Metamaterial research at Aalto University

Aalto University
School of Electrical Engineering
Department of Radio Science and Engineering

Sergei Tretyakov and colleagues
Outline

• University, Department, SMARAD Center of Excellence, research group

• Overview of recent research
  – Electromagnetics of complex media
  – Invisibility and cloaking
  – Isotropic artificial magnetics in the visible
  – Some other topics
About myself and my visit to Jena...

Optics and photonics

Jena, Germany

Electromagnetics, microwave engineering

Espoo, Finland
Aalto University
(former Helsinki University of Technology)

• The oldest and the biggest technical university in Finland
  – About 15000 students and 250 professors
• School of Electrical Engineering (former faculty of Electronics, Communications, and Automation)
• Department of Radio Science and Engineering
  – Electromagnetics, circuit theory, microwave to terahertz techniques (antennas, devices) and measurements, space technology, radio wave propagation, advanced artificial electromagnetic materials
• Research groups lead by professors
About geography
There is no such place called ”Aalto”

- Campuses of the Aalto University are in Espoo and Helsinki
How it looks like?
Aalto is growing:

SIX Tenure Track PROFESSOR Positions

The School of Electrical Engineering seeks experts in the following fields:

• Electrical engineering, Power and energy, Automatic control, Embedded systems, Smart living environment;
• Radio science and engineering, Radio astronomy, Space science and engineering, Optoelectronics;
• Communications and networking engineering.

The positions are open at all levels from assistant professor to full tenured professor.

Application deadline is September 30, 2012.
Department of Radio Science and Engineering (RAD)

The RAD department was established in the beginning of 2008 by integrating four laboratories of TKK (TKK is today Aalto University School of Science and Technology), namely Radio Laboratory, Electromagnetics Laboratory, Circuit Theory Laboratory, and Laboratory of Space Technology, into a single unit.

Personnel:
- 8 professors
- Over 20 other researchers with a doctor degree
- About 30 doctoral students
- Total number of employees about 100

RAD department is involved in SMARAD CoE in research selected by the Academy of Finland for 2002–2007 (as Smart and Novel Radios Research Unit) and 2008–2013 (as Finnish Centre of Excellence in Smart Radios and Wireless Research).

RAD department is also involved in the MilliLab (Millimetre Wave Laboratory of Finland), which has the status of External Laboratory of the European Space Agency (ESA). MilliLab is a joint research institute between Aalto and VTT.
The Virtual Institute for Artificial Electromagnetic Materials and Metamaterials ("Metamorphose VI") is a non-for-profit international association whose purposes are the research, the study and the promotion of artificial electromagnetic materials and metamaterials.

About 20 European universities and institutions are members.
6th International Congress
on Advanced Electromagnetic Materials in
Microwaves and Optics

Metamaterials 2012
St. Petersburg, Russia
17-22 September 2012

congress2012.metamorphose-vi.org
Distributed European Doctoral School on Metamaterials

• Led by Dr. Carsten Rockstuhl, U. Jena
• www.school.metamorphose-eu.org
• METAMORPHOSE Virtual Institute
  www.metamorphose-vi.org
The next EUPROMETA school

- Reconfigurable and tunable metamaterials
  - September 21-22, 2012, in conjunction with the *Metamaterials'2012* Conference
  - St. Petersburg, Russia
Artificial electromagnetic materials and applications
Research group

4 senior researchers (doctoral degree)
4 doctoral students
visitors + undergraduate students
Research group: Main current research directions

- Artificial materials (metamaterials) with unusual and extreme electromagnetic properties – engineering materials for applications
- Nano-scale composite materials and artificial surfaces
- New designs of antennas and microwave devices
- New designs for terahertz and optical devices (imaging and sensing, nano-scale optics...)
- New applications (cloaks, superlenses, solar cells, thermophotovoltaics...)
# Classification of electromagnetic nanostructured materials

<table>
<thead>
<tr>
<th>Nanostructures</th>
<th>Optically dense ((q \cdot a &lt; 1))</th>
<th>Optically sparse ((q \cdot a &gt; 1))</th>
<th>Optically dense in one direction, while either optically sparse or with extended inclusions in other direction(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3D, bulk</strong></td>
<td>Bulk MTM of small inclusions</td>
<td>Photonic crystals and quasi-crystals, Optically sparse random composites</td>
<td>Wire media, multilayer optical fishnet structures, alternating solid plasmonic and dielectric nanolayers</td>
</tr>
<tr>
<td></td>
<td>Bulk nanostructured materials without useful and unusual electromagnetic properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2D, surface</strong></td>
<td>Metasurfaces / metafilms</td>
<td>Plasmonic diffraction grids, optical band-gap surfaces and optical frequency selective surfaces</td>
<td>Artificial impedance surfaces with long inclusions or slots</td>
</tr>
<tr>
<td></td>
<td>nanostructured optically dense surfaces without useful and unusual electromagnetic properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1D, linear</strong></td>
<td>Metawaveguides</td>
<td>Not yet investigated, but possible</td>
<td></td>
</tr>
</tbody>
</table>
Bianisotropic constitutive relations

\[ D = \varepsilon \cdot E + \xi \cdot H \]
\[ B = \zeta \cdot E + \mu \cdot H \]

\[ \xi = \chi^T - j\kappa^T \]
\[ \zeta = \chi + j\kappa \]

Lossless: \( \xi = \xi^* \Rightarrow \chi^T - j\kappa^T = (\chi + j\kappa)^* \Rightarrow \chi, \kappa \) real

Reciprocal: \( \xi = -\xi^* \Rightarrow \chi^T - j\kappa^T = -(\chi + j\kappa)^T \Rightarrow \chi = 0, \kappa \) arbitrary

(Ari Sihvola)
# Classification of bianisotropic materials

<table>
<thead>
<tr>
<th>Symmetric part: 6 parameters</th>
<th>Dielectric crystal (RECIPROCAL)</th>
<th>Magnetic medium</th>
<th>Chiral medium</th>
<th>Tellegen (Cr$_2$O$_3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-symmetric part 3 parameters</td>
<td>Magneto-plasma (NON-RECIPROCAL)</td>
<td>Biased ferrite</td>
<td>Omega medium</td>
<td>Moving medium</td>
</tr>
</tbody>
</table>

(Ari Sihvola)
Material optimized for the purpose?
The "optimal" spiral

The resonant frequency (the total length of the wire) is fixed. For which shape the particle has the max energy in a given external field?

Answer: For single-turn spirals $\alpha_{opt} = 13.65^\circ$ (the solution to $\sin^2 \alpha + 4 \cos^2 \alpha = 1$)
Optimal metamaterials
Chiral media

\[
\begin{align*}
\mathbf{D} &= \epsilon \mathbf{E} - j\kappa \sqrt{\varepsilon_0 \mu_0} \mathbf{H} \\
\mathbf{B} &= \mu \mathbf{H} + j\kappa \sqrt{\varepsilon_0 \mu_0} \mathbf{E}
\end{align*}
\]

\[k = k_0(n \pm \kappa), \quad n = \sqrt{\frac{\varepsilon \mu}{\varepsilon_0 \mu_0}}\]

"Optimal" spiral inclusions: \(n=0, \kappa=1\) – "extreme parameter values"
Negative refraction, negative reflection, "standing spirals",...


Optimal metamaterials for linear polarization
Omega media

\[ p_z = \alpha_{ee} E_z + \alpha_{em} H_y, \quad m_y = \alpha_{mm} H_y + \alpha_{me} E_z \]
Omega coupling is a very general phenomenon
Particle energy (omega particle)

\[-W = \frac{1}{2} \text{Re}\{\mathbf{p} \cdot \mathbf{E}^* + \mathbf{m} \cdot \mathbf{H}^*\}\]

\[-W = \frac{1}{2} |E|^2 \text{Re} \left\{ \alpha_{ee} + \alpha_{em} \left( \frac{1}{Z} - \frac{1}{Z^*} \right) + \alpha_{mm} \frac{1}{|Z|^2} \right\}\]

For travelling waves the wave impedance \(Z\) is real, and the term proportional to \(\alpha_{me}\) cancels out.

But for evanescent waves the impedance is imaginary and we can optimize the particle shape to maximize the particle energy.
Bianisotropic materials optimized for strong interactions with electromagnetic fields

<table>
<thead>
<tr>
<th>Wave</th>
<th>Proper Particle</th>
<th>Particle Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-LP</td>
<td>Omega</td>
<td>$W = -\frac{1}{2}</td>
</tr>
<tr>
<td>E-CP</td>
<td>Tellegen</td>
<td>$W = -\frac{1}{2}</td>
</tr>
<tr>
<td>P-LP</td>
<td>Moving</td>
<td>$W = -\frac{1}{2}</td>
</tr>
<tr>
<td>P-CP</td>
<td>Chiral</td>
<td>$W = -\frac{1}{2}</td>
</tr>
</tbody>
</table>
Total absorption in thin bianisotropic layers

<table>
<thead>
<tr>
<th>Proper Particle</th>
<th>Condition for total absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omega</td>
<td>$\eta_0 \hat{\alpha}<em>{ee} \pm 2 \hat{\alpha}</em>{em} - \frac{1}{\eta_0} \hat{\alpha}_{mm} = 0$</td>
</tr>
<tr>
<td></td>
<td>$\eta_0 \hat{\alpha}<em>{ee} + \frac{1}{\eta_0} \hat{\alpha}</em>{mm} = -\frac{2S}{\omega} j$</td>
</tr>
<tr>
<td></td>
<td>$\hat{\alpha}_{em} = 0$</td>
</tr>
<tr>
<td>Chiral</td>
<td>$\eta_0 \hat{\alpha}<em>{ee} - \frac{1}{\eta_0} \hat{\alpha}</em>{mm} = 0$</td>
</tr>
<tr>
<td></td>
<td>$\eta_0 \hat{\alpha}<em>{ee} + \frac{1}{\eta_0} \hat{\alpha}</em>{mm} = -\frac{2S}{\omega} j$</td>
</tr>
<tr>
<td></td>
<td>$\hat{\alpha}_{em} = 0$</td>
</tr>
<tr>
<td>Moving</td>
<td>$\eta_0 \hat{\alpha}<em>{ee} - \frac{1}{\eta_0} \hat{\alpha}</em>{mm} = 0$</td>
</tr>
<tr>
<td></td>
<td>$\eta_0 \hat{\alpha}<em>{ee} \pm 2 \hat{\alpha}</em>{em} + \frac{1}{\eta_0} \hat{\alpha}_{mm} = -\frac{2S}{\omega} j$</td>
</tr>
<tr>
<td></td>
<td>$\hat{\alpha}<em>{cr} = \hat{\alpha}</em>{mm} = 0$</td>
</tr>
<tr>
<td>Tellegen</td>
<td>$\eta_0 \hat{\alpha}<em>{ee} - \frac{1}{\eta_0} \hat{\alpha}</em>{mm} = 0$</td>
</tr>
<tr>
<td></td>
<td>$\eta_0 \hat{\alpha}<em>{ee} + 2 \hat{\alpha}</em>{em} - \frac{1}{\eta_0} \hat{\alpha}_{mm} = 0$</td>
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<td></td>
<td>$\eta_0 \hat{\alpha}<em>{ee} + \frac{1}{\eta_0} \hat{\alpha}</em>{mm} = -\frac{2S}{\omega} j$</td>
</tr>
<tr>
<td></td>
<td>$\hat{\alpha}_{cr} = 0$</td>
</tr>
</tbody>
</table>
Example: Total absorption in an omega-layer

\[ \lambda_{\text{MPA}} = 361.9 \text{ nm} \]  
\[ \text{Power Absorption} = 99\% \]
General approach to design of thin layers for any desired electromagnetic response

\[
E_r = - \frac{j \omega}{2S} \left[ \left( \eta_0 \hat{\alpha}_{ee}^{co} + \hat{\alpha}_{em}^{cr} + \hat{\alpha}_{me}^{cr} - \frac{1}{\eta_0} \hat{\alpha}_{mm}^{co} \right) \hat{I}_t \right. \\
+ \left( \eta_0 \hat{\alpha}_{ee}^{cr} - \hat{\alpha}_{em}^{co} - \hat{\alpha}_{me}^{co} - \frac{1}{\eta_0} \hat{\alpha}_{mm}^{cr} \right) \hat{J}_t \right] \cdot E_{inc}
\]

\[
E_t = \left\{ \left[ 1 - \frac{j \omega}{2S} \left( \eta_0 \hat{\alpha}_{ee}^{co} + \hat{\alpha}_{em}^{cr} - \hat{\alpha}_{me}^{cr} + \frac{1}{\eta_0} \hat{\alpha}_{mm}^{co} \right) \right] \hat{I}_t \right. \\
- \frac{j \omega}{2S} \left( \eta_0 \hat{\alpha}_{ee}^{cr} - \hat{\alpha}_{em}^{co} + \hat{\alpha}_{me}^{co} + \frac{1}{\eta_0} \hat{\alpha}_{mm}^{cr} \right) \hat{J}_t \right\} \cdot E_{inc}
\]
Example: Twist polarizer

\[
\begin{cases}
E_r = 0 \\
E_t = A \bar{J}_t \cdot E_{inc}
\end{cases}
\]
Electromagnetic cloaking

- Cloaking: Reduction of an object’s **total** scattering cross section (SCS)

\[
\sigma = \lim_{R \to \infty} 4\pi R^2 \frac{S_{sc}}{S_{inc}} = \lim_{R \to \infty} 4\pi R^2 \frac{|E_{sc}|^2}{|E_{inc}|^2} = \lim_{R \to \infty} 4\pi R^2 \frac{|H_{sc}|^2}{|H_{inc}|^2}
\]

- Total scattering cross section = \( \int (\sigma) \, d\Omega \)
- In the case of infinitely high structures we speak about the total scattering width: The integration is done over one angle in a **plane**
Broadband cloaking devices/approaches developed at Aalto University

- Transmission-line cloak

- Metal-plate cloak


Transmission-line cloak

- Designed for TE polarization
- HFSS simulations of E-fields at 10 GHz (complete structure, no homogenization!)

Metal-plate cloak

- Designed for TE polarization
- HFSS simulations of E-fields at 10 GHz (complete structure, no homogenization!)

Bistatic measurements

- Cloak: metal-plate cloak
- Object to be hidden: metal cylinder (diameter 30mm, height 184mm)

<table>
<thead>
<tr>
<th>$D$</th>
<th>$H$</th>
<th>$h$</th>
<th>$L_1$</th>
<th>$L_2$</th>
<th>$t$</th>
<th>$w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>9.2</td>
<td>6</td>
<td>61</td>
<td>32</td>
<td>0.1</td>
<td>2</td>
</tr>
</tbody>
</table>

1$\lambda$ at 10 GHz
Bistatic X-band measurement setup at DLR

- Bistatic measurements can be carried out in the xy-plane for angles 22 - 180 deg
- Frequency range: X-band, specifically, 8.2 GHz – 12.4 GHz
- The measured object is placed at the origin
Normalized total scattering widths

- Solid lines: HFSS simulations (full integration)
- Dashed lines: HFSS simulations (integration from 22 \( \ldots \) 180)
- Dotted lines: measurements (integration from 22 \( \ldots \) 180)

\[
\sigma_{W,norm}(f) = \frac{\int |E_{\text{sc},01}(f, \phi)|^2 d\phi}{\int |E_{\text{sc},02}(f, \phi)|^2 d\phi}
\]
Challenge: Isotropic magnetic material in the visible
Another design idea

Silver core – plasmonic electric response
Si shell – Mie magnetic response
Individual polarizabilities

$r_1 = 30 \text{ nm}, \ r_2 = 130 \text{ nm}$
Maxwell Garnett

Effective material parameters:

- Periodic 3D array
  - Plot PER

- Random 3D array
  - Plot RAND
Field distributions

$\lambda = 1153 \text{ nm}$

$\lambda = 1071 \text{ nm}$
Field distributions

\[ \lambda = 877 \text{ nm} \quad \lambda = 833 \text{ nm} \]
Field distributions

Refraction indices retrieved from all these pictures are values between those predicted by plots PER and RAND:

Our interpretation:

Compensation of radiative losses of a particle is incomplete

\[ \lambda = 750 \text{ nm} \]
Arrays of resonant nanoparticles
Regular vs random arrays

Graph 1:
- Regular grid: $r_n = 1$
- Random grid: $r_n = 0$
- Random grid: $r_n = 1/2$
- Random grid: $r_n = 3/4$
- Random grid: $r_n = 19/20$

Graph 2:
- Regular grid: $r_n = 1$
- Random grid: $r_n = 0$
- Random grid: $r_n = 1/2$
- Random grid: $r_n = 3/4$
- Random grid: $r_n = 19/20$
$p = \alpha_{ee}(E_{\text{inc}} + \beta_{ee}p), \quad m = \alpha_{mm}(H_{\text{inc}} + \beta_{mm}m)$

\[
\frac{\varepsilon_0 a^3}{\alpha_{ee}} = \left( \frac{A_e}{\omega^2_{0e} - \omega^2 - i\omega \Gamma_e} \right)^{-1} - i \frac{k_0^3 a^3}{6\pi}
\]

\[
\frac{\mu_0 a^3}{\alpha_{mm}} = \left( \frac{A_m}{\omega^2_{0m} - \omega^2 - i\omega \Gamma_m} \right)^{-1} - i \frac{k_0^3 a^3}{6\pi}
\]

\[
\beta_{\text{regular}} = \text{Re}(\beta) - i \frac{k_0^3 a^3}{6\pi} + i \frac{k_0 a}{2}
\]

\[
\beta_{\text{amorph}} = \text{Re}(\beta) + i \frac{k_0 a}{2}
\]
Enhancement of micron-gap thermophotovoltaic systems

Modification of the micron gap between the hot and photovoltaic surfaces of a thermophotovoltaic system by inserting Carbon NanoTubes or nanowires. The interdigital arrangement
1. transforms the gap into an indefinite medium layer
2. prevents the phonon transfer (which would suppress the photovoltaic operation).

Radiative heat transfer spectral density $q''_\lambda$ across a 1 $\mu$m gap normalized to the black-body heat transfer density $q''_{p\lambda}$. Blue line – with CNT. Red line – without them. Hot surface - $T=300^\circ$K, cold surface - $T=0$. 

Aalto University
Light-trapping structures for thin-film solar cells

The results of the simulation of EM fields in a unit cell of the array of Au nanoantennas illuminated by a normally incident plane wave at 370 THz. It is seen that the nanoantenna produces hot spots which are fully located in the spacings between metal nanoelements and do not heat them. The transmittance through the photoabsorbing layer averaged over the frequency range is equal to 0.08: the heating of the substrate is also suppressed.

The enhancement of photo-absorption in the presence of nanoantennas versus frequency (simulations). Nanoantennas are far from the plasmon resonance So-called domino modes help to create a broadband cavity between the substrate and the superstrate.
Electromagnetic characterization of metasurfaces

\[ \varepsilon_r = 12 \quad (\Theta = 45^\circ) \]

\[ \varepsilon_r = 12 \quad (\Theta = 45^\circ) \]

Substrate-induced biaxial anisotropy appears when \( \varepsilon_r \gg 1 \).
An ultra-broadband electromagnetically indefinite medium formed by aligned carbon nanotubes
Thank you!

http://users.tkk.fi/~sergei