Metamaterials: a new dimension in electromagnetism

John Pendry, Imperial College London
The metamaterial concept

Metamaterials give access the material properties never before available. Unlike photonic materials their properties are described by $\varepsilon$ and $\mu$ simplifying the design process. They have enabled the new design paradigm of ‘transformation optics.’ Intense concentrations of EM energy within their structures greatly enhances non linear properties – can be exploited in switching, time reversal, 4 wave mixing etc.
The rise of metamaterials

Citations in Each Year

- 1999 Marconi paper
- 2000 -ve refraction demonstrated at UCSD
- 2006 cloaking invented and demonstrated
Practical realisation of the split ring structure

(Marconi: Mike Wiltshire, ca 1998)
Negative refraction: $\varepsilon < 0, \mu < 0$

Structure made at UCSD by David Smith
Negative refractive index metamaterials

Diagram (left) and scanning electron microscope image (right) of a ‘fishnet’ structure fabricated by the Xiang group at Berkeley California. The structure consists of alternating layers of 30nm silver and 50nm magnesium fluoride.
<table>
<thead>
<tr>
<th>DC</th>
<th>giant paramagnetism</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRI</td>
<td>safe pick up coils (Richard Syms, IC)</td>
</tr>
<tr>
<td>RF</td>
<td>cell phones and satcoms (cheap and light phased array - Kymeta)</td>
</tr>
<tr>
<td>THz</td>
<td>enhanced cascade laser efficiency (Capasso, Harvard)</td>
</tr>
<tr>
<td>IR</td>
<td>control of thermal radiation, broad band absorbers</td>
</tr>
<tr>
<td>visible</td>
<td>plasmonics, enhanced non linear phenomena, single molecule detection, giant chirality</td>
</tr>
<tr>
<td>acoustics</td>
<td>sound proofing of domestic environment, stealth technology</td>
</tr>
<tr>
<td>mechanics</td>
<td>materials with novel mechanical properties - Vincenzo Vitelli, Leiden</td>
</tr>
</tbody>
</table>
Metamaterials – our recent research

- controlling light in nanoscale structures
- understanding light harvesting in plasmonic systems
- non locality in the dielectric response (with Duke)
- electron energy loss in plasmonic systems
- Van der Waals forces between complex nanostructures
- heat transfer on the nanoscale
- switchable metasurfaces

New coordinates in terms of the old: \( x'^j(x^j) \)

In the new coordinate system we must use renormalized values of the permittivity and permeability, \( \varepsilon, \mu \):

\[
\varepsilon'^{ij} = \left[ \det(\Lambda) \right]^{-1} \Lambda_i^i \Lambda_j^j \varepsilon^{ij}
\]

\[
\mu'^{ij} = \left[ \det(\Lambda) \right]^{-1} \Lambda_i^i \Lambda_j^j \mu^{ij}
\]

where,

\[
\Lambda_j^j = \frac{\partial x'^j}{\partial x^j}
\]

For the special case of conformal transformations in 2D systems, \( \varepsilon, \mu \) are unchanged.
How to make something invisible using transformation optics

*Science* 312 1780-2 (2006), JB Pendry, D Schurig, and DR Smith

1. define a region that is to be invisible
2. surround it with an optical medium that can bend light
3. design the medium to bend the light rays inside the cloak away from the invisible region – this ensures no one can see inside
4. check that rays outside the cloak are never disturbed – this ensures no one can detect that the cloak is present
Creating a hidden space

In mathematical notation the following coordinate transformation will open a hole in space,

\[
\begin{align*}
    r' &= R_1 + r \left( R_2 - R_1 \right) / R_2, \\
    \theta' &= \theta, \\
    \phi' &= \phi
\end{align*}
\]

From the transformation we can find the refractive index, as a function of radius, needed to make the cloak.
Cloaking Static Magnetic Fields


Cloaking works for fields as well as waves!

deflection of rays
(far field)

deflection of field lines
(near field)
Lattice of superconducting plates
The proposed magnetic cloak

The shaded region in the centre is hidden from external magnetic fields. The plates form broken circles (in cross section); the full circles show the ferrite or amorphous metal.
Schematic of the cloaking material consisting of an array of superconducting and soft ferromagnetic elements.

(b) Apparatus geometry.

(c) Top-view schematic showing the locations of two Hall sensors and magnetic field lines in empty space. Sensor 1 detects the field that penetrates through the cloak, and sensor 2 is positioned to capture external field perturbations due to the presence of the cloak.
Cloaking magnetic fields using *metamaterials* excludes fields from inside the cloak, and leaves the external field undisturbed.
Transformation optics & negative refraction

The Veselago lens can be understood in terms of transformation optics if we allow ‘space’ to take on a negative quality i.e. space can double back on itself so that a given event exist on several manifolds:
Surface plasmons ... give rise to some extraordinary effects such as the giant Raman resonance or SERS.

Singularities in the surface geometry attract intense concentrations of fields. For example when two curved surfaces meet. The field density, $|E|^2$, can be enhanced by several orders of magnitude. The Raman signal scales as $|E|^4$ giving spectacular enhancements of the signal.

Right: simulation of light incident from above on two touching cylinders. The geometric singularity at the touching point enhances field density by a factor of around $10^4$. 
“The market segmentation revolves around four verticals namely types of artificial materials, device types, application, and geography. The market is expected to grow at a CAGR of 41.25% to reach $643 million by 2025.”
# Metamaterials – UK activity

*UK academic groups in the field (probably incomplete):*

<table>
<thead>
<tr>
<th>University</th>
<th>Research Areas</th>
<th>Researchers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birmingham</td>
<td>optical</td>
<td>Zhang, Li</td>
</tr>
<tr>
<td>Cambridge</td>
<td>optical</td>
<td>Baumberg</td>
</tr>
<tr>
<td>Exeter</td>
<td>RF, plasmonics, acoustics</td>
<td>Sambles, Hibbins, Barnes</td>
</tr>
<tr>
<td>Imperial</td>
<td>optical, some THz, acoustics</td>
<td>Hess, Maier, Syms, JBP</td>
</tr>
<tr>
<td>KCL</td>
<td>optical</td>
<td>Zayats</td>
</tr>
<tr>
<td>Liverpool</td>
<td>acoustic</td>
<td>Movchan</td>
</tr>
<tr>
<td>Loughborough</td>
<td>RF</td>
<td>Vardaxoglou</td>
</tr>
<tr>
<td>Manchester</td>
<td>graphene based metamaterials</td>
<td>Grigorenko</td>
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<tr>
<td>Oxford</td>
<td>RF</td>
<td>Grant, Shamonina</td>
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<tr>
<td>QMUL</td>
<td>RF</td>
<td>Hao, Parini</td>
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<tr>
<td>QUB</td>
<td>RF</td>
<td>Fusco</td>
</tr>
<tr>
<td>Southampton</td>
<td>mainly optical</td>
<td>Zheludev</td>
</tr>
<tr>
<td>UEA</td>
<td>optics</td>
<td>Andrews</td>
</tr>
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</table>
Ping Sheng: single membrane with negative effective mass density gives a low frequency acoustic stop band.
Metamaterials and satcom – Kymeta meets Toyota
Metamaterials and satcom – Kymeta meets Toyota
In 2013, Intellectual Ventures spun out Evolv Technologies, Inc

Evolv: Commercializing new metamaterials-based imaging and detection technology for use in airports and other high-risk facilities.

Intellectual Ventures spinout Evolv gets $11.8M from Bill Gates and others, aims to transform security scanning. The second company to commercialize an invention from IV’s portfolio of metamaterials patents.
Endoscopically Compatible MR-Safe Magneto-inductive Imaging Catheter

R.R.A. Syms\textsuperscript{1}, I.R. Young\textsuperscript{1}, M.M. Ahmad\textsuperscript{1},
S. Taylor-Robinson\textsuperscript{2}, M. Rea\textsuperscript{2}
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\textsuperscript{2}St. Mary’s Hospital, Imperial College NHS Trust, London, UK

TEL +44 207 594 6203; email r.syms@imperial.ac.uk
MR-Safe Cables

- Solution to subdivide cable using transformers
  - Each segment then too short to support external standing waves
- Periodic nature of structure generally ignored
  - Actually magneto-inductive waveguide

Weiss et al.
“Transmission line for improved RF safety of interventional devices”
MRM 54, 182-189 (2005)
laser waveguide  laser aperture

Group creates metamaterial waveguides for collimated quantum cascade laser output. The paper reports that by using a “metasurface” design to tailor the dispersion of terahertz surface plasmons, one can improve the power throughput and significantly reduce the beam divergence of terahertz quantum cascade lasers.
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