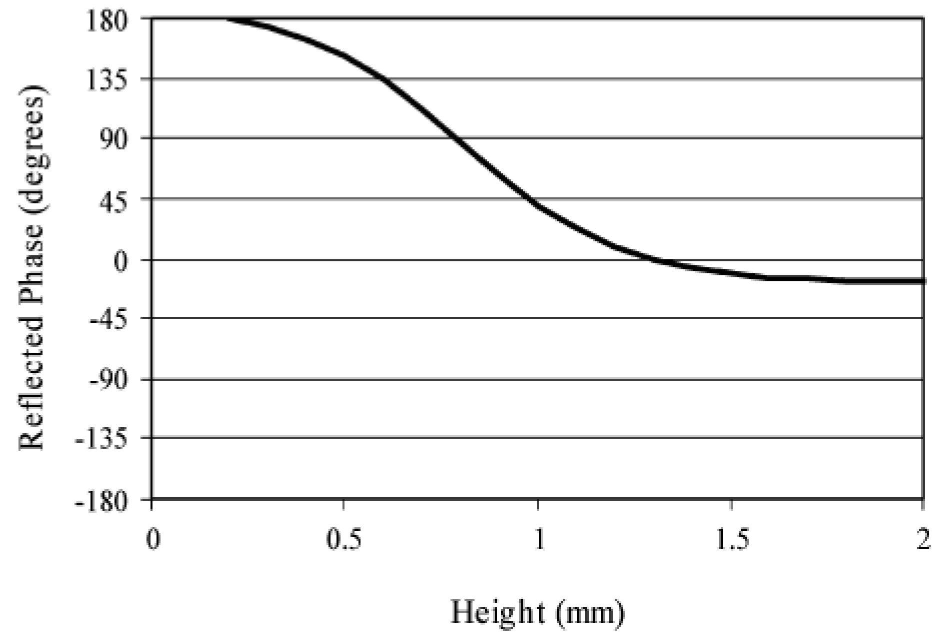
$$[Z][I]=[V_{ex}]$$

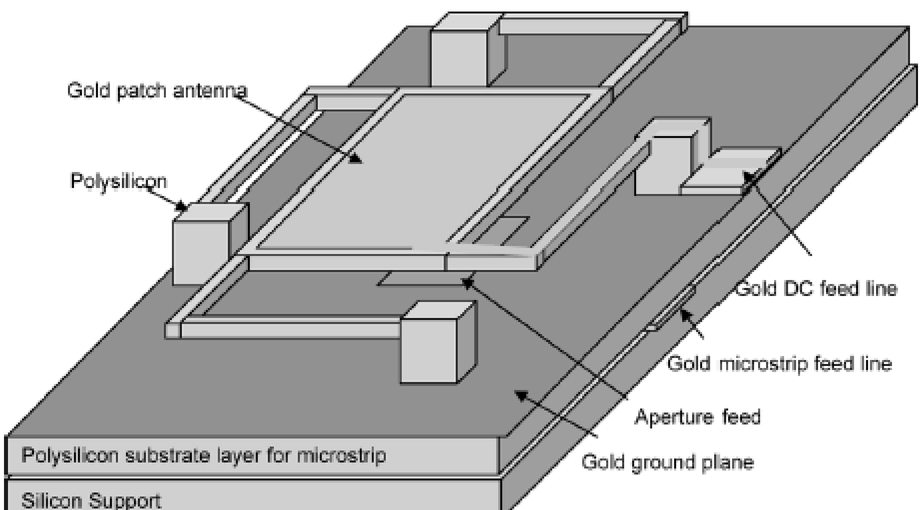
$$[Z_{mom}][I]+[Z_{load}][I]=[V_{ex}]$$

[Zload] is a diagonal matrix containing the load impedances

Tuneable reflectarrays : moving radiating element







GIANVITTORIO AND RAHMAT-SAMII: RECONFIGURABLE PATCH ANTENNAS FOR STEERABLE REFLECTARRAYS, IEEE TRANSACTIONS ON AP, VOL. 54, NO. 5, MAY 2006, pp. 1388-1392

EPFL

Modeling issues

- The entire structure is moving, and needs to be analyzed using a full wave procedure for each state.

Requirements for commercial EM simulation tools

- Fast and reliable
- Reliable and clear definition of ports, also non transmission line ports. Precise description in the documentation on model induced parasitics
- Possibility to run the code once for different excitations (without having to resolve the entire problem for MoM codes), which means an acess deeper into the core of the solver
- Better optimization tools

Conclusion

- The MEMS and Antenna communities need to lobby in order to obtain commercial EM solvers responding to their needs.
- The solution to these needs are inherently available in the tools, but the access is not granted
- The activity in MEMS reconfigurable antennas is increasing fast, and the outcomes are very promising