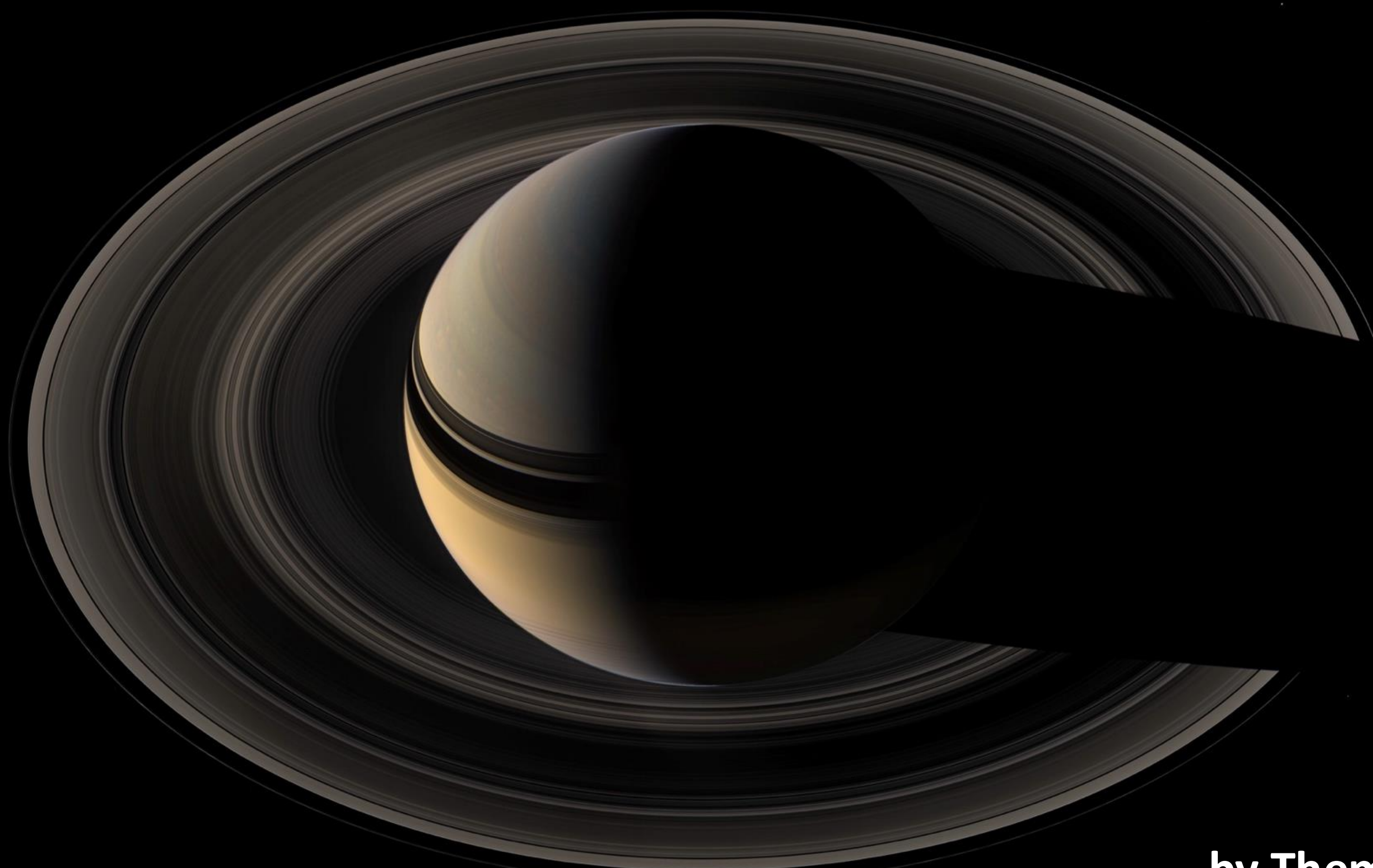
Nonlinear Optimization Technique for the Homogenization of Metamaterials from Scattering Parameters



by Themos Kallos
Department of Materials Science - University of Patras
Metamaterial Technologies Inc.

Cassini space probe view of the unilluminated side of Saturn's rings (2007)

3 things you (probably) didn't know about James Clerk Maxwell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1831-1879
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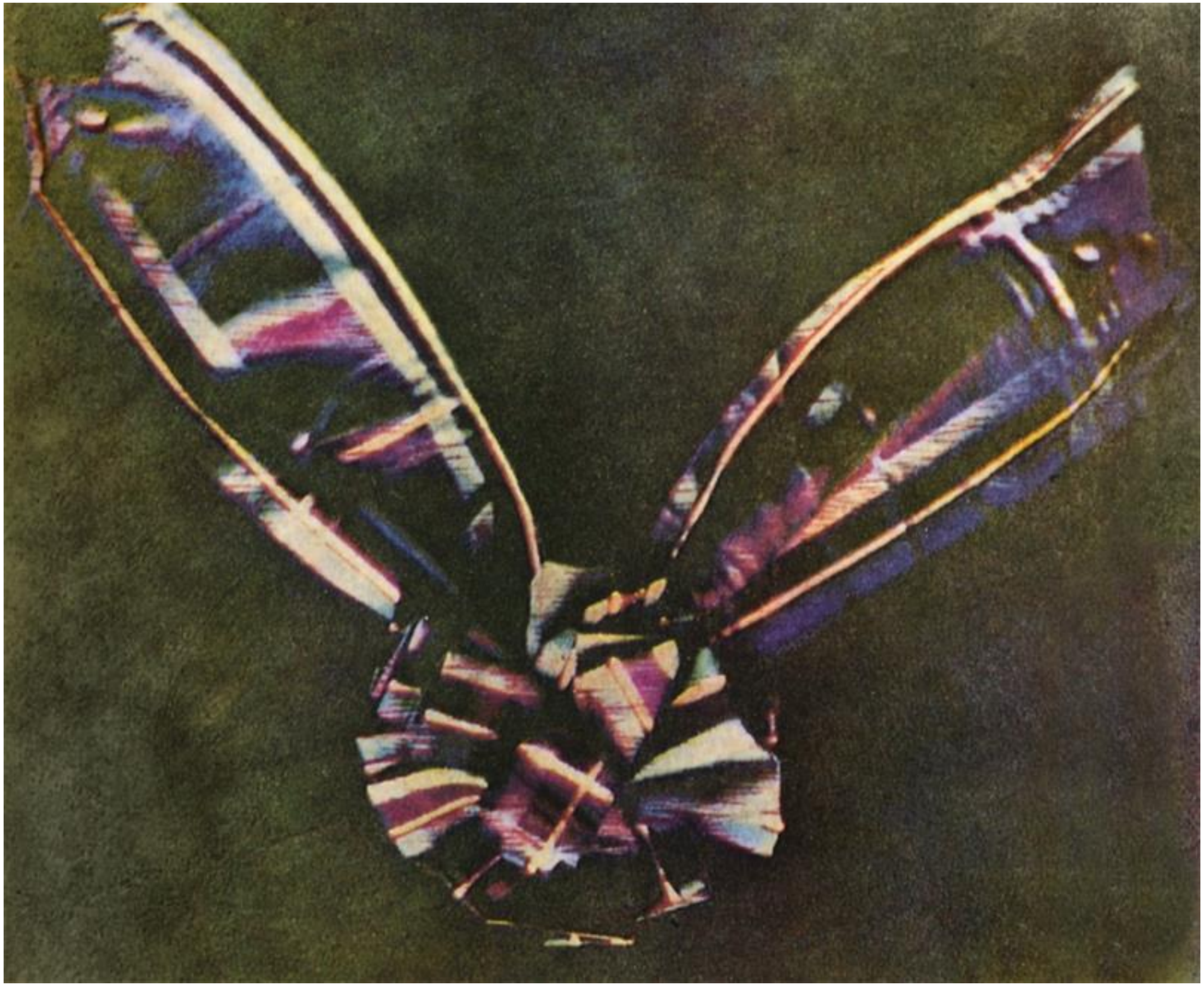
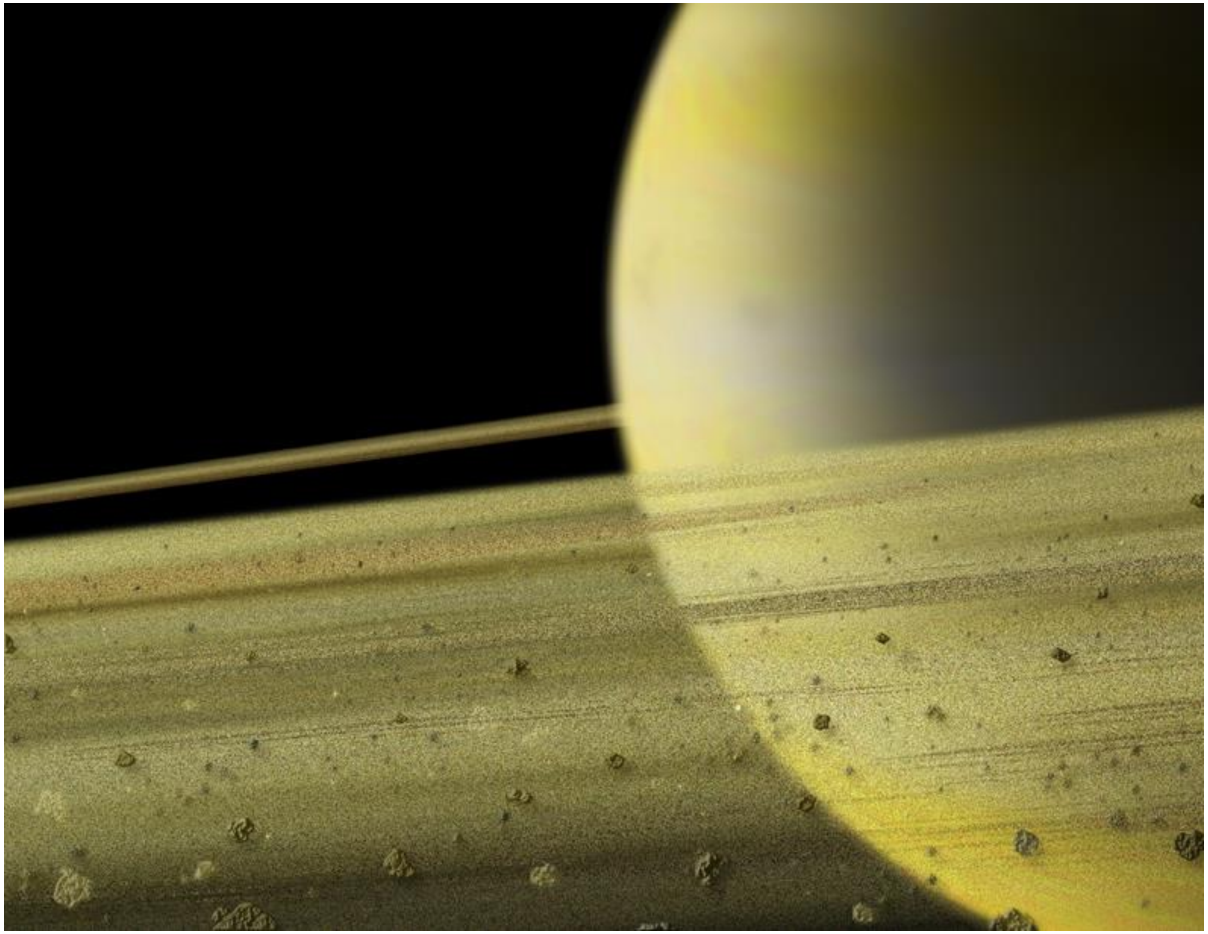


wikipedia



universetoday.com

Today's Menu

- Apéritif
  - **Homogenization of Periodic Structures**
- Entrée
  - **S-parameters & Field Distributions**
- Le plat principal
  - **A nonlinear optimization algorithm**
- Le fromage
  - **Examples for optical silver nanorods**
- Le dessert

Acknowledgements

METAMATERIAL TECHNOLOGIES INC.
Mastering Light

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- **Vassilios Yannopapas**
- **Emmanouil Paspalakis**
- **George Kallos**
- **George Palikaras**

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NSRF 2007-2013
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Co- financed by Greece and the European Union

METAMATERIAL TECHNOLOGIES INC.
Mastering Light

- Launched in 2010
- 5 + 25 people
- $1.3m of federal support
- 4 optical metamaterial patents

LAMDA GUARD
by Metamaterial Technologies Inc.

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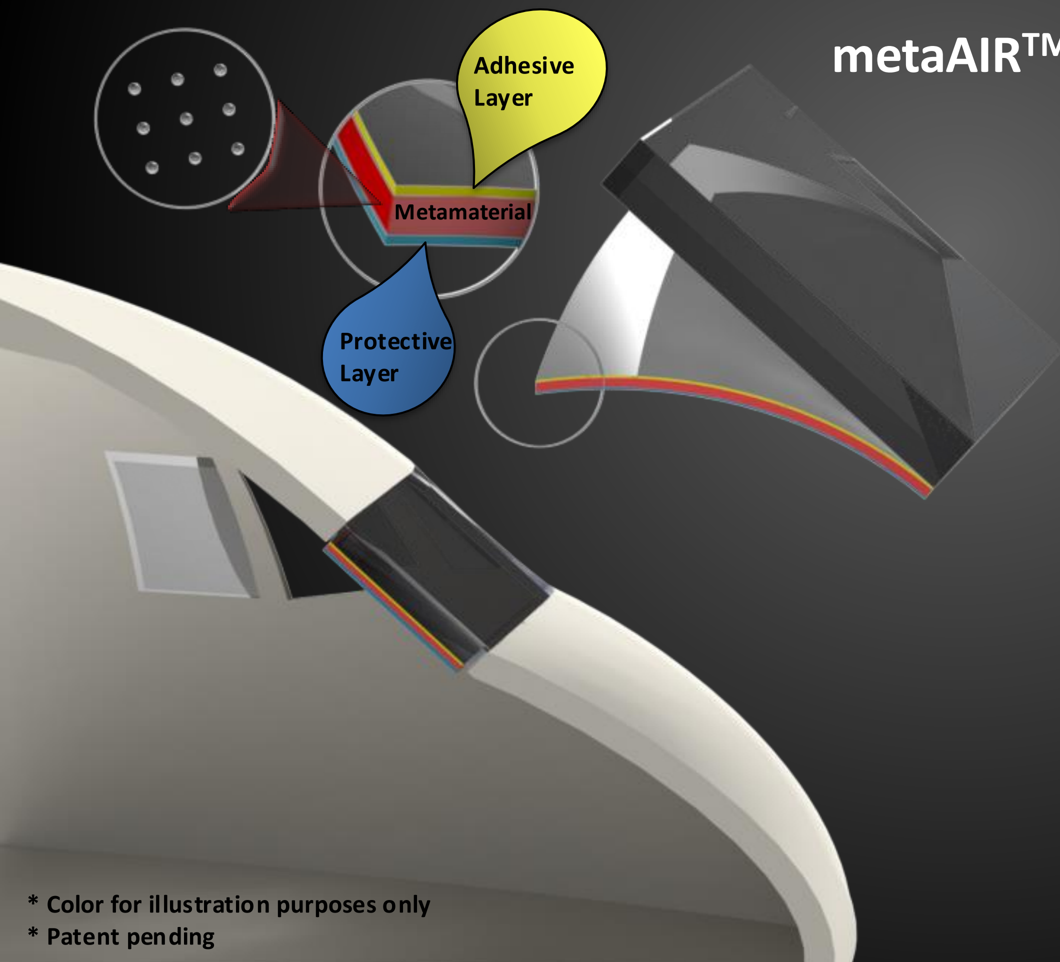

MTI Areas of interest:

- ✓ Laser filtering
- ✓ Light enhancement (LED)
- ✓ Absorption enhancement (solar panels)
- ✓ Optical metamaterials

* Color for illustration purposes only
* Patent pending

University of Patras

Department of Materials Science

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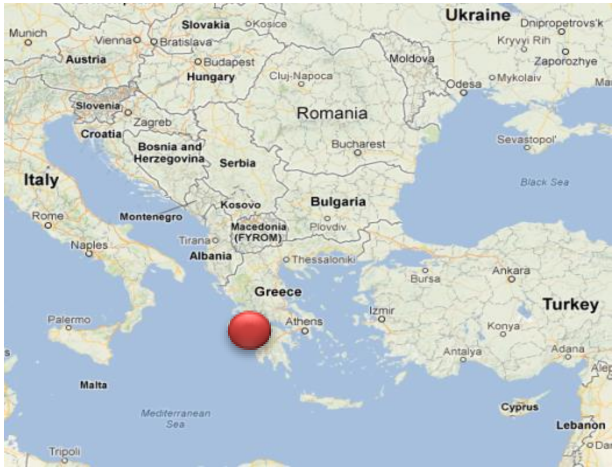
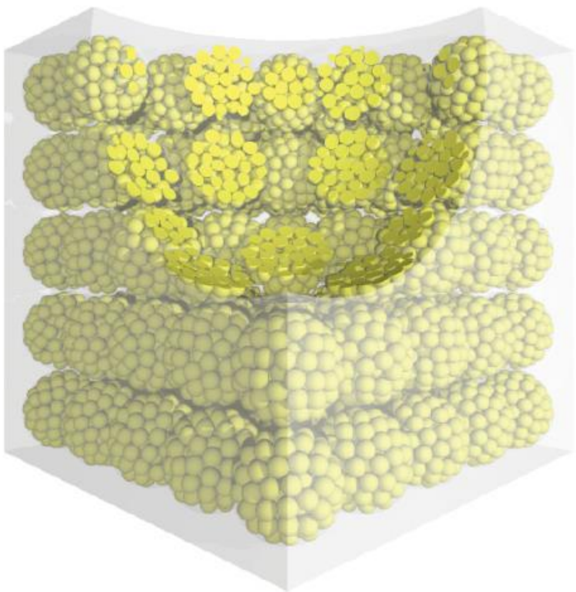
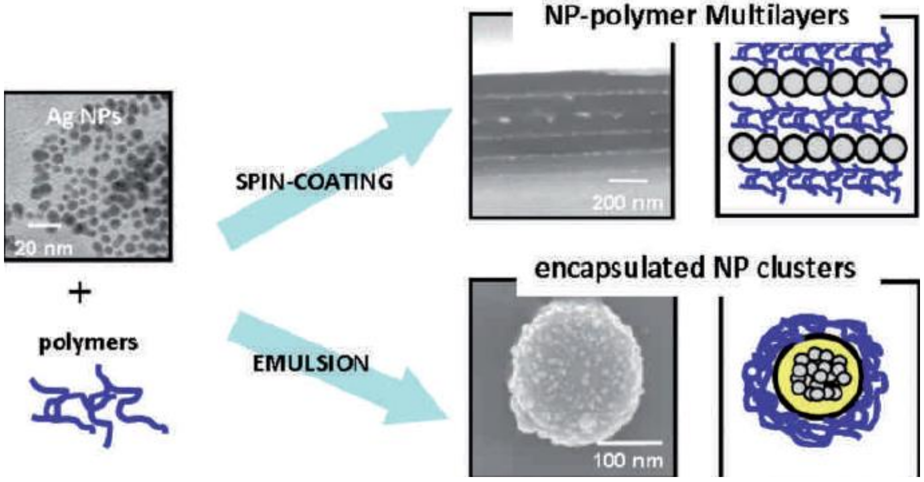


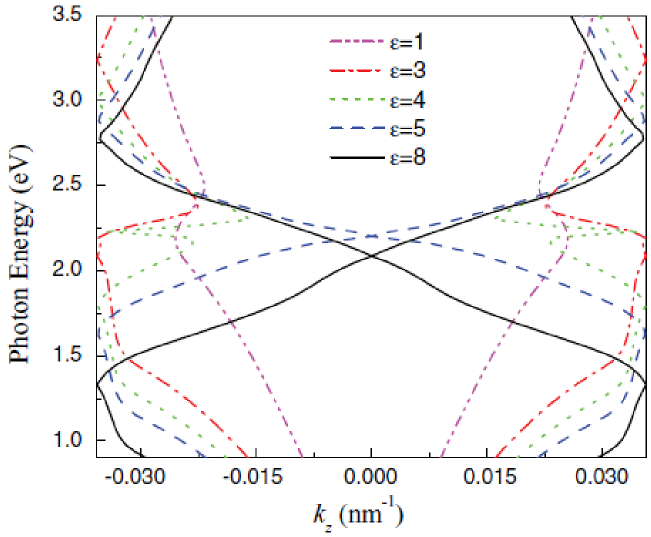
Gold Nanoclusters



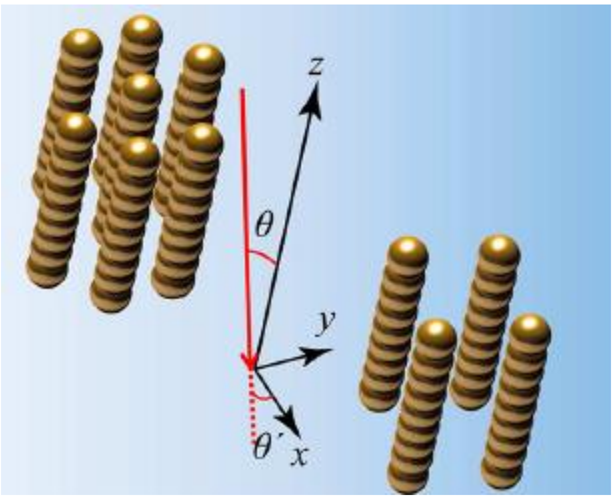


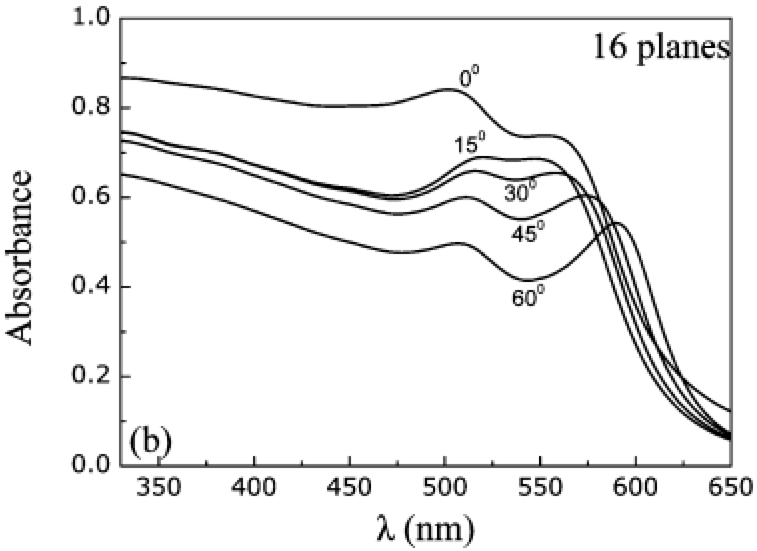
- Gold Nanoparticle radius 9 nm
- Cluster radius 43 nm

- Negative Index meta-metamaterial
- Dirac point



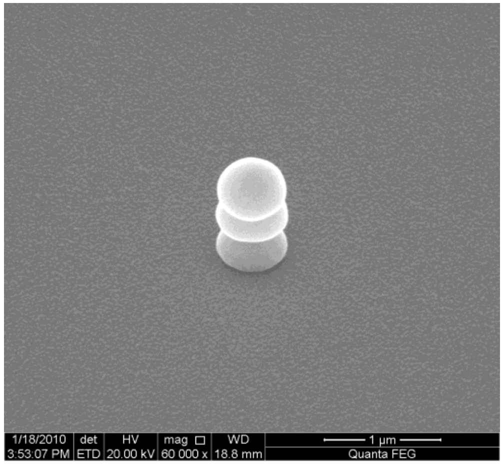
Nanostring Super-absorbers





- Hexagonal lattice of gold nanostrings
- Period 10 nm
- Embedded in nematic liquid crystal
- 3 nm diameter

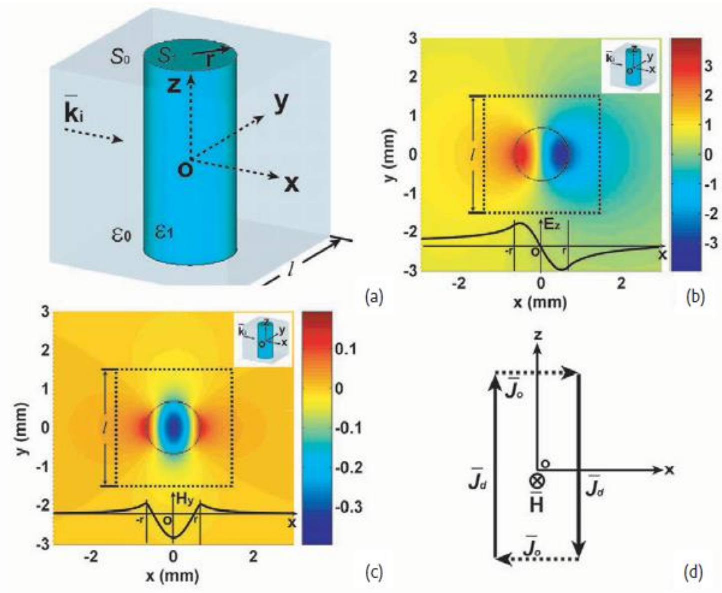
- Gray body: 79% absorption over all angles and polarizations

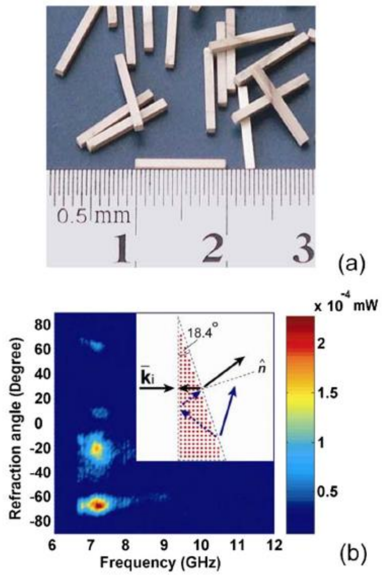


Yannopapas et al., JPCC (2012); SEM Photo by Laser Zentrum Hannover (LZH)

Apéritif
All-Dielectric Metamaterials

Cylindrical Dielectric Resonators

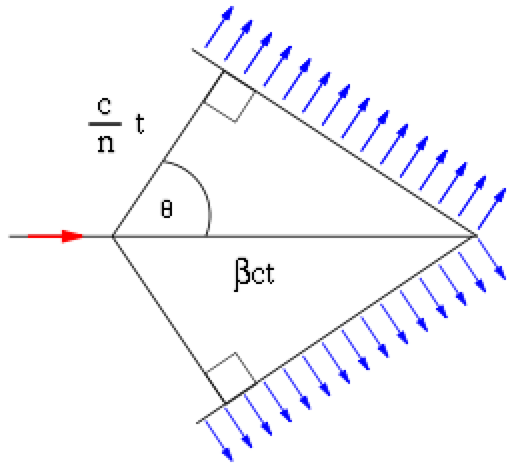


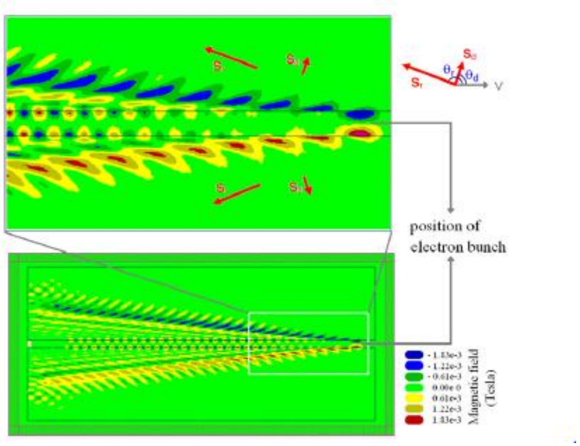


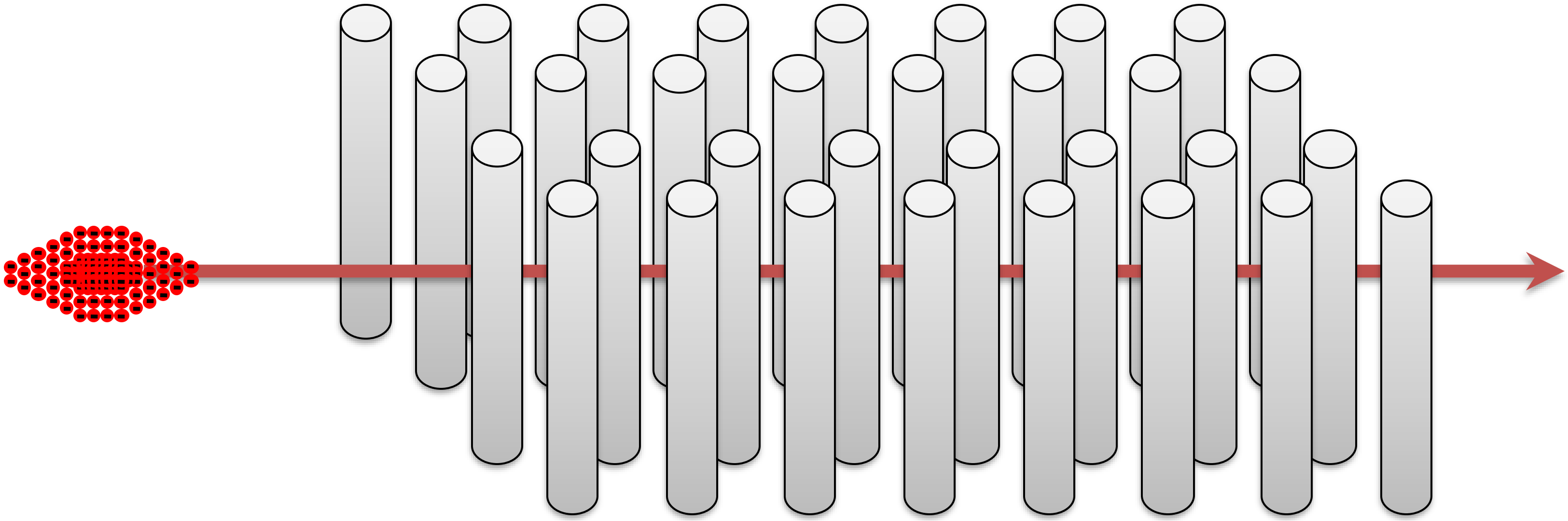
- Avoid plasmonic losses
- Physical principle: polarization currents
- Need high-ε materials (e.g. Si at optical frequencies)
- Anisotropic response
- → Retrieve effective medium parameters

Peng et al., PRL (2007)

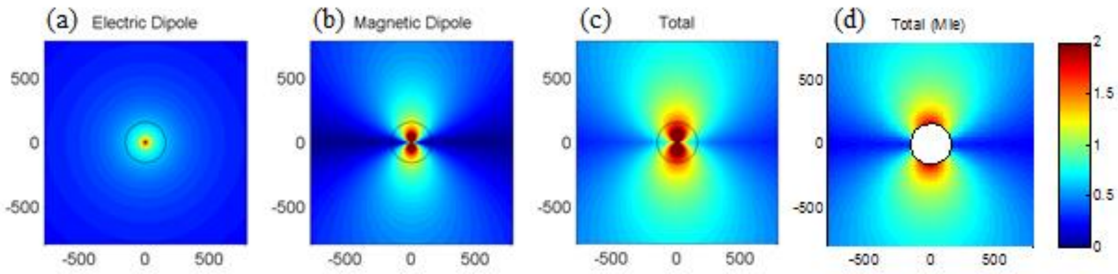
Inverse Cherenkov Radiation

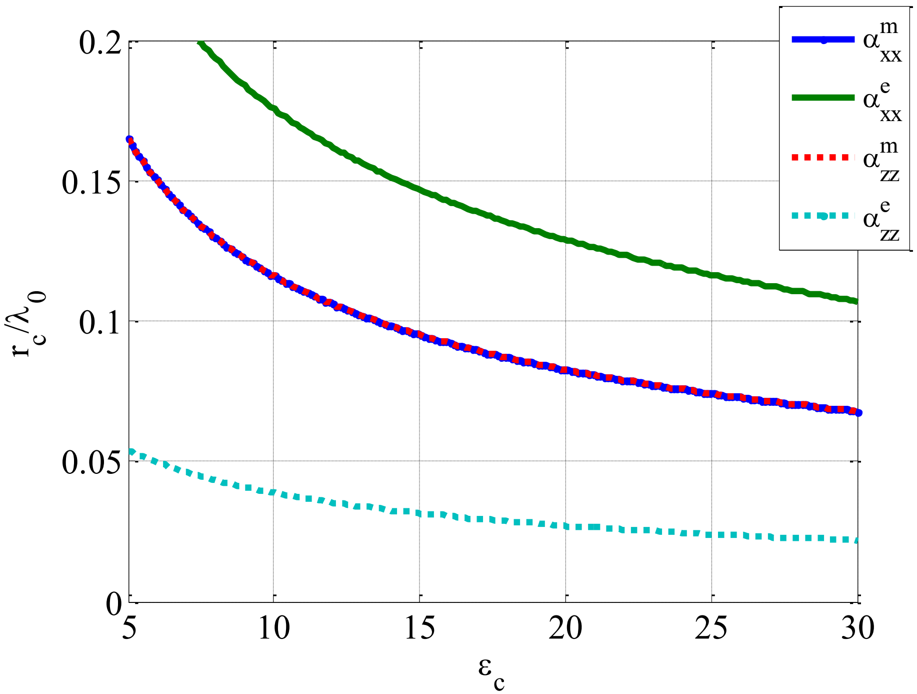


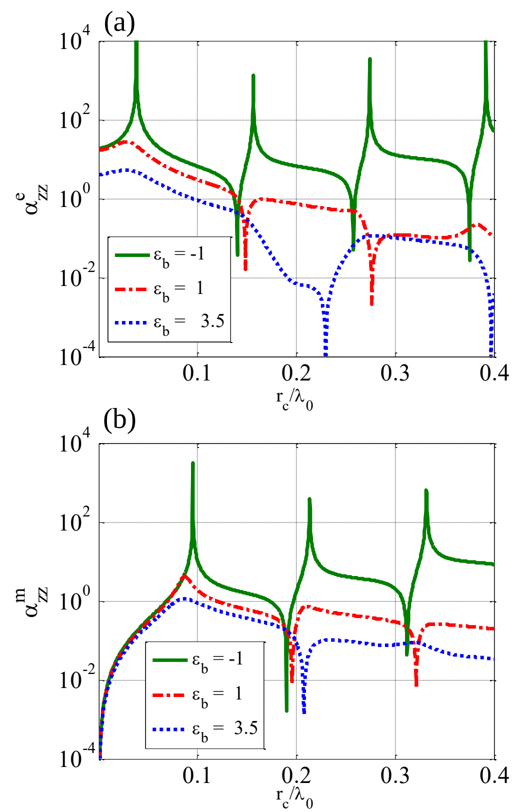




Resonance Hunter



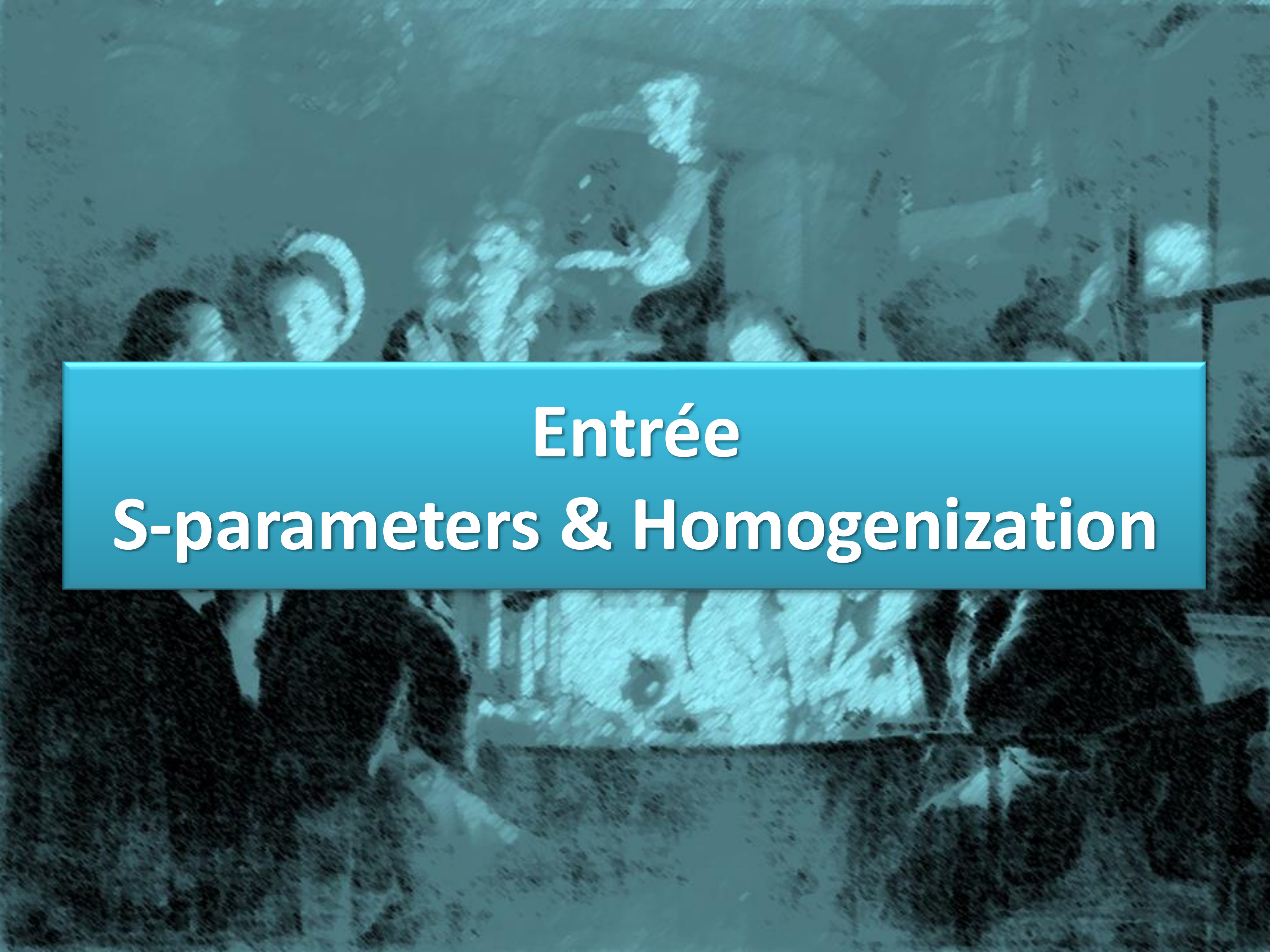




- r_c =158 nm cylinder
- Lossless Silicon (ε=18)
- $\lambda=4*r_c$

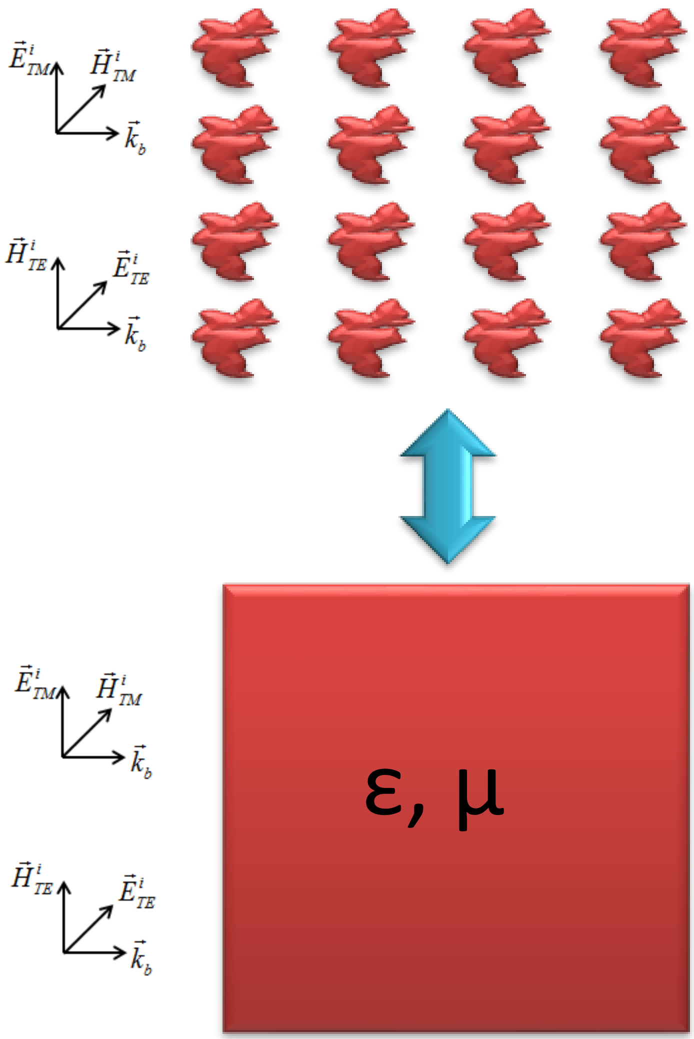
Kallos et al., PRB (2012)

Entrée
S-parameters & Homogenization



Homogenization

NRW Method



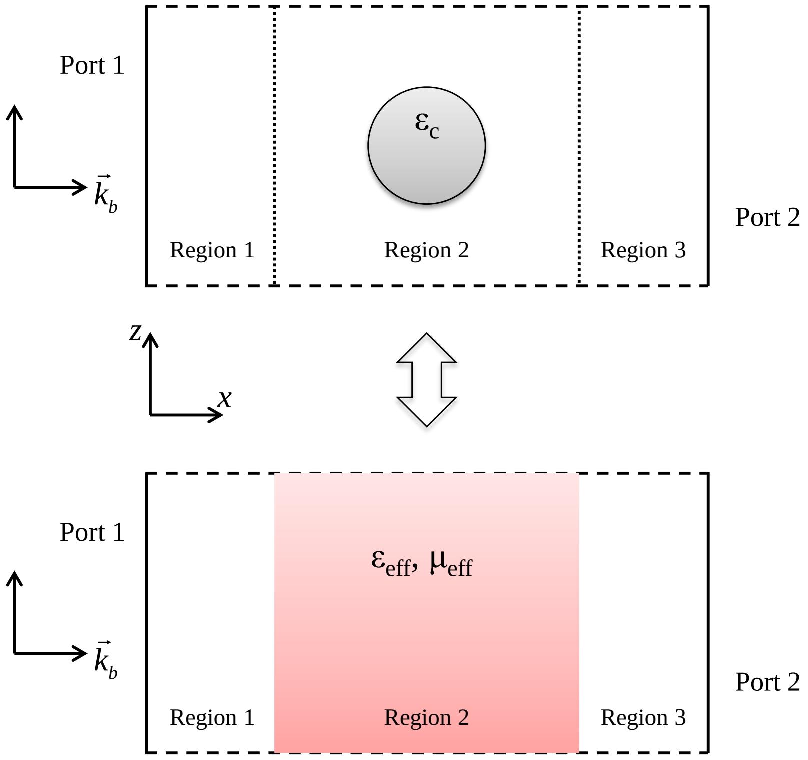
$$\mathrm{Re}(n) = \pm \mathrm{Re}\left(\frac{\cos^{-1}\left(\frac{1}{2t'}\left[1-(r^2-t'^2)\right] \right)}{kd} \right) + \frac{2\pi m}{kd}$$

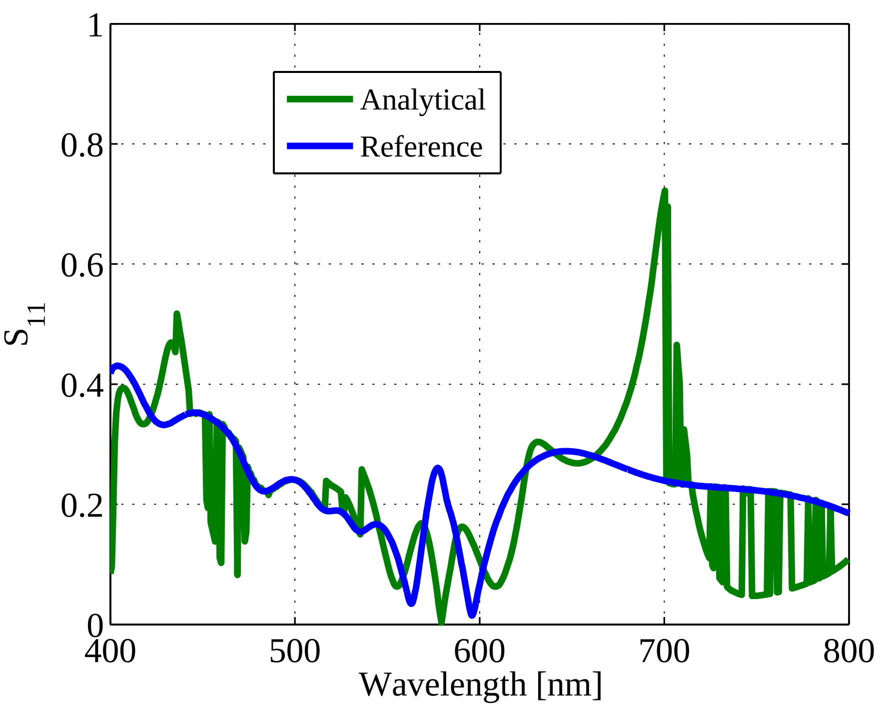
$$\mathrm{Im}(n) = \pm \mathrm{Im}\left(\frac{\cos^{-1}\left(\frac{1}{2t'}\left[1-(r^2-t'^2)\right] \right)}{kd} \right)$$

Weir, Proc. IEEE (1974); Smith et al., PRB (2002)

Analytical NRW

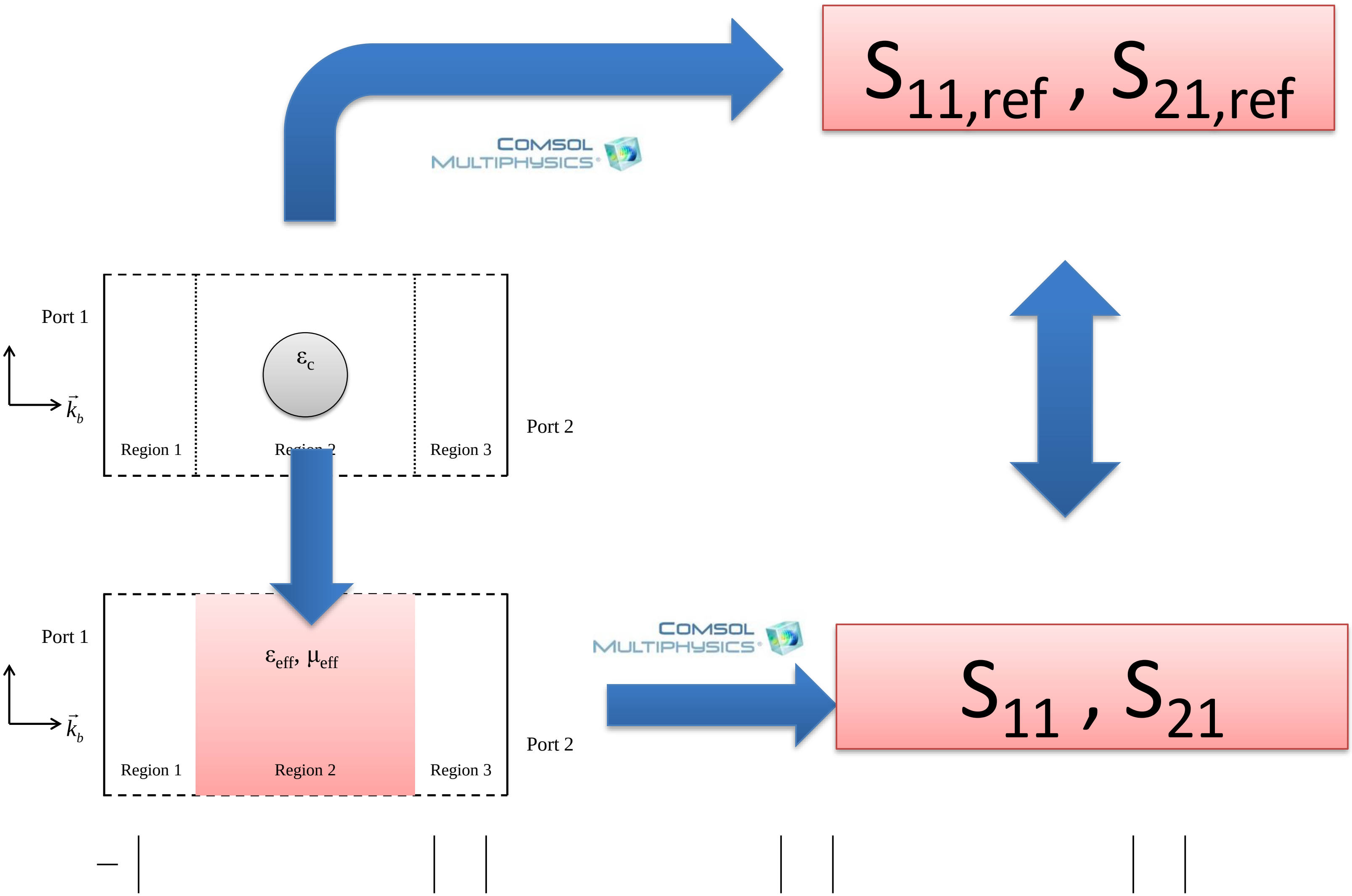
Silver nanorod columns, TM plane waves



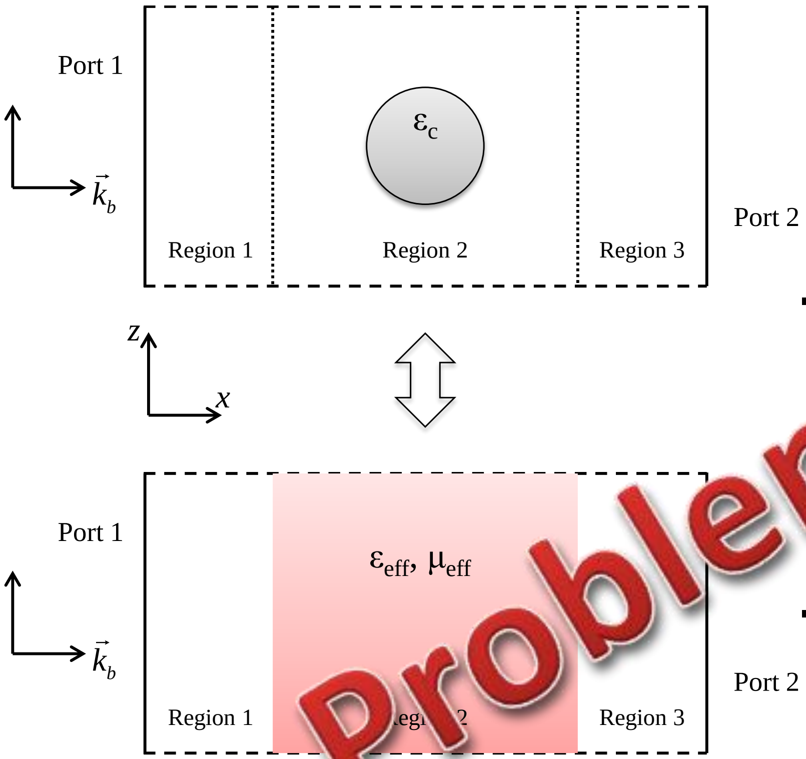


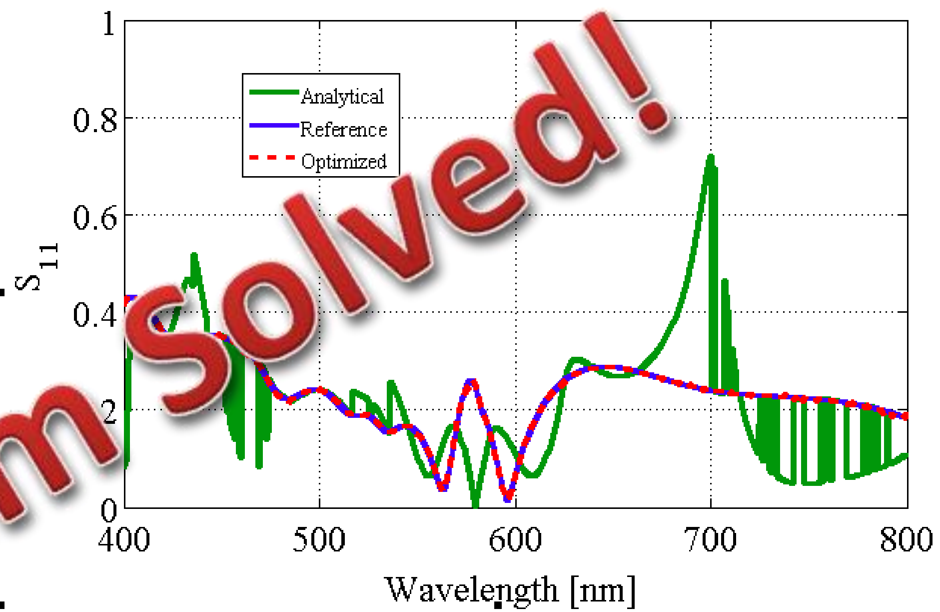
- Column of r_c =158 nm cylinders
- Drude Silver
- 600 nm x 600 nm unit cell

A New Approach



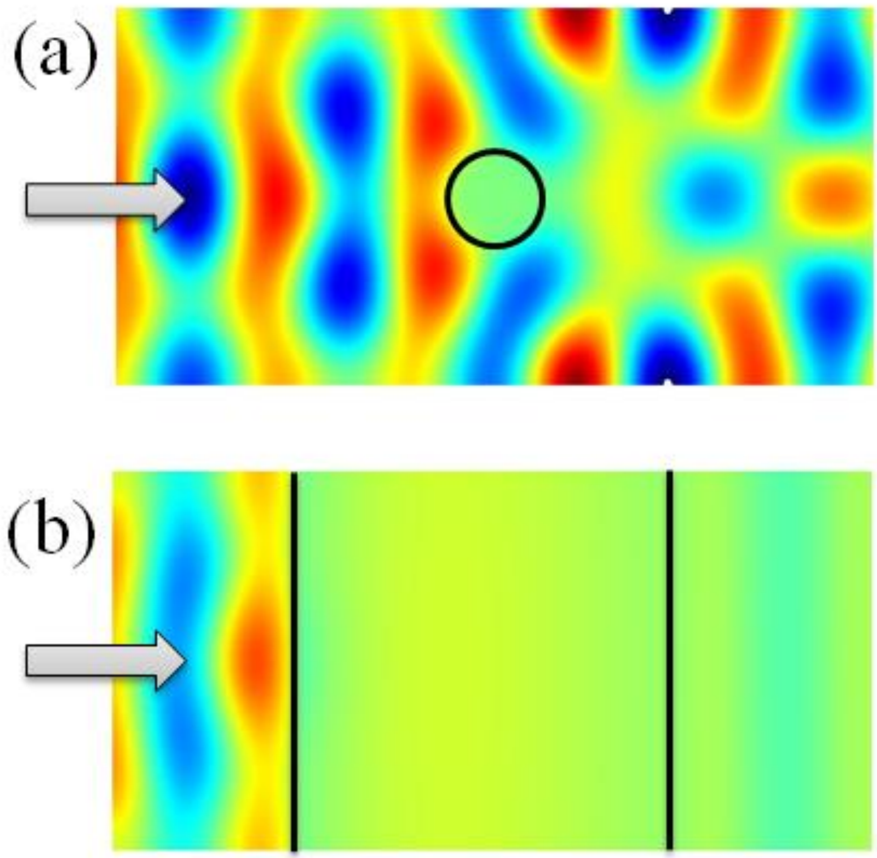
Optimization Results



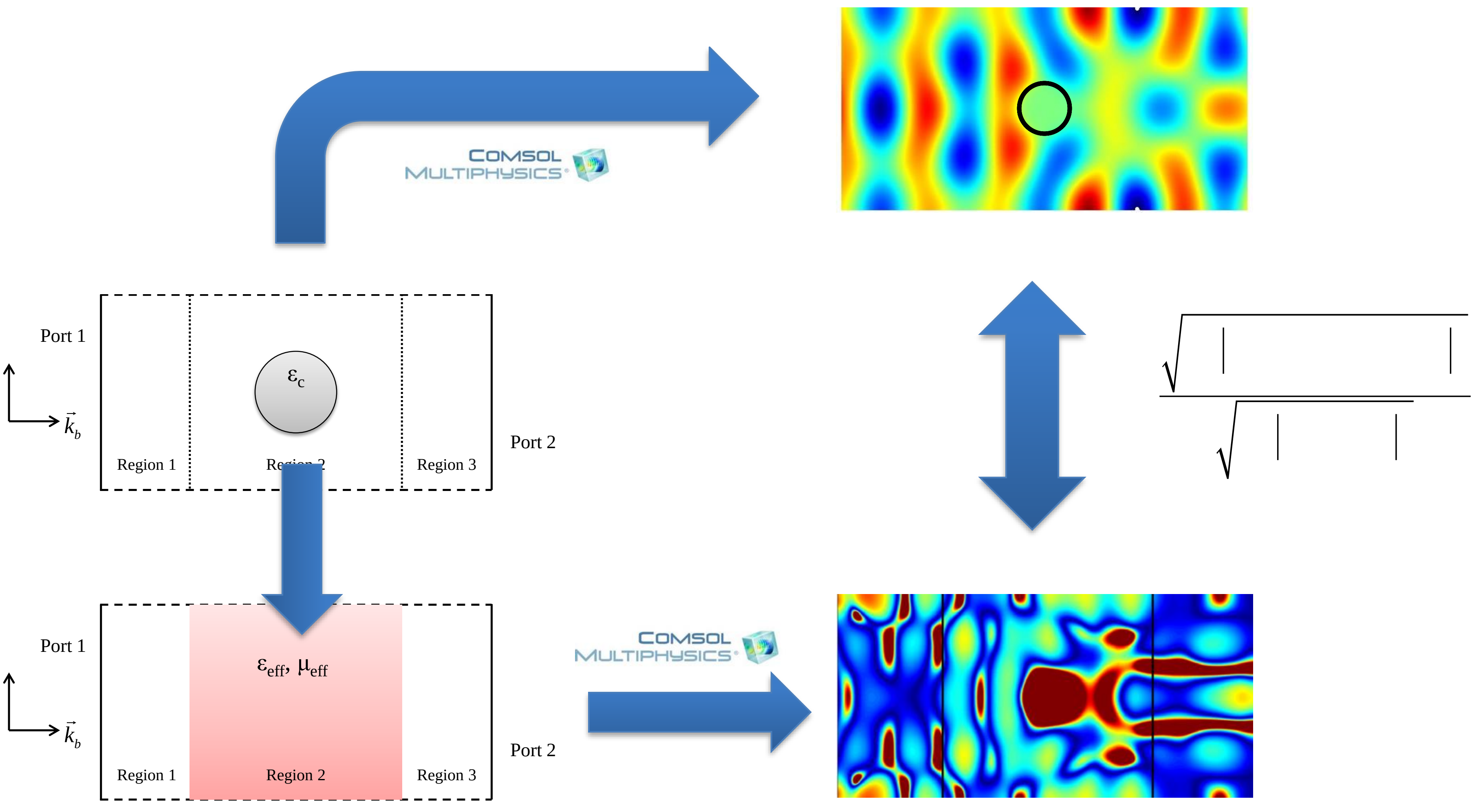


But…

TM Fields at 500nm



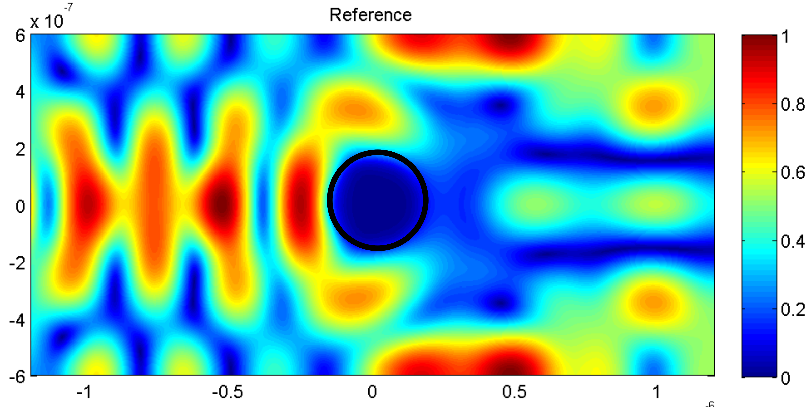
Field Optimization



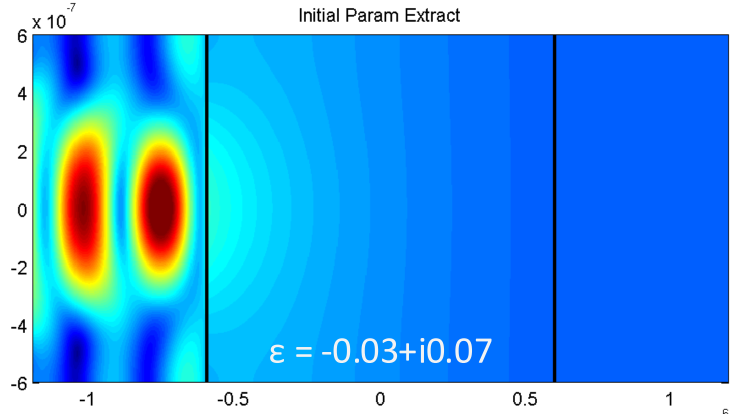
Field Optimization Results

TE waves at 500 nm

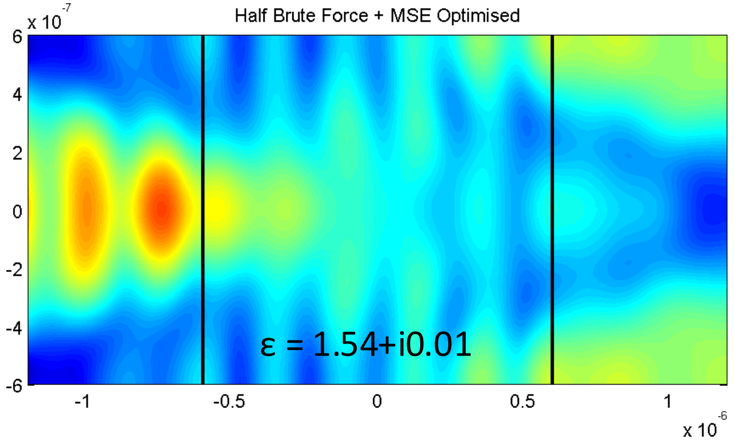
Reference



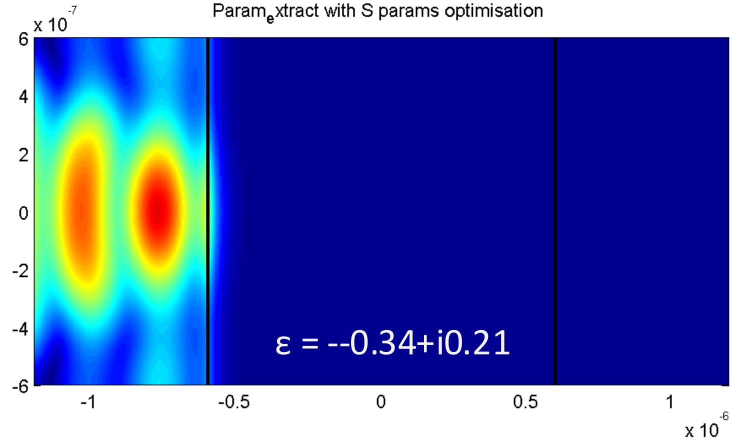
NRW



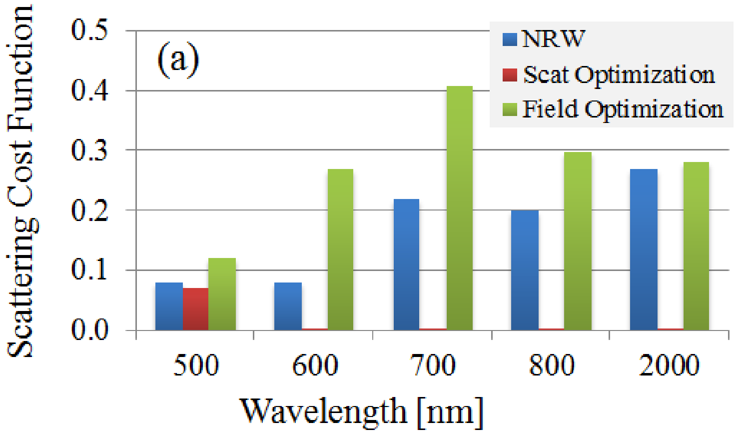
Field Optimization

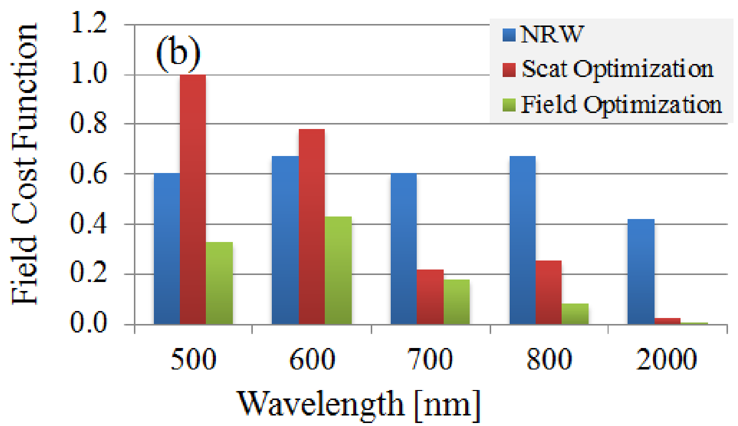


Scattering Optimization



Scattering Parameters vs. Fields



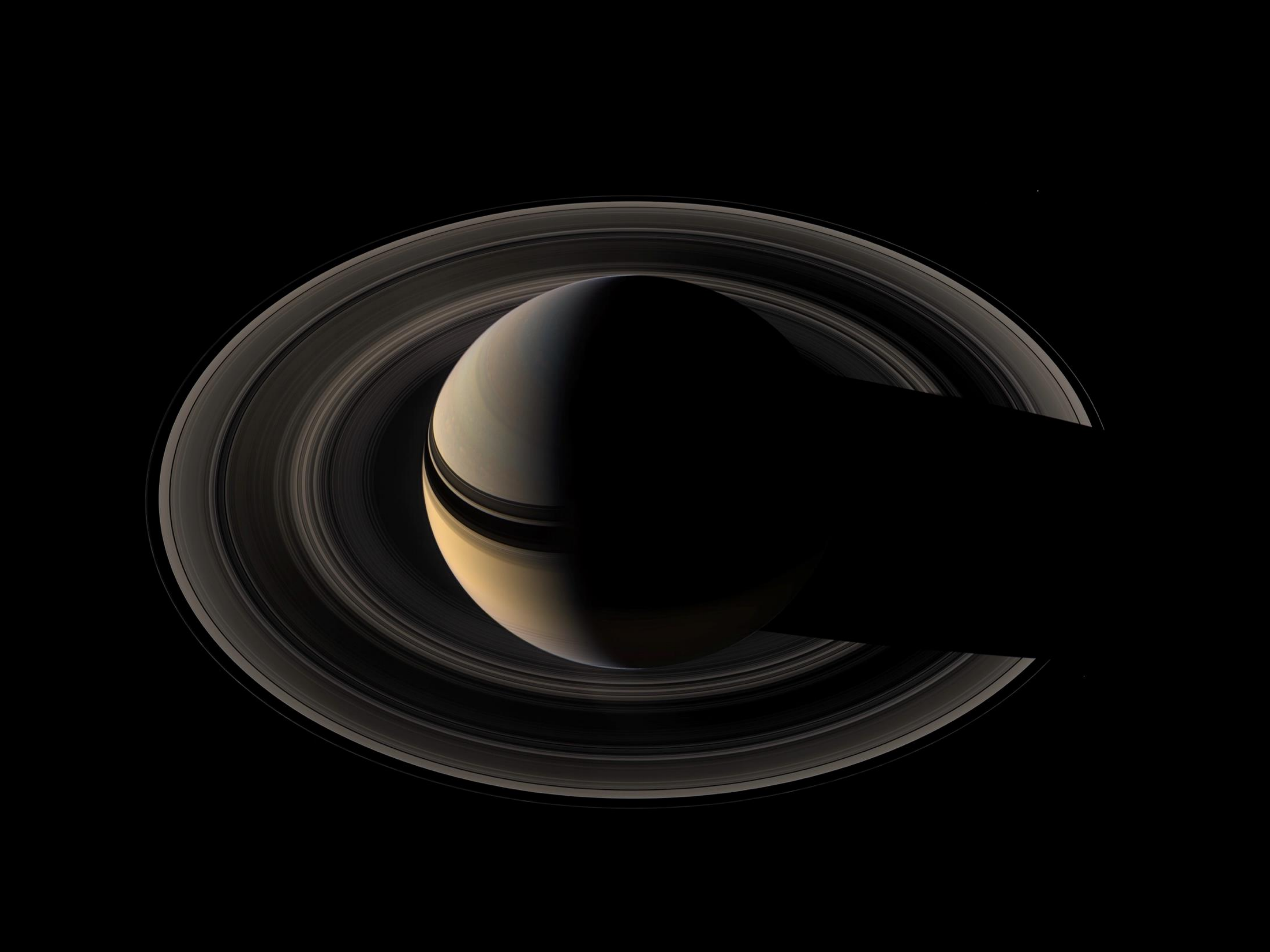


Kallos et al. (in preparation)

Summary

- Homogenization using nonlinear optimization
- Comparing estimated vs. reference parameters
- Scattering optimization works for S-parameters, but…
- … leads to non-realistic field distributions
- Field optimization algorithms
- Expand to 3D, multi-angle, complex structures

Dessert
Back to Saturn



Thank You!

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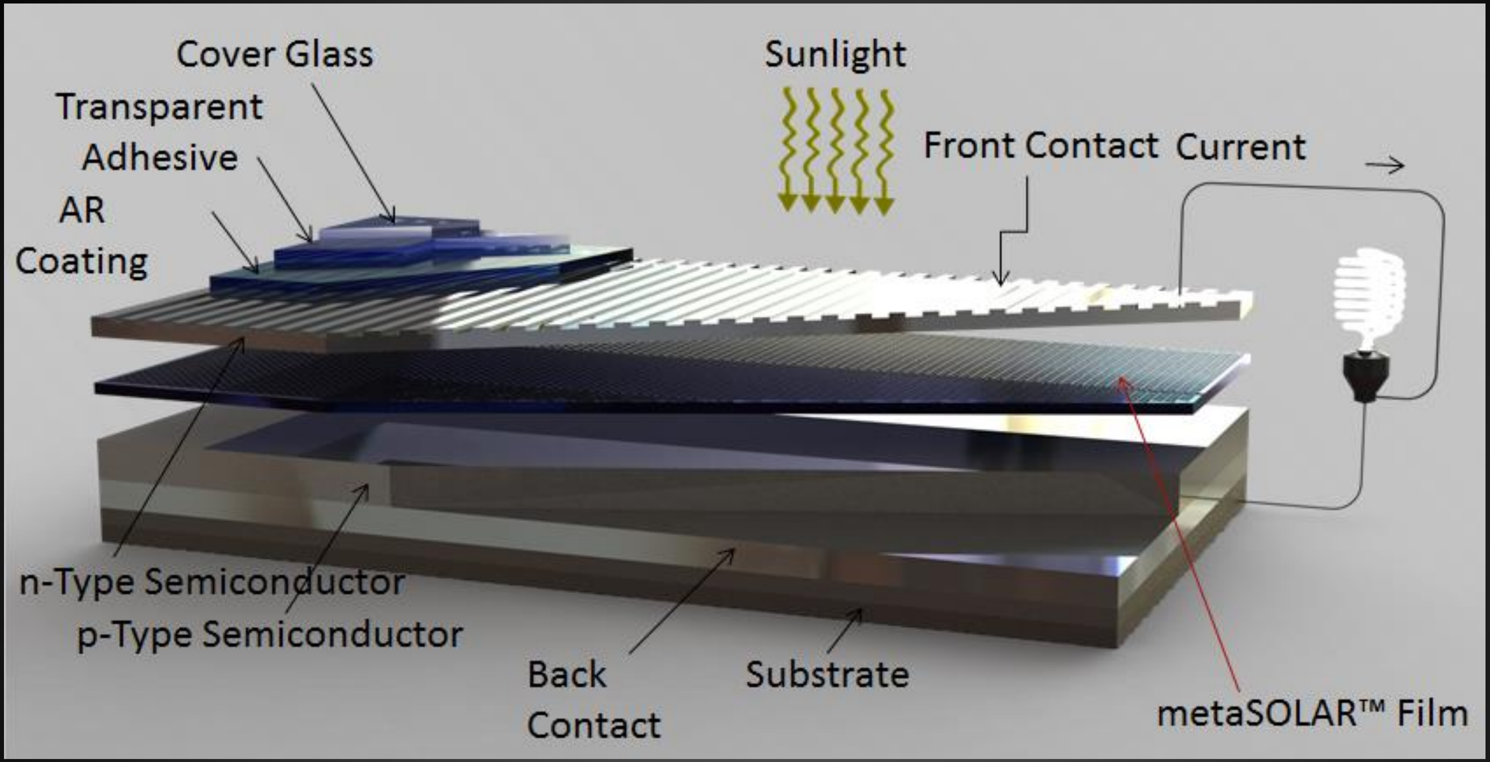
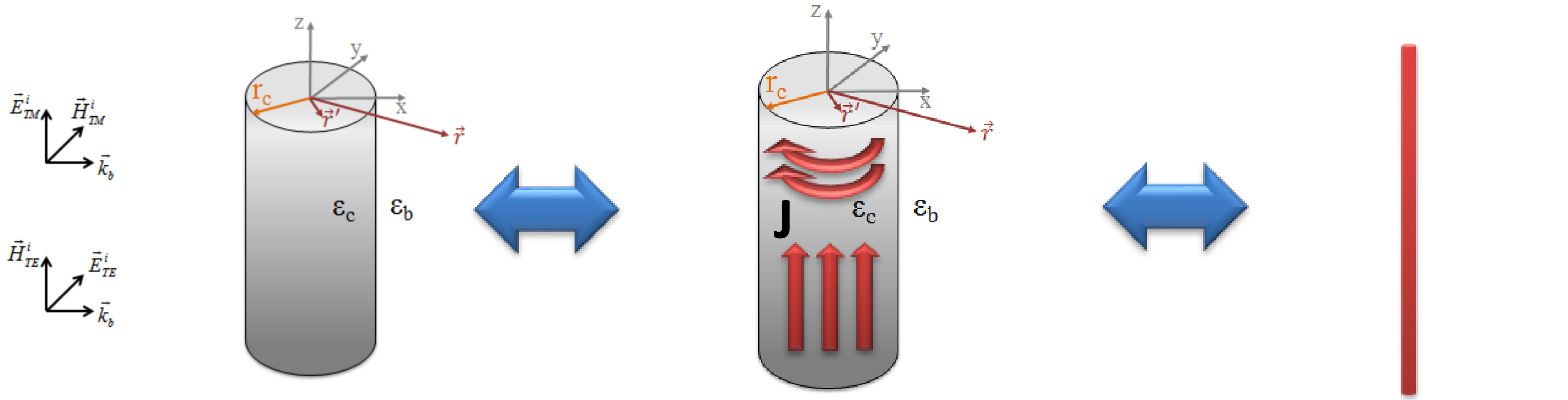
Lamda Solar Inc. – metaSOLAR™ Solution

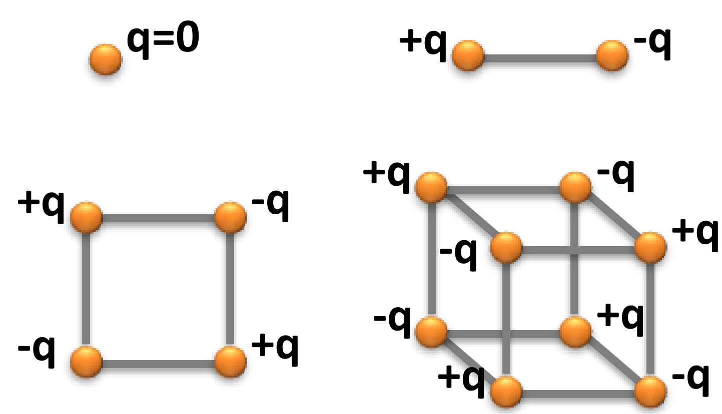


✓ A nano-structured metamaterial that is inserted after the glass in solar panels which will potentially enhance their efficiency by as much as 200%.

Principle of Multipole Expansion

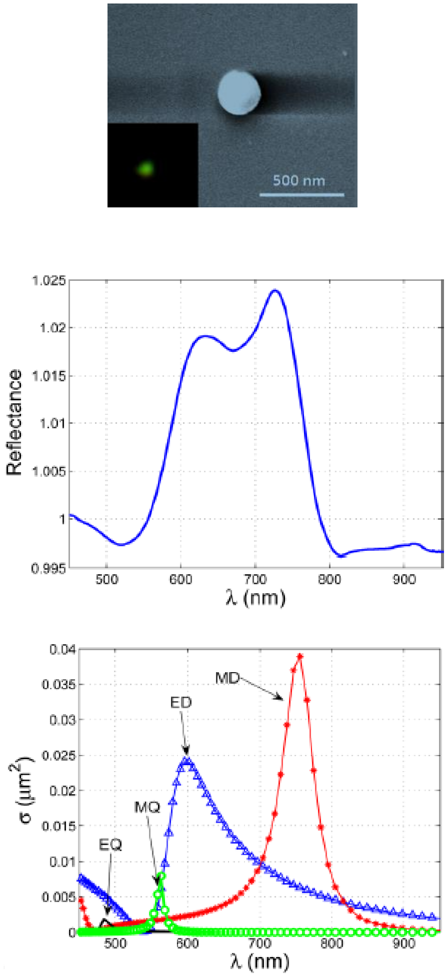
Incident Fields | Currents | Multipole Sources

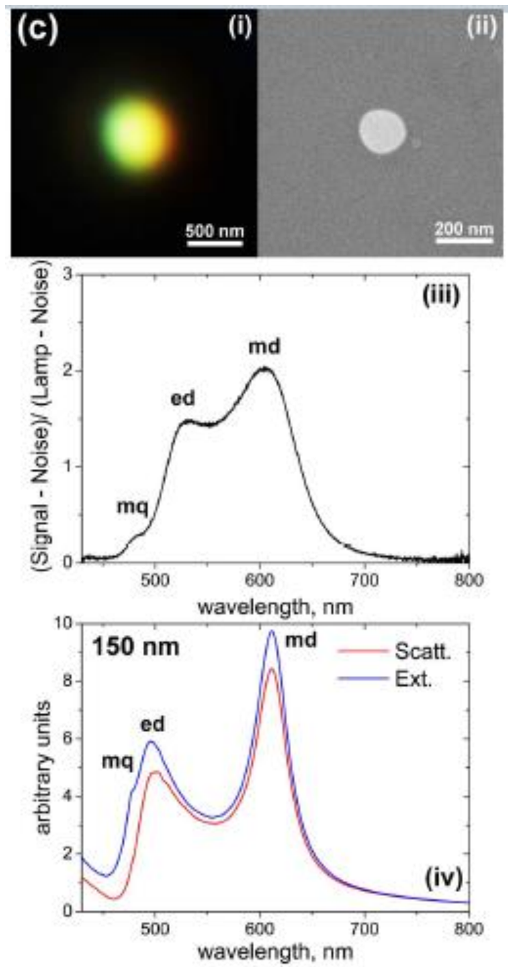


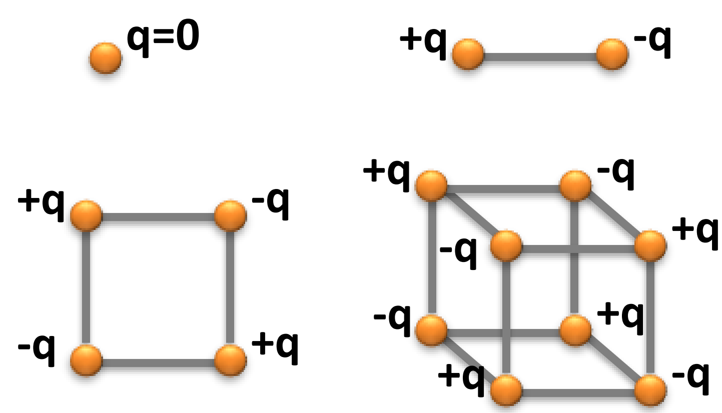


- Manipulate equivalent point-like elements
- Compatible with existing models (Maxwell-Garnett, etc.)

Verified for Si Nanoparticles







Evlyukhin et al., Nanoletters (2012), Kuznetsov et al., Nature Scientific Reports (2012)

$$\vec{f}_0 + \vec{f}_1 = \frac{iK^2}{4\varepsilon_0} \cdot \frac{1}{c_b} g\vec{m} \times \hat{n} + \frac{iK^2}{4\varepsilon_0 c_b} \vec{p} c_b$$

$$= \frac{iK^2}{4\varepsilon_0 c_b} \left(\vec{p} c_b + g\vec{m} \times \hat{n} \right) =$$

$$\frac{1}{m^2} \cdot \frac{m}{F} \cdot \frac{V}{m} \cdot c_b \cdot \frac{m}{s}$$

$$\vec{E} = \frac{iK^2}{4\varepsilon_0 c_b} \left[\vec{p} c_b - g\vec{m} \times \hat{n} \right] \underbrace{\sqrt{\frac{2}{\pi}} e^{-i\pi/4} \frac{e^{+ikr}}{\sqrt{kr}}}_{h}$$

$$Z_b = \sqrt{\frac{\mu_0}{\varepsilon_0}} \cdot \sqrt{\frac{\mu_b}{\varepsilon_b}} = Z_0 / \sqrt{\varepsilon_b}$$

$$\frac{1}{\varepsilon_0 c_b} = \frac{1}{\varepsilon_0 \cdot \frac{c}{\sqrt{\varepsilon_b}}} = \frac{\sqrt{\varepsilon_b}}{\varepsilon_0 \cdot \frac{1}{\sqrt{\varepsilon_0 \mu_0}}} = \frac{\sqrt{\varepsilon_b}}{\sqrt{\frac{\varepsilon_0}{\mu_0}}} = Z_0 \sqrt{\varepsilon_b}$$

$$Z_b \cdot \sqrt{\varepsilon_b} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \cdot \sqrt{\varepsilon_b} = \frac{\sqrt{\varepsilon_b}\sqrt{\varepsilon_0\mu_0}}{\sqrt{\varepsilon_0}} \quad 1/Z_0$$

$$\vec{E} = \sqrt{\varepsilon_b} \cdot Z_0 \cdot \frac{iK^2}{4} \left[\vec{p} c_b - g\hat{n} \times \vec{m} \right] \sqrt{\frac{2}{\pi}} e^{-i\pi/4} \frac{e^{+ikr}}{\sqrt{kr}}$$

$$\vec{H} = -\frac{1}{Z_b} \vec{E} \times \hat{n} = -\frac{\sqrt{\varepsilon_b}}{Z_0} \cdot \sqrt{\varepsilon_b} \cdot Z_0 \cdot \frac{iK^2}{4} \left[\vec{p} c \times \hat{n} + (\vec{m} \times \hat{n}) \times \hat{n} \right]$$

$$= \varepsilon_b \cdot \frac{iK^2}{4} \left[(\hat{n} \times \vec{p} c_b) + g(\hat{n} \times \vec{m} \times \hat{n}) \right] \sqrt{\frac{2}{\pi}} e^{-i\pi/4} \frac{e^{+ikr}}{\sqrt{kr}}$$

$$\vec{p} \begin{cases} \vec{E} = Z_0 \frac{iK^2}{4} \vec{p} c \cdot h \\ \vec{H} = \frac{iK^2}{4} \cdot \hat{n} \times \vec{p} c \cdot h \end{cases}$$

$$\vec{m} \begin{cases} \vec{H} = \frac{iK^2}{4} \vec{m} \cdot h \\ \vec{E} = -Z_0 \frac{iK^2}{4} \cdot \hat{n} \times \vec{m} \cdot h \end{cases}$$

$$\vec{E} = \sqrt{\varepsilon_b} Z_0 \cdot \frac{iK^2}{4} \left(\vec{p} c_b - g\hat{n} \times \vec{m} \right) \sqrt{\frac{2}{\pi}} e^{-i\pi/4} \frac{e^{+ikr}}{\sqrt{kr}}$$

$$\vec{H} = \varepsilon_b \frac{iK^2}{4} \left(\hat{n} \times \vec{p} c_b + g\vec{m} \right) \sqrt{\frac{2}{\pi}} e^{-i\pi/4} \frac{e^{+ikr}}{\sqrt{kr}}$$

Let $\vec{E} = h \cdot (b_0 + 2 b_1 \cos\varphi) \hat{z}$

$$\hat{z} b_0 = \sqrt{\varepsilon_b} Z_0 \cdot \frac{iK^2}{4} \cdot c_b \cdot \vec{p} \rightarrow$$

$$= \frac{iK^2}{4\varepsilon_0} \vec{p} \rightarrow$$

$$\frac{\vec{p}}{\varepsilon_0} = +\hat{z} \frac{4}{iK^2} b_0$$

$$(\hat{x}\cos\varphi + \hat{y}\sin\varphi) \times (m_x \hat{x} + m_y \hat{y}) = \hat{z}\cos\varphi\, m_y - \hat{z} m_x \sin\varphi$$

$$2 b_1 \cos\varphi\, \hat{z} = -\sqrt{\varepsilon_b} Z_0 \frac{iK^2}{4} g\hat{x} \times \vec{m}$$

$$= -\hat{z} \sqrt{\varepsilon_b} Z_0 \frac{iK^2}{4} 2 m_y \cos\varphi \quad = -\hat{z}\, \varepsilon_b \cdot Z_b$$

$$Z_b \vec{m} = -\hat{y} \frac{4 b_1}{iK^2 \varepsilon_b}$$

Multipole Expressions

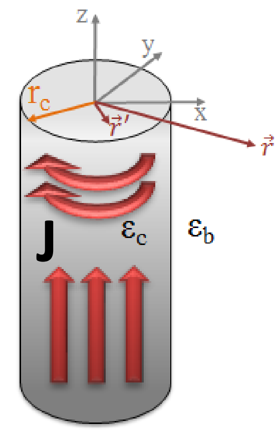
$$\vec{E}_{TM}/Z_b = +k_b^2\hat{z}\left[p_z c_b G + 2m_j\, jG'\right]$$

$$\vec{H}_{TM} = +2k_b^2\left[\hat{n}m_n\left(G+G''\right)+\hat{j}\,m_j\left(G+\frac{G'}{k_b r}\right)\right]+k_b^2\hat{j}\left[p_z c_b jG'\right]$$

$$\vec{E}_{TE}/Z_b = +k_b^2\left[\hat{n}p_n c_b\left(G+G''\right)+\hat{j}\,p_j c_b\left(G+\frac{G'}{k_b r}\right)\right]-k_b^2\hat{j}\left[m_z jG'\right]$$

$$-\frac{k_b^2}{2}\left[\hat{n}wQ_{nn}\left(G'+G'''\right)+\hat{n}wQ_{jj}\left(\frac{G''}{k_b r}-\frac{G'}{\left(k_b r\right)^2}\right)+\hat{j}\,wQ_{nj}\left(G'-\frac{2G'}{\left(k_b r\right)^2}+\frac{2G''}{k_b r}\right)\right]$$

$$\vec{H}_{TE} = -k_b^2\hat{z}\left[p_j c_b jG' - m_z G - \frac{j}{2}wQ_{nj}\left(G''-\frac{G'}{k_b r}\right)\right]$$



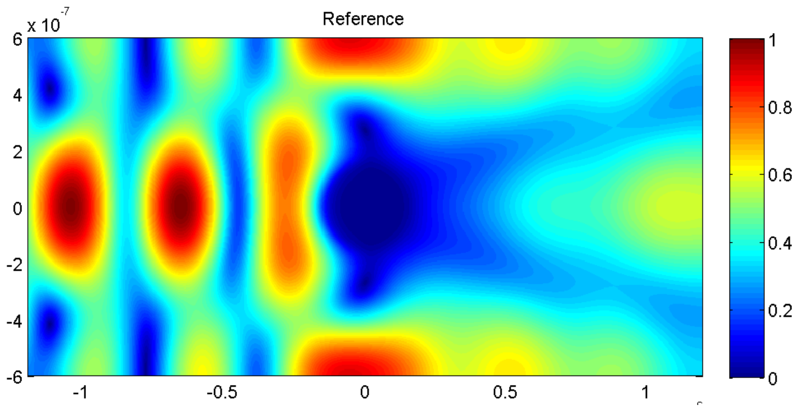
$$\vec{E}_{3D}/Z = +k^3\left[\left(\hat{n}\cdot\vec{pc}\right)\hat{n}G''+\left(\vec{pc}\right)G+\left(\hat{n}\times\vec{m}\right)jG'\right]$$

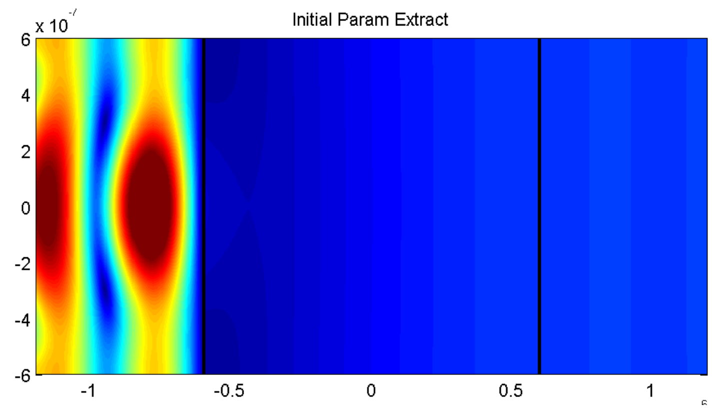
$$\vec{H}_{3D} = -k^3\left[\left(\hat{n}\cdot\vec{m}\right)\hat{n}G''+\vec{m}G+\left(\hat{n}\times\vec{pc}\right)jG'\right]$$

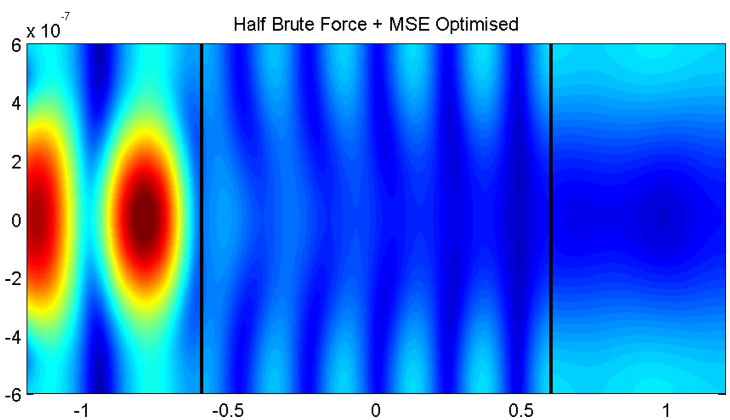
Kallos et al., PRB (2012)

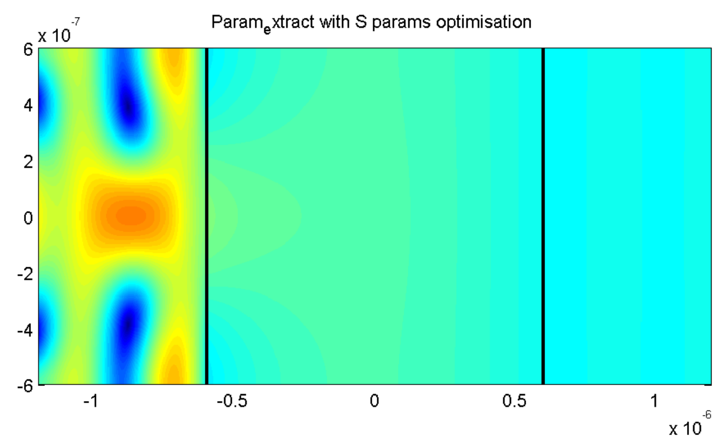
H_z Field Optimization Results

700 nm

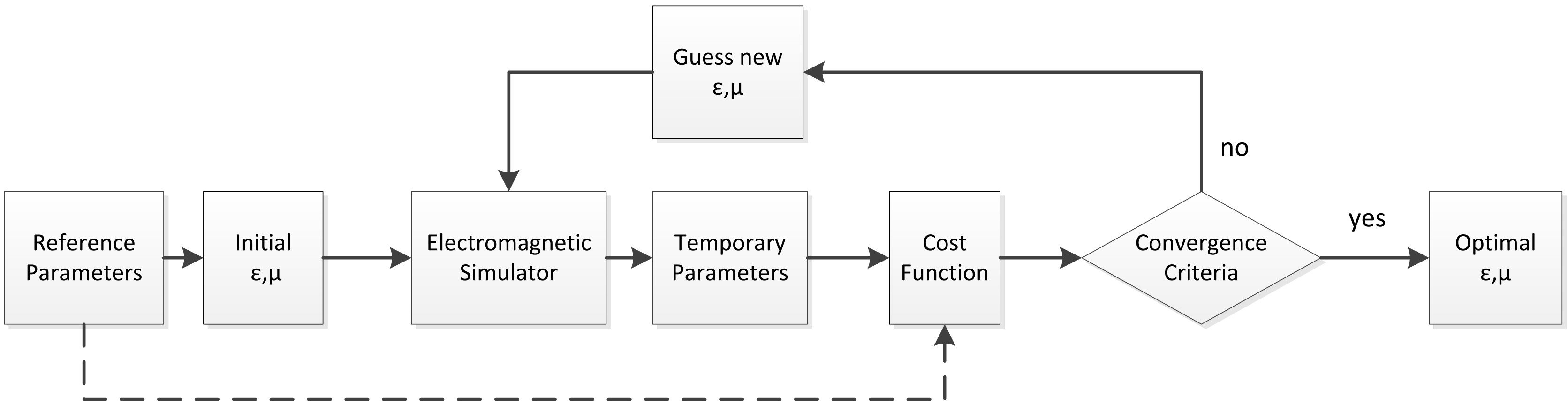




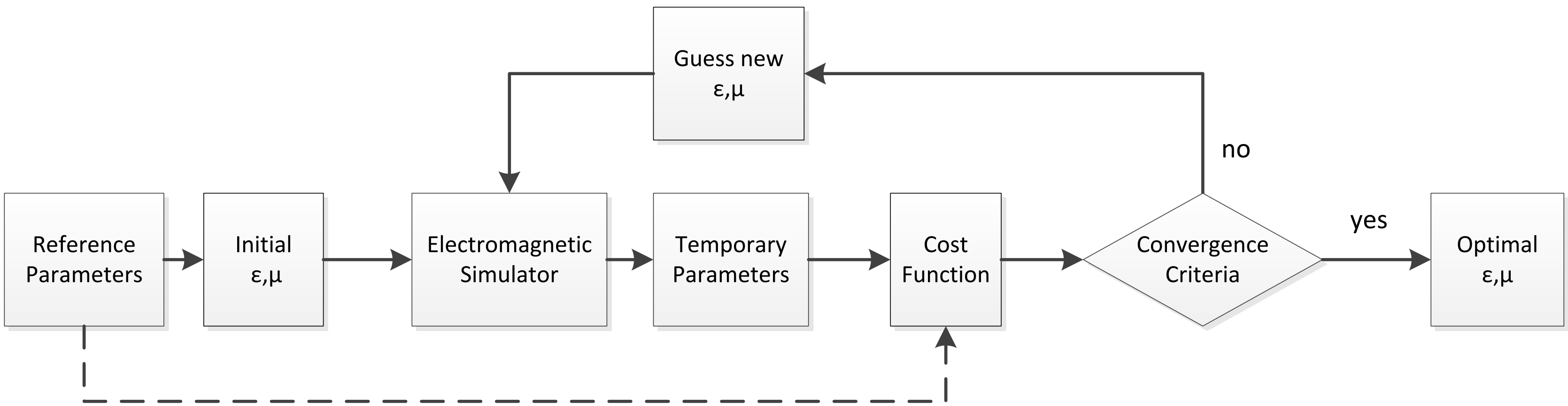


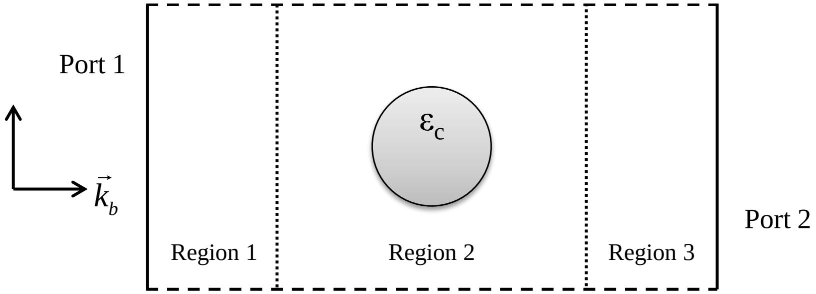


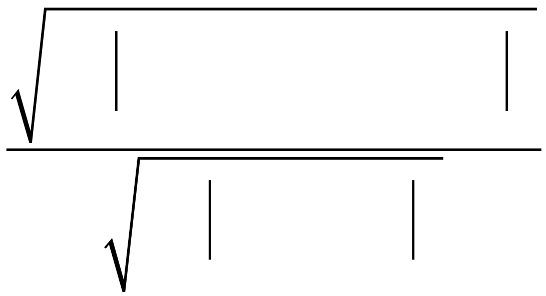
A New Approach

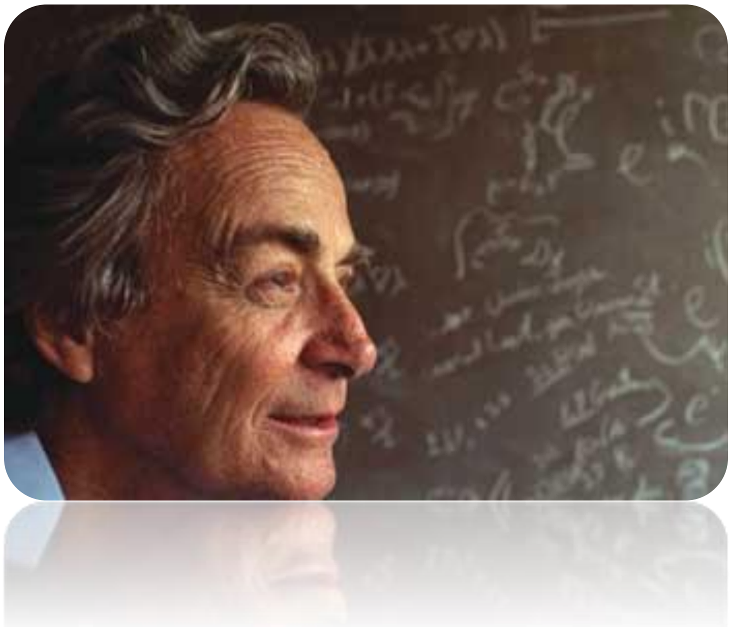


The Algorithm Strikes Back









"I can't see what exactly would happen,

but I can hardly doubt that when we have some control of the arrangement of things in the small scale,

we will get an enormously greater range of possible properties that substances can have."

1959

R. Feynman, There's Plenty of Room at the Bottom
http://www.zyvex.com/nanotech/feynman.html

The Hype Curve

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