New metamaterials and geometries for next generation antennas

Alastair Hibbins

...but representing the work of a host of others

Metamaterials - definition

As defined by the recent National Security and Investment Bill:

“a composite materials in which the constituents are designed and spatially arranged through a rational design-led approach to change the manner in which electromagnetic, acoustic or vibrational energy interacts with the material, in order to achieve a property or performance that is not possible naturally.”
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Electromagnetic
- THz, Microwave, RF, Optics
- Permittivity, Permeability, Refractive index, Chirality
- Wave speed, loss

Acoustic
- Airborne and Underwater
- Mass density, bulk modulus, refractive index
- Wave speed, loss

Mechanical
- Youngs and Shear Modulus, Deformation Resistance, Poisson’s Ratio
- Strength, Rigidity, Stiffness, Deformability

Thermal
- Diffusion
- Thermal conductivity, specific heat, melting point, thermal expansion

Haberman and Guild; Physics Today ©2016 American Institute of Physics
Zheng et al.; Science Copyright © 2014, American Association for the Advancement of Science
Technology Enabler

Metamaterials can be used to deliver:

- Better (thinner) and cheaper camera lenses
- Thinner, smaller, lighter, efficient antennas
- Improved imaging / sensing using light & sound
- Noise control
- Strength without weight
- Wireless energy transfer
- Fast, efficient computing
- Heat control
- Vibration reduction
- Optical / Light control
- Energy harvesting

Zhai et al, Science 2017

University of Missouri

HRL Laboratories, LLC
Duke University
Metamaterial Technologies Inc
Snap buys WaveOptics, a company that makes parts for augmented reality glasses, in $500 million deal

KEY POINTS

- Snap is acquiring WaveOptics, a company that creates lenses and other parts that are used in augmented reality glasses.
- The acquisition will give Snap many of the components to create glasses that people can wear and then see computer-generated imagery overlaid on top of the real world.
- Snap unveiled its first augmented reality Spectacles glasses on Thursday.

How 5G will affect augmented reality and virtual reality

The low-latency properties of 5G offer promise for AR and VR applications, but converting promise to results will take time.
EPSRC Big Idea
EPSRC Advanced Materials Theme (Danny Smith)

Metamaterials Revolution:
Next generation control of energy & information

A national programme of intervention, to provide investment and coordination to turn physics into devices; to build the technology demonstrators; to train future leaders, and drive the virtuous circle of science-led innovation.

$\text{£}$$\text{£}$$\text{£}$
Global Metamaterial Device Market
Zero $\Rightarrow$ $\text{£}11$bn in 10 years
• **Network investigators:** Prof Alastair Hibbins (PI); Dr Anja Roeding (CoI) (KTN - Steve Morris)

• **Award lifetime:** 1 March 2021 – 28 February 2024 (3 years)

• **Key objectives:**
  - Community building (incl ‘shop-window’)
  - Awareness raising (incl road map, industry & government engagement)
  - Talent development (from outreach to ECR career support)

• **Current membership:** >250 UK experts from academia, industry, and Governmental agencies

Join the Network and Expert Database: www.metamaterials.network
Can Metamaterials help with…

• Making antennas more compact
• Reducing the weight of systems
• Making systems conformal
• Improving efficiency
• Broad-band or Multi frequency response
• Bespoke directivity, and radiation patterns (scattering)
Superdirective antennas

Conventional superdirective antennas: Yagi-type

- Phase difference is governed by retardation effect
- Size = \( \lambda/2 \)
- Directivity = 5.75 = 7.6 dBi

Meta-atom inspired superdirective antennas

- Phase difference is governed by coupling between elements
- Size \( << \lambda \), the smaller the better
- Directivity = 5.25 = 7.2 dBi
Experimental frequency dependence of $D$

Frequency dependence of $D$, $a = 16$ mm
Artificial Magnetic Conductors

• A metasurface structure that may be used as a ground plane for conformal antennas to reduce the total height

• On vehicles - low-profile conformal antennas will reduce drag, fuel burn and likelihood of damage

• Requirements –
  • Always a trade off between thickness and bandwidth
Artificial Magnetic Conductors - 1

Bandwidth: 24% (0.6 GHz)
Thickness (z): 2.55% of λ
95% of theoretical maximum

Phase difference between incident and reflected signals
Artificial Magnetic Conductors - 2

- A patterned copper frequency selective surface placed above a copper ground plane forms a resonant reflecting boundary [1]

[1] Enhanced bandwidth artificial magnetic ground plane for low-profile antennas
L. Yousefi, B. Mohajer-Iravani, and O. M. Ramahi,
Artificial Magnetic Conductors - 2

• A patterned copper frequency selective surface placed above a copper ground plane forms a resonant reflecting boundary [1]

• By filling the space between FSS and ground plane with a magneto-dielectric, it is possible to improve the bandwidth of resonance [2]

• Carbonyl iron powder – Polyurethane composites used here for magneto-dielectric filler

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Magnetic Metamaterials

- Enables antenna miniaturization and impedance matching.
- Greater tunability than all-dielectric solutions.
- Dissipates electromagnetic energy through magnetic loss, instead of heat.

Experimental data, 800nm 40% vol

High power electronics
- 5G materials
- EMW absorbers
- RF components

Maxwell’s equations:
Solved using the FDTD method
\[ \frac{\partial B}{\partial t} = -\nabla \times E \]
\[ \varepsilon \frac{\partial E}{\partial t} = \nabla \times H - \sigma E \]

\[ B = \mu_0(M+H) \]

Micromagnetics of material:
Landau-Lifshitz-Gilbert (LLG) equation
\[ \frac{dM}{dt} = -\gamma |M| \times H_{\text{eff}}(M) + \frac{\alpha}{M} \left( M \times \frac{dM}{dt} \right) \]

FDTD software to design and optimise magnetic components and devices for radio-frequency, microwave and millimeter wave applications.
Metamaterials for Shaping Radiation

- Analytic coupled-dipole model to describe the effect of several scatterers upon the emitter
- Efficient optimisation algorithm to adjust scatterer locations to enhance power emission and design directivity.

Iterative design method based on perturbation theory:

$$\delta E(r) = k_0^2 \int G(r, r') \cdot E(r') \delta \varepsilon(r') d^3 r'$$
Metamaterials for Shaping Radiation

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Example: Radiation pattern shaping

Iterative design method based on perturbation theory:

$$\delta \mathbf{E}(\mathbf{r}) = k_0^2 \int G(\mathbf{r}, \mathbf{r}') \cdot \mathbf{E}(\mathbf{r}') \delta \varepsilon(\mathbf{r}') d^3 r'$$
Metallic superscatterers

- Adding plates to the end of the dipole can make a small antenna have the power and frequency of a much larger one.

- Using 3D printing, various shapes with unique mode structures can be produced.

Enhancing efficiency of small antennas

**Purcell effect:** manipulation of EM environment to enhancing local density of states

- Antenna with no structure: fundamental resonance at 15 GHz
- Dielectric structure iteratively designed with aim to enhance radiative efficiency at a chosen off resonance frequency
Enhancing efficiency of small antennas

- Near-complete radiation efficiency on both resonance conditions
- Unstructured dielectric: 2.5 GHz, but only 40% efficiency
Dynamically reconfigurable spatial modulators

Electronics:
- Varactors, Diodes
- Phased arrays, etc.

- LC devices
- DMDs
- Phase change materials

Dr Ian Hooper, Dr Lauren Barr, Prof Euan Hendry
University of Warwick
QinetiQ
One approach - Si-based photomodulators

Photoexcite charge carriers in Si

Charge carrier concentration builds up – steady state concentration depends on generation and recombination rates

Change the conductivity – change the transmission of radiation through the wafer

Can easily spatially pattern the photoexcitation to produce a conductivity profile

A spatial AND temporal modulator
Enhancing efficiency...

Reduce charge recombination at the surfaces by coating the Si with “passivating” layers

Slower recombination = higher conductivity for a given photoexcitation intensity = larger change in transmission (modulation depth)

3-4 orders of magnitude increase in efficiency

Total blocking of mm-waves using light with 1/10th the intensity of strong daylight

With long carrier lifetimes, switching becomes proportionally slower, and the lateral diffusion of charge carriers becomes longer - blurring out any spatial patterning.

Solution: Metasurfaces can enhance the interaction of the mm-waves with the modulator, overcoming some of these trade-offs.
The Leadership Team

Special Interest Groups (SiGs)
- Active metamaterials (D Wright, Exeter; TBC)
- Flexible and conformable metasurfaces (A Di Falco, St Andrews; S Schulz, St Andrews)
- Modelling and AI-design (Anastasia Kral, Manchester; TBC)
- Biophotonics applications (A Clark, Glasgow; M Kenny, Nottingham)
- Manufacturing and scale up (C Dancer, Warwick; N Grant, Warwick)
- Multifunctional and mechanical metamaterials (F Scarpa, Bristol; TBC)
- Early Career Researchers (A Gower, Sheffield; O Looman, M Ventures)
- Horizon scanning / disruptive concepts (A Souslov, Bath; N Meinzer, Nature)
- Wireless and microwave applications (L Ford, Sheffield; S Henthorn, Sheffield)
- Industry (A Alexeev, Waveoptics; N Crew, Airbus)
- Outreach & Education (R Assier, Manchester; A Roeding, Exeter)
- Acoustic Metamaterials (G Momoi, Sussex; T Starky, Exeter)

Forums

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