Metamaterial Roadmap

Metamorphose vision for the future advancements

April 2008
Sergei Tretyakov, Ekmel Özbay, Christophe Crayene, and many other Metamorphose partners
Metamaterial is an arrangement of artificial structural elements, designed to achieve advantageous and unusual electromagnetic properties.

More precisely, properties that cannot be achieved at the atomic or molecular level are achieved through the electromagnetic interaction between the “particles” formed at levels much higher than the atomic level and whose dimensions are small compared to the wavelength of operation.
Metamaterials Research

Published Items in Each Year

Citations in Each Year

Search in SCI for “metamaterials”
Other common names, LHM, BW etc. not included
A Comparison of Metamaterials Research

<table>
<thead>
<tr>
<th>Field: Country/Territory</th>
<th>Record Count</th>
<th>% of 671</th>
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Search in SCI for “metamaterials”
Other common names, LHM, BW etc. not included
METAMORPHOSE

• A European network of excellence (NoE) dedicated to metamaterials
• Coordinator: Prof. Sergei Tretyakov (TKK, Finland)
• Strategic Manager: Dr. Vladimir Podlozny (TKK, Finland)
• Lifetime: June 2004 - May 2008
• www.metamorphose-eu.org
## Participants

<table>
<thead>
<tr>
<th></th>
<th>University Name</th>
<th>Abbreviation</th>
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<td>UCL</td>
<td>Belgium</td>
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<td>ETU</td>
<td>Russia</td>
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<tr>
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<td>FORTH, Institute of Electronic Structure and Laser</td>
<td>FORTH</td>
<td>Greece</td>
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<td>21</td>
<td>Institute of Electronic Materials Technology</td>
<td>ITME</td>
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Life after METAMORPHOSE?

- Lifetime of Metamorphose: June 2004 - May 2008
- New structure: Metamorphose VI
- One of the first virtual institutes envisioned by the EU Commission to follow-up NoE
- [www.metamorphose-vi.org](http://www.metamorphose-vi.org)
- 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
- A research roadmap is one of the VI instruments
What is a roadmap?

WIKIPEDIA

A roadmap may refer to:

A map of roads (where they might lead nobody knows), and possibly other features, to aid in navigation

A plan, e.g.

Road map for peace, to resolve the Israeli-Palestinian conflict

Technology roadmap, a management forecasting tool
Goals

• Get a clear idea of opportunities and challenges offered by metamaterials

• Obtain a structured view of possible research orientations

• Organise research at European level
  o to avoid overlaps
  o to achieve good coverage
  o to be fast picking up the fruits of joint efforts
Classification

![Diagram showing classification with axes $\mu$ and $\varepsilon$, and regions labeled ENG, DPS, DNG, MNG, BW, and FW. ENG and DPS regions are marked with "no propagation".](image)
\[ D = \varepsilon E + (\chi - j\kappa)H \]
\[ B = (\chi + j\kappa)E + \mu H \]
<table>
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<th></th>
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<th>$\mu$</th>
<th>$\eta$</th>
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<td>perfect electric conductor</td>
<td>large</td>
<td>small</td>
<td>undefined</td>
</tr>
<tr>
<td>PMC</td>
<td>perfect magnetic conductor</td>
<td>small</td>
<td>large</td>
<td>undefined</td>
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<tr>
<td>ZIM</td>
<td>zero-index material</td>
<td>small</td>
<td>small</td>
<td>very small</td>
</tr>
<tr>
<td>IIM</td>
<td>infinite-index material</td>
<td>large</td>
<td>large</td>
<td>very large</td>
</tr>
<tr>
<td>ZEM</td>
<td>zero-electric material</td>
<td>very small</td>
<td>undefined</td>
<td>small</td>
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<td>IMM</td>
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</table>
Three wavelength regimes with different challenges:

1. Microwaves: based on well-established research in the field of antennas and microwave circuits.

2. TeraHertz: new field because of strong instrumental limitations at this stage.

3. Optics: also based on strong background, but bigger challenges, related to availability of low-loss nano-structured metamaterials and nano-fabrication techniques.
Different goals in different frequency ranges

1. Develop new processes and materials with engineered micro- or nano-scopic structure for improvement of microwave and millimetre-wave devices and creation of new devices with new capabilities, mainly for information technologies. The issues of tunability, including electrical control, and integration in larger systems are at the forefront.
2. Create new artificial materials, devices and applications for **TeraHertz frequencies**, based on special phenomena, like left-handed materials. The cost of fabrication and testing still being very high in this frequency range, the research roadmap in the field of TeraHertz technologies will **partly rely on conceptual experiments at microwave frequencies**.
Different goals in different frequency ranges

3. At **optical frequencies**, the first objective is to prove the **feasibility** of lensing metamaterials with the help of artificial materials like plasmonic devices, split-ring resonators and new types of materials and engineered (structural) thin sheets. Second, materials with extreme dielectric or magnetic properties are also looked for. A big challenge for material scientists is to find low-loss plasmonic materials.
Roadmap formation process

Matematerials are still at a relatively fundamental level:

Some applications are almost commercial (collimators, microwave antennas, phase shifters), while others are still purely at conceptual level (invisibility).

Work at some intermediate level: functionality

« Properties for which metamaterials could be used »
Miniaturation and optimization of existing devices

Theoretical methods: numerical and analytical

Fabrication methods

Characterization methods
<table>
<thead>
<tr>
<th>Functionality</th>
<th>Phenomenology</th>
<th>Application (system)</th>
<th>Fabrication &amp; measurement</th>
<th>Analysis techniques</th>
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</thead>
<tbody>
<tr>
<td>Imaging and sensing</td>
<td>Collimation Low-epsilon materials, low-mu materials, spatial dispersion</td>
<td>MRI imaging, health applications,</td>
<td>Mechanical assembly</td>
<td>ASM, Method of Moments</td>
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<tr>
<td>lensing</td>
<td>Matching + Refraction index close to -1, using DNG, SNG or chiral material, plasmonic surfaces, strong spatial dispersion</td>
<td>Imaging, detection, focusing of power, health applications</td>
<td>Photo-lithography, FTIR (Infrared and visible domain), 3D microwave imaging, micro and nano-machining</td>
<td>Special treatment of resonant structures in Finite Element Method Eigenmode analysis</td>
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<td>Sensing</td>
<td>Resonance frequency shift</td>
<td>Biosensors</td>
<td>nanolithography</td>
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<td>Functionality</td>
<td>Phenomenology</td>
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<tr>
<td>Sources and radiators</td>
<td>Composite magnetic materials, (artificial) low-epsilon materials, reduction of mutual coupling, reduction of overall size with the help of DNG materials</td>
<td>Mobile terminals, compact antennas, large scan angles and highly efficient systems, UMTS, WIMAX, WIFI</td>
<td>Various deposition techniques, optical lithography</td>
<td>Finite Element Methods</td>
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<tr>
<td>Miniaturisation and optimisation</td>
<td>Backward and forward waves, high-Q resonance</td>
<td>Front-end module of wireless communications</td>
<td>Thin film and screen-printing technique, multilayer ceramic technology, PCB and other planar microelectronic technologies</td>
<td>Method of Moments, Electromagnetic software</td>
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<tr>
<td>Functionality</td>
<td>Phenomenology</td>
<td>Application (system)</td>
<td>Fabrication &amp; measurement</td>
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<tr>
<td>Multi-functionnal reconfigurable systems</td>
<td>Reconfigurability /tunability</td>
<td>Dielectric response of ferro-electric material or varactors, tunable constitutive elements, ferroelectric varactors, non-linear metamaterials, photonic FSS’s. Integration of MEMS switches HBV</td>
<td>Photo and e-beam lithography, Thin film and screen-printing technique, multilayer ceramic technology, PCB, RF-MEMS, Micro-milling, magnetron and laser sputtering, lithography e-beam lithography, nano-imprint Nano soft lithography, self assembly of nanostructures</td>
<td>Electromagnetic software, and electrical solvers. Time-domain solvers for non-linear materials, Sonnet, Momentum, Harmonic balance simulations for large signal (non-linear)</td>
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</table>
Expected achievements in 5 coming years:

- Microwaves
- 3-D cloaking devices

2007
- Wideband tunable passive
- Focusing of high power transmission
- Active metamaterials
- Microwave devices

2011
- Wideband antenna
- High-performance
- 3-D cloaking
- Wideband tuning fillers
- Tunable wide-angle scanning antennas
- Phase-shifting lines
- DNG lensing in MRI imaging
Expected achievements in 5 coming years:

- TeraHertz
  - transparency
  - biosensing

- Superlensing
- Focusing of high power transmission

- Antennas
  - Left-handed TeraHertz devices
  - TeraHertz switches

- Tunable circuits

- Programmed arrays

- Invisibility
  - Light bending and mirages

- Cloaking

- Imaging systems
  - Single molecule addressing

- 2007 to 2011
Expected achievements in 5 coming years:

Optics

- Magnetism
- Nano-antennas
- Sub-wavelength imaging
- Imaging arrays
- Nano-materials
- Plasmonic optoelectronic circuits
- Cloaking at optical frequencies
- DNG superlensing at visible frequencies

2007

Optical biosensors
- Metamaterials in lithographic processes
- Tuneable metamaterials as high-density memory disks
- Magnetism
- Beaming

2011

Integrated designs

Imaging arrays
Conclusions and further prospects

- Research topics (re)organized along 3 axes: functionalities, methods and frequencies
- Long-term expectations projected per frequency
- Contributions and cooperations determined
- Cooperation results will be reviewed every year

Yearly cycle within the Virtual Institute

- avoid overlap
- get coverage
- reaping fruits of efforts
New tunable metamaterial transmission lines based on CSRRs and varactors (UAB)
Metasurfaces for enhanced radiation properties (UPNa, LOUGH, TKK)
Forth – UNISI - Bilkent
Efficient beaming at optical frequencies.
Figure 2: Trans-surface (left) and reflected $E_x$ (Ecop) and $E_y$ (Ecross) measured results.


**Metamorphose, NoE on Metamaterials**  
http://www.metamorphose-eu.org/
Self-organized metamaterials from eutectics
(ITME, Bilkent, Siegen)
Tunable metamaterial transmission lines based on ferromagnetic nanowires (UCL)

Mu-negative

By adding a shunt inductance, a DNG structure is achieved.

Generate a macroscopic ferromagnetic resonance

Magnetic field variation
A point source is resolved by a 3-layer NIM superlens with a resolution of 0.13\(\lambda\). The beam size in free space is on the order of wavelength.

At 3.74 GHz real part of \(\varepsilon\) and \(\mu\) are equal, \(\varepsilon=\mu=-1.8\).

\(\varepsilon\) and \(\mu\) are both negative btw. 3.63 and 3.93 GHz. Refractive index is also negative.

Two subwavelength features separated by distances of \(\lambda/8\), \(\lambda/5\) and \(\lambda/3\) are resolved with the superlens.
Tunable Dual-Band Microwave Filter Based on a Combination of Left/Right-Handed Transmission Lines

Multilayer LTCC implementations of spurious-free stepped-impedance resonators and dual-band filters based on a combination of right- and left-handed transmission line (RH and LH TL) sections was derived. The measured microwave performance of the devices exhibited high resolution and excellent reproducibility. Based on the analysis of the tunability of the devices based on RH and LH TLs sections, the functionality of these miniature devices is further enhanced. The one-band tunable filter was designed using varactor diodes. The combination of careful design of combined structures with a reliable three-dimensional low-cost fabrication technology opens a wide potential for commercial applications.
Paired Spiral Resonators & Antennas (QUB)

Stacked spirals above ground

Sub-wavelength resonators: $\lambda/10$

<table>
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<th>Frequency, GHz</th>
<th>S11, dB</th>
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<tr>
<td>1.41</td>
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</tr>
<tr>
<td>6.285</td>
<td>-12.06</td>
</tr>
<tr>
<td>10.29</td>
<td>-10.56</td>
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</table>

Farfield
- Field: $f=1.41$ [1]
- Abs: Directivity
  - Main lobe magnitude: 1.6 dBi
  - Main lobe direction: 95.0 deg.
  - Angular width (3 dB): 41.9 deg.
Tunable metamaterial-based stop-band filters in RF-MEMS technology

Actuation voltage: 17V
Meta-surfaces illuminated by dipole antennas

- Dipole antenna tuned to the pass band of the meta-surface
- **Thin profile** = 0.137 \( \lambda_0 \) at \( f_r = 10.48 \) GHz
- **Good matching** \( S_{11} = -15 \) dB;
- **Enhanced directivity** \( D = 8.2 \) dBi
- **High aperture efficiency**: \( \eta_{ap} = 1.1 \)
- **High radiation efficiency** \( \eta_r \):
  - \( \eta_{r\text{ dipole}} = 0.98 \); \( \eta_{r\text{ superstrate}} = 0.90 \)
- **Low back radiation**
- **Mutual coupling reduction** in array configuration

Field confined on the aperture

In collaboration with Bilkent University and Helsinki University of Technology
Decorrelation of two close antennas with a Metamaterial AMC Spacer (UPC, Spain)

Introduction

• A bidirectional CLL based metamaterial slab provides a PMC response (phase\{S11\}|_{f=f_0} = 0^\circ) on both sides.
• Applied to close antennas, decoupling (low S21) and decorrelation (high C11 and low C12) has been achieved for a wide bandwidth. Results compared with Air and PEC spacers.
• Radiation with an AMC spacer is concentrated into a half-space, obtaining quasi-orthogonal patterns

Application → Compact antenna systems (routers, handhelds).

S-parameters

Correlation-parameters

Electromagnetic cloaking based on transmission-line networks (TKK)

Transmission-line networks designed for the reduction of the total scattering cross section of periodic structures (2D arrays of metal rods here)

Total SCS is shown to be greatly reduced in a large bandwidth

Electric field at 2 GHz:
Impedance-matched microwave lenses (TKK)

Transmission-line networks are designed to have a certain index of refraction while maintaining impedance-matching with free space in a large bandwidth.

Simulated electric field phase with the proposed lens and a reference dielectric lens at 2.4 GHz.
Cooperation

**NMP Theme**

Call identifier: FP7-NMP-2007-CSA-1
COORDINATING AND SUPPORT ACTION (Coordinating)

Project acronym: **ECONAM**

Project full title: **Electromagnetic Characterization of Nanostructured Materials**

Work programme topics addressed: NMP-2007-2.1-3 Characterisation of nanostructured materials
THANK YOU!

Gracias!
Dank u!
Kiitos!
TEŞEKKÜR!
Merci!
Спасибо!
Tag!

Dziękuję!
Danke schön!
ευχαριστώ πολύ!
GRAZIE!