Design/Modeling for Periodic Nano Structures for EMC/EMI

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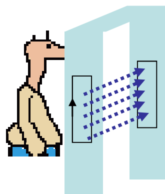
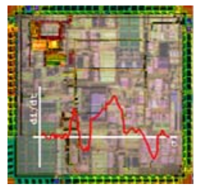
Outline

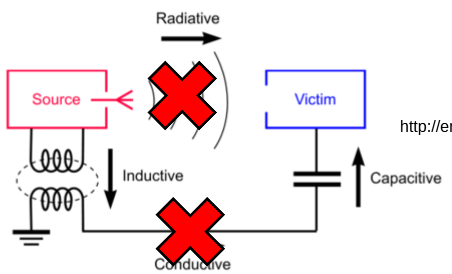
- Introduction
- Composite Materials Design with Numerical Mixing-Law
- FDTD design of Nano-scale FSS
- Stochastic analysis
- Conclusions

Introduction

Electromagnetic Compatibility /Electromagnetic Interference

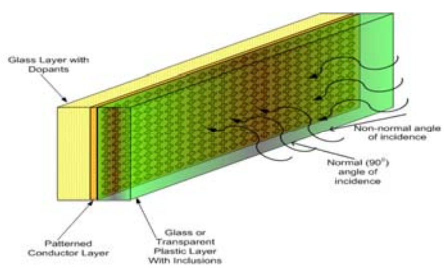


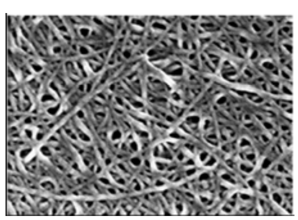


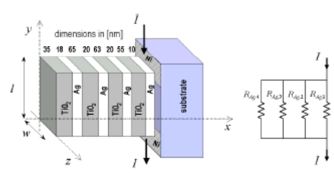


http://en.wikipedia.org/wiki/Electromagnetic_compatibility

Shielding







NASA JSC Nanotube

http://research.jsc.nasa.gov/BiennialResearchReport/PDF/Eng-8.pdf http://www.ursi.org/Proceedings/ProcGA05/pdf/E01.3(01681).pdf

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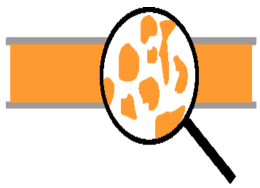
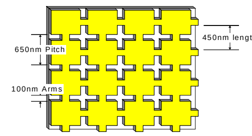
Shielding Materials with Periodic Structures





Effective Medium
$\lambda >> d$

Photonic Crystal
$\lambda \sim < d$

FSS
$\lambda \sim < d$

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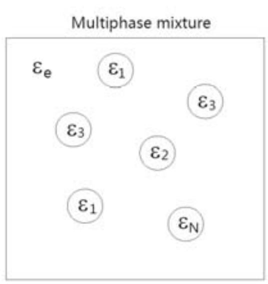
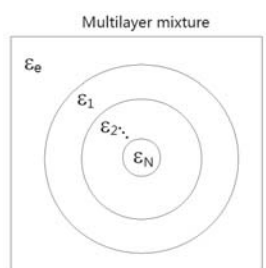
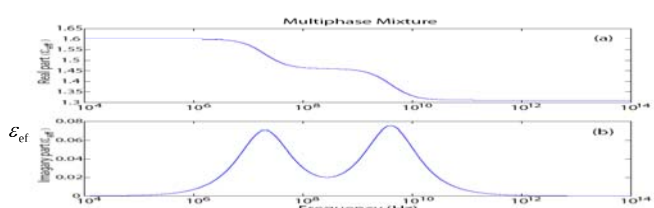
Composite Materials with Numerical Mixing-Law







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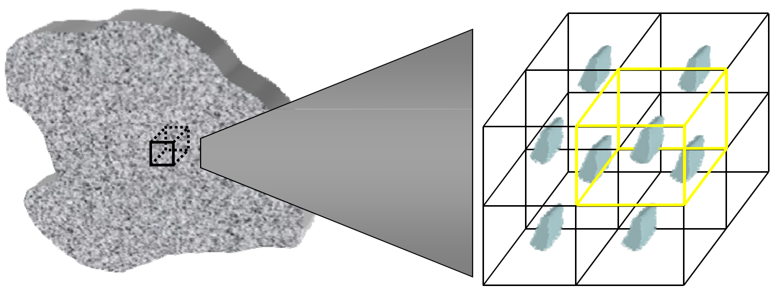
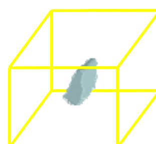
Composite Materials with Numerical Mixing-Law



Periodic Composite Material **3D Periodical Structure**



Unit Element

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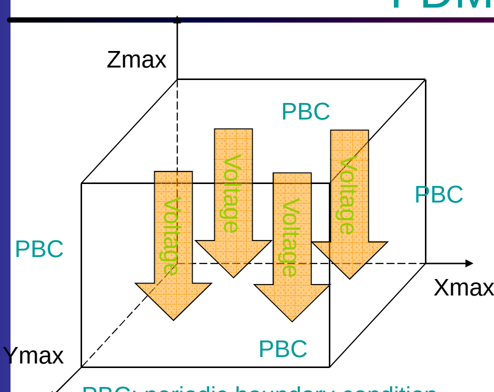
FDM

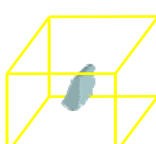


PBC: periodic boundary condition

$$\varepsilon_z^{eff} = \frac{(dz \cdot Z_{max})}{(dx \cdot X_{max}) \cdot (dy \cdot Y_{max})} \cdot \frac{Q}{V}$$

$$= \frac{(dz \cdot Z_{max})}{(dx \cdot X_{max}) \cdot (dy \cdot Y_{max})} \cdot \frac{\int_S \varepsilon_z(i,j,Z_{max}) \bar{E}(i,j,Z_{max}) \cdot d\bar{S}}{V}$$

$$= \frac{(dz \cdot Z_{max})}{(dx \cdot X_{max}) \cdot (dy \cdot Y_{max})} \cdot \frac{\int_S \varepsilon_z(i,j,Z_{max}) \frac{\phi(i,j,Z_{max}) - \phi(i,j,Z_{max-1})}{dz} dS}{V}$$



Unit Element

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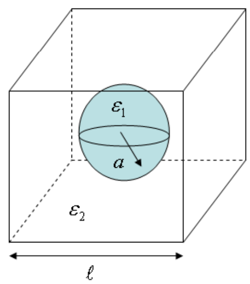
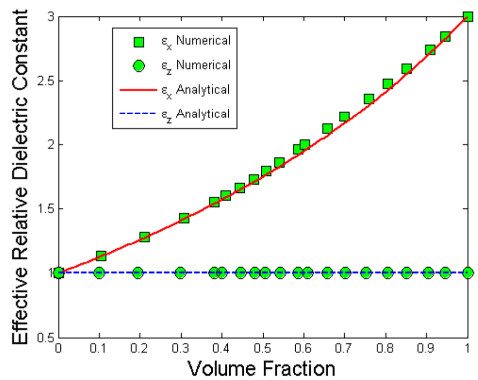
Effect of Inclusion Electrical Properties





$$\ell = 1\text{cm}, \varepsilon_{r\_host} = 1,$$
$$\varepsilon_{rx\_inclusion} = 3, \varepsilon_{ry\_inclusion} = \varepsilon_{rz\_inclusion} = 1$$

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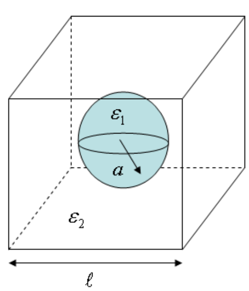
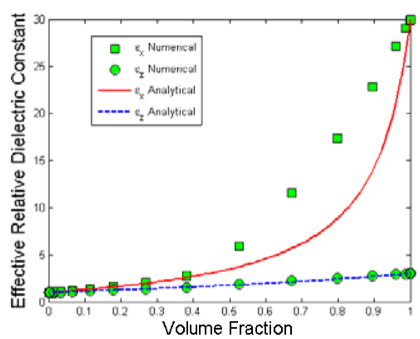
Effect of Inclusion Electrical Properties





$$\ell = 1\text{cm}, \varepsilon_{r\_host} = 1,$$
$$\varepsilon_{rx\_inclusion} = 30, \varepsilon_{ry\_inclusion} = \varepsilon_{rz\_inclusion} = 3$$

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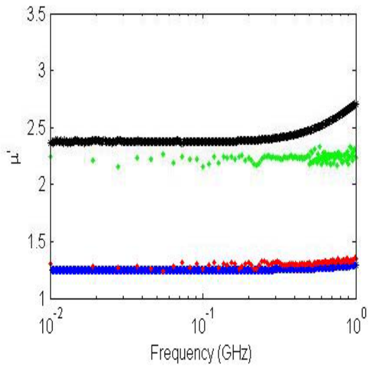

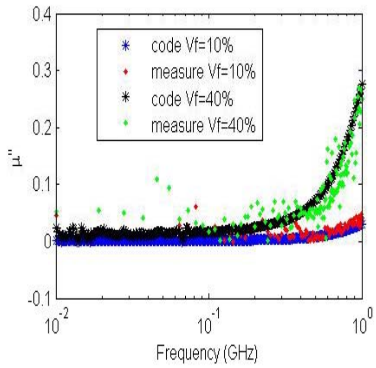

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Electrical Properties Versus Frequency

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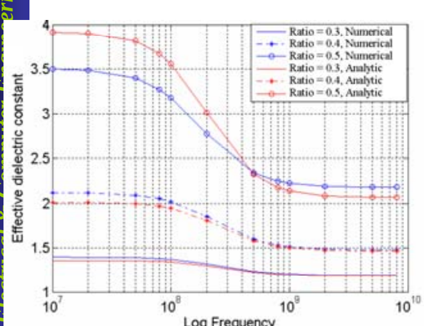

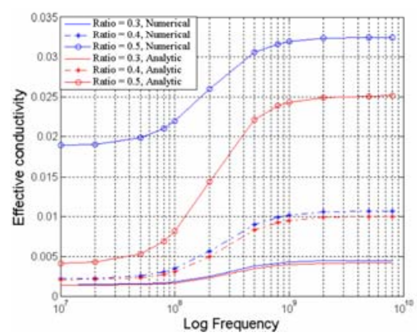

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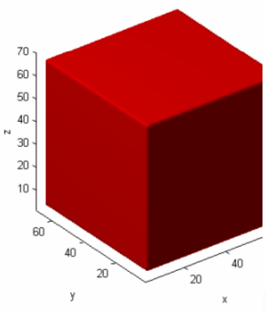
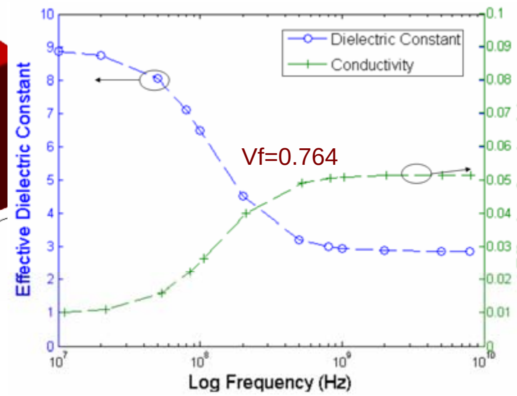
Cubic Inclusion

$\sigma_{host} = 0.001$ S/m
$\sigma_{inclusion} = 0.1$ S/m
$\varepsilon_{r\_host} = 1.0$
$\varepsilon_{r\_inclusion} = 4.0$





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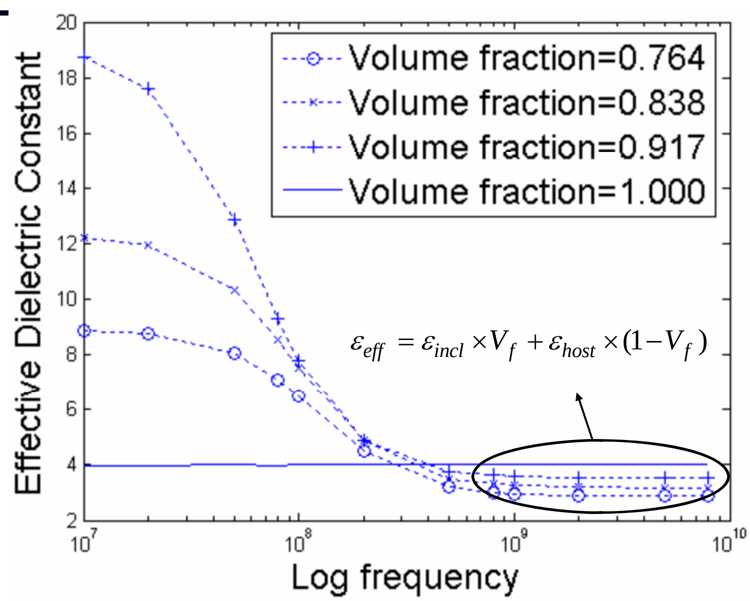
Numerical Results Versus Frequency



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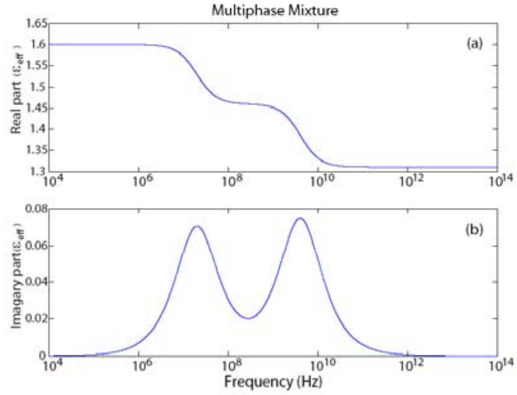
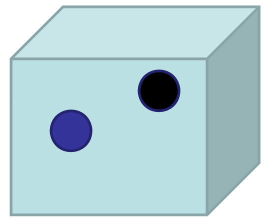
Optimization for Multiphase Mixture





volume fractions 0.1.

espr: 4.42 and 4.04

Conductivity : 0.00715 S/m and 1.369 S/m

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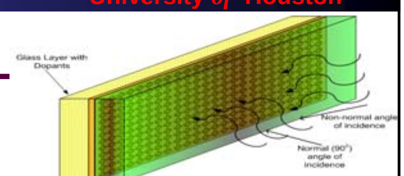
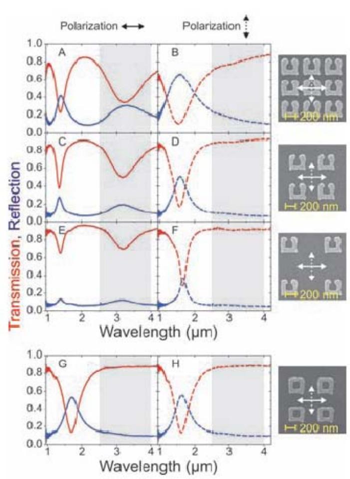
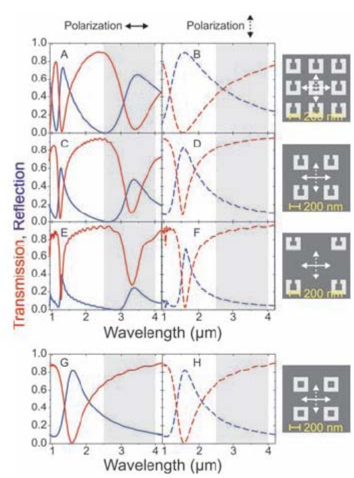
FDTD Modeling







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Challenge in the Modeling of IR FSSs

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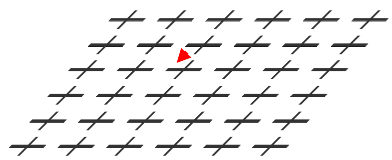
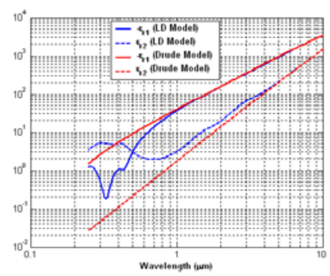
- PEC assumption is not valid any more
  - The metal is highly frequency-dependent now
  - It has both negative permittivity and conductive loss
  - But all of the tradition microwave designs are based on this assumption.
- FDTD Modeling for Periodic Structures



Lorentz-Drude Model (gold)

$$\varepsilon_r(\omega)=\varepsilon_r^f(\omega)+\varepsilon_r^b(\omega)$$
$$=\left(1-\frac{\Omega_p^2}{\omega(\omega-j\Gamma_0)}\right)+\left(\sum_{i=1}^{k}\frac{f_i\omega_p^2}{(\omega_i^2-\omega^2)+j\omega\Gamma_i}\right)$$



Finite-Sized Electromagnetic Source

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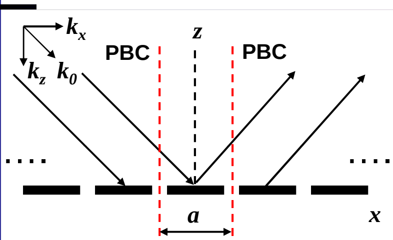
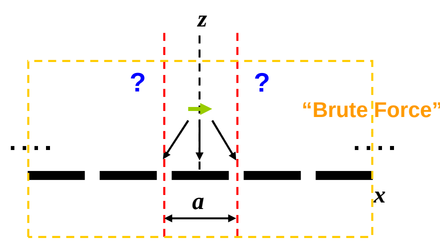


Plane Wave Incidence



Finite Size Source Incidence

➢Plane wave incidence

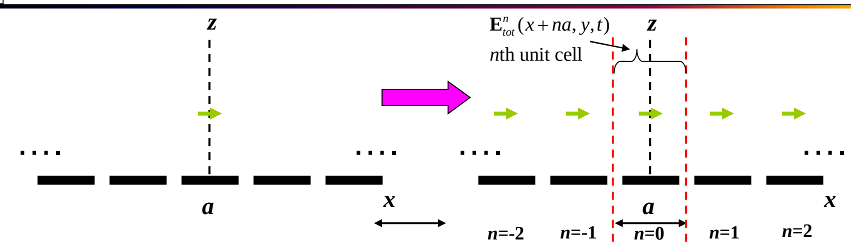
$$\left[E(x+a),H(x+a)\right]=\left[E(x),H(x)\right]e^{-jk_x a}$$

- **Periodic boundary condition (PBC) can be applied for above equation in both frequency and time domains**

➢Finite size source incidence

- **Assumption is no longer valid**
- **In time domain, "Brute Force" FDTD simulation is needed**

ASM-FDTD Method



- Spectral domain transformation of the finite size source

$$\tilde{J}^i(x,y,k_x)=\sum_{n=-\infty}^{\infty} J^i(x_0,y_0)\delta(x-x_0-na)\delta(y-y_0)e^{-jk_x na} \Longleftrightarrow J^i(x_0,y_0)=\frac{a}{2\pi}\int_{-\pi/a}^{\pi/a}\tilde{J}^i(k_x)dk_x$$

- The field in the 0th unit cell excited by this source can be represented as

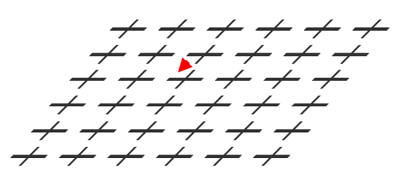
$$\mathbf{E}^0_{tot}(x,y,t)=\frac{a}{2\pi}\int_{-\pi/a}^{\pi/a}\mathbf{E}^0_{tot}(k_x,y,t)dk_x$$

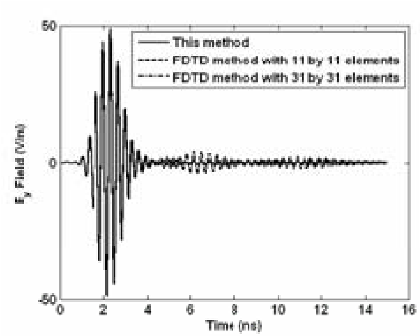
- The 0th unit cell spectral domain solution $\mathbf{E}^0_{tot}(k_x,y,t)$ can be obtained by FDTD simulation when following PBC is applied

$$\mathbf{E}^0_{tot}(a,y,t)=\mathbf{E}^0_{tot}(0,y,t)e^{-jk_x a}$$

- The field in *n*th cell is found by $\mathbf{E}^n_{tot}(x+na,y,t)=\frac{a}{2\pi}\int_{-\pi/a}^{\pi/a}\mathbf{E}^0_{tot}(k_x,y,t)e^{-jk_x na}dk_x$

Numerical Examples





dipole source 45 mm above the structure
dipole strip 12 mm by 3 mm
periodicity 15 mm in both directions
field sampled 90 mm under the dipole source

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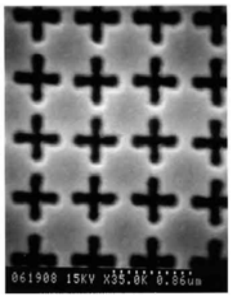
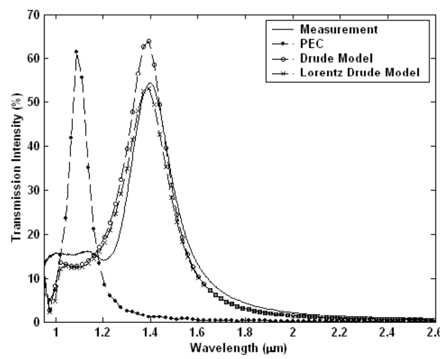
Different Model Impacts On The Final Result





Simulated transmission intensity of an Au cross slot array on the quartz substrate (a=650nm, L=500nm, W=110nm, thickness=300nm and substrate dielectric constant is 2.1316

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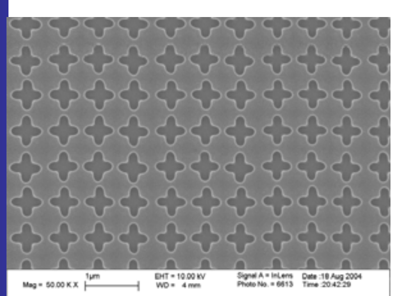
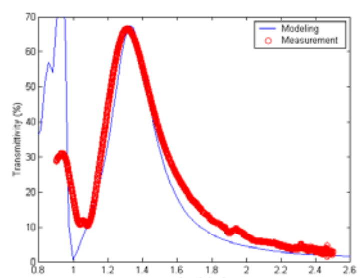
Three Practical Patterns I: Standard Case





Simulated transmission intensity of an Au cross slot array on the quartz substrate (a=660nm, L=510nm, W=160nm, thickness=220nm and substrate dielectric constant is 2.1316

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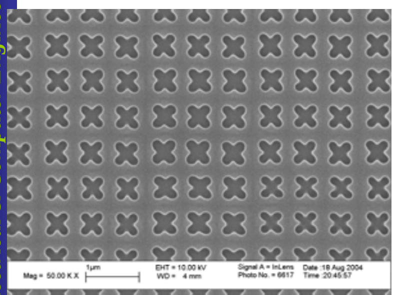
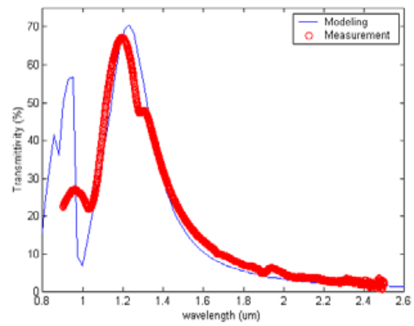
Five Practical Patterns II: Faced Centered Case





Simulated transmission intensity of an Au cross slot array on the quartz substrate (a=660nm, L=500nm, W=170nm, thickness=220nm and substrate dielectric constant is 2.1316

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Variation quantification

- Composite mixtures have inherent randomness
- The homogenized EM property needs to be evaluated
- Sources of randomness includes
  - -- material electrical properties
  - -- component geometry

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Variation quantification techniques

- Monte-Carlo (MC) : Simple to implement, computationally expensive
- Perturbation: Limited to small fluctuation
- Stochastic collocation method (SCM): Can handle large fluctuations, highly efficient, transforms the stochastic analysis into a series of deterministic simulations

Introduction to SCM

- Suppose we have N random parameters $\{\xi_n\}_{n=1}^N$
  - we use the abbreviation $\vec{\xi} = \{\xi_1, \xi_2, \ldots, \xi_N\}$
  - the parameters could be distributed according to a joint PDF $\rho\left(\vec{\xi}\right)$
  - each ξ_n could be distributed independently according to its probability density function (PDF) $\rho_n(\xi_n)$

$$\rho\left(\vec{\xi}\right) = \prod_{n=1}^{N} \rho_n(\xi_n)$$

- Realization = a output $f(\vec{\xi})$ from the deterministic simulation tool for a specific choice of $\vec{\xi} = \{\xi_n\}_{n=1}^N$

Introduction to SCM (cont.)

- One may be interested in *statistics of outputs*
  - average or expected value

$$E[f] = \int_\Gamma f(\vec{\xi})\rho(\vec{\xi})d\vec{\xi}$$

  - variance

$$Var[f]$$
$$= E[f^2] - E[f]^2$$
$$= \int_\Gamma f^2(\vec{\xi})\rho(\vec{\xi})d\vec{\xi} - \left(\int_\Gamma f(\vec{\xi})\rho(\vec{\xi})d\vec{\xi}\right)^2$$

$$\int_\Gamma G(f(\vec{\xi}))\rho(\vec{\xi})d\vec{\xi}$$

  - higher moments

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Introduction to SCM (cont.)

- Integrals of the type

$$\int_\Gamma G(f(\vec{\xi}))\rho(\vec{\xi})d\vec{\xi}$$

cannot, in general, be evaluated exactly

- Thus, these integrals are approximated using a quadrature rule

$$\int_\Gamma G(f(\vec{\xi}))\rho(\vec{\xi})d\vec{\xi} = \sum_{q=1}^{Q} \omega_q \rho(\vec{\xi}_q) G((f(\vec{\xi}_q)))$$

for some choice of
quadrature weights $\{\omega_q\}_{q=1}^{Q}$
and
quadrature points $\{\vec{\xi}_q\}_{q=1}^{Q}$

Introduction to SCM (cont.)

- To use such a rule, one needs to know the simulation output $G(f(\vec{\xi}))$ at each of the quadrature points $\{\vec{\xi}_q\}_{q=1}^{Q}$

  -- for this purpose, one can build a polynomial approximation $\tilde{G}(f(\vec{\xi}))$ and then evaluate that approximation at the quadrature points

  -- the simplest means of doing this is to use the set of Lagrange interpolation polynomials $\{L_s(\vec{\xi})\}_{s=1}^{N_{sample}}$ corresponding to the sample points $\{\vec{\xi}_s\}_{s=1}^{N_{sample}}$

$$\tilde{G}(f(\vec{\xi})) = \sum_{s=1}^{N_{sample}} G(f(\vec{\xi}_s))L_s(\xi) \Longrightarrow$$

$$\int_\Gamma G(f(\vec{\xi}))\rho(\vec{\xi})d\vec{\xi} = \sum_{q=1}^{Q}\omega_q\rho(\vec{\xi}_q)G((f(\vec{\xi}_q))) = \sum_{s=1}^{N_{sample}} G(f(\vec{\xi}_s))\sum_{q=1}^{Q}\omega_q\rho(\vec{\xi}_q)L_s(\vec{\xi}_q)$$

- Then we have the approximation for the mean:

$$E[f] = \int_\Gamma f(\vec{\xi})\rho(\vec{\xi})d\vec{\xi} = \sum_{s=1}^{N_{sample}} f(\vec{\xi}_s)\sum_{q=1}^{Q}\omega_q\rho(\vec{\xi}_q)L_s(\vec{\xi}_q)$$

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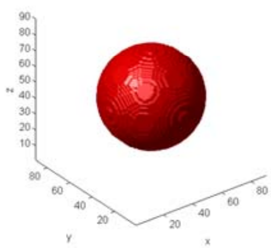
Numerical example



$\varepsilon_{r\_host} = 1, \sigma_{host} = 0$

$\ell_x = \ell_y = \ell_z = 1.0\mu m,$

Mean values:

$E[VF]: 15\%$

$E[\varepsilon_{r\_inclusion}] = 8, E[\sigma_{inclusion}] = 1$

- **Goal: Evaluating the global sensitivity of effective permittivity due to variation in certain mixing parameters**
- **Varying parameters:** *inclusion relative permittivity , inclusion conductivity and volume fraction;* **all of which are assumed to be Gaussian variables.**

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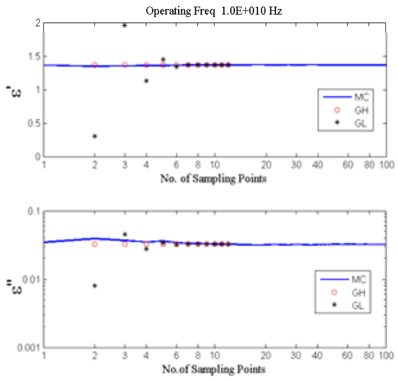
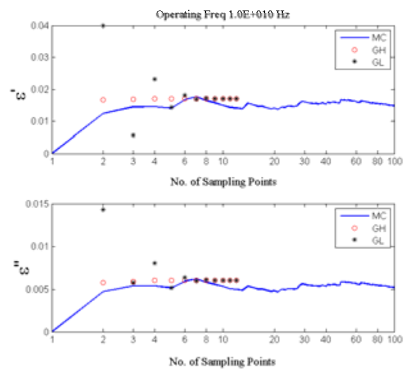
Convergence Test

- Operating Frequency: 1e10 Hz
- Variable: inclusion permittivity, has a $\pm 30\%$ variance around its mean value



mean



Standard deviation

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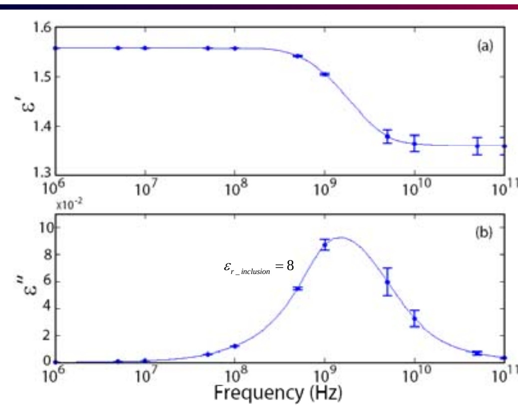
The Effect of *Inclusion Relative Permittivity* Variation



$$\varepsilon_c = \varepsilon_{r\_host} - j\frac{\sigma_{host}}{\omega\varepsilon_0}$$

This case involves a variance of 30% around the mean value $\varepsilon_{r\_inclusion} = 8$

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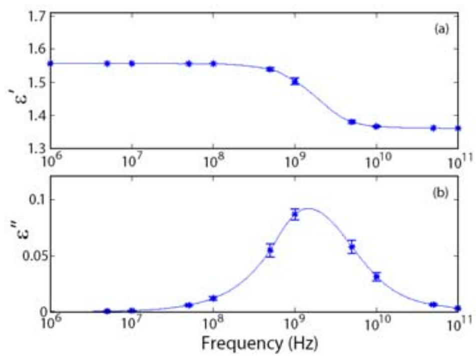
The Effect of *Inclusion Conductivity* Variation



$$\varepsilon_c = \varepsilon_{r\_inclusion} - j\frac{\sigma_{inclusion}}{\omega\varepsilon_0}$$

This case involves a variance of 30% around the mean value $\sigma_{inclusion} = 1$

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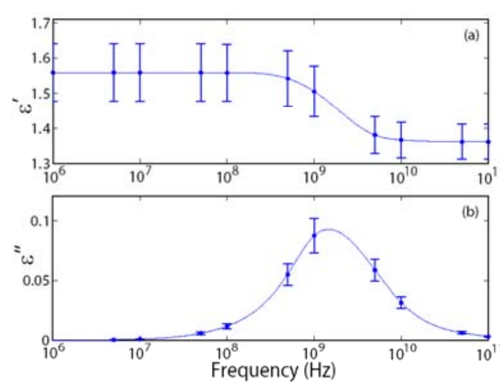
The Effect of *Volume Fraction* Variation



This case involves a variance of 30% around the mean value $\%VF = 15\%$

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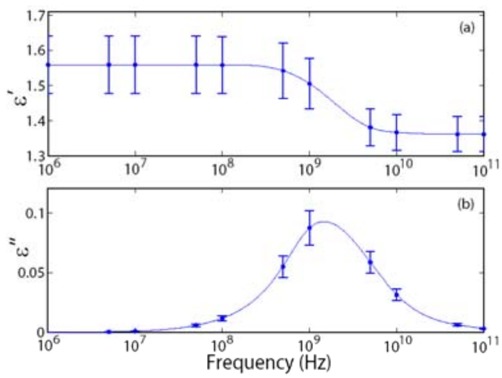
The Effect of *Volume Fraction* Variation



This case involves a variance of 30% around the mean value $\%VF = 15\%$

Conclusion

- New FDTD methods for periodic structures
- Applications include
  - FSS
  - Meta-materials
  - Nano-scale devices
- Multi-layer periodic structures at different periodicities