UNIVERSITY OF EXETER | Centre for Metamaterial Research and Innovation | incorporating EPSRC Centre for Doctoral Training in Metamaterials XM^2

New metamaterials and geometries for next generation antennas

Alastair Hibbins

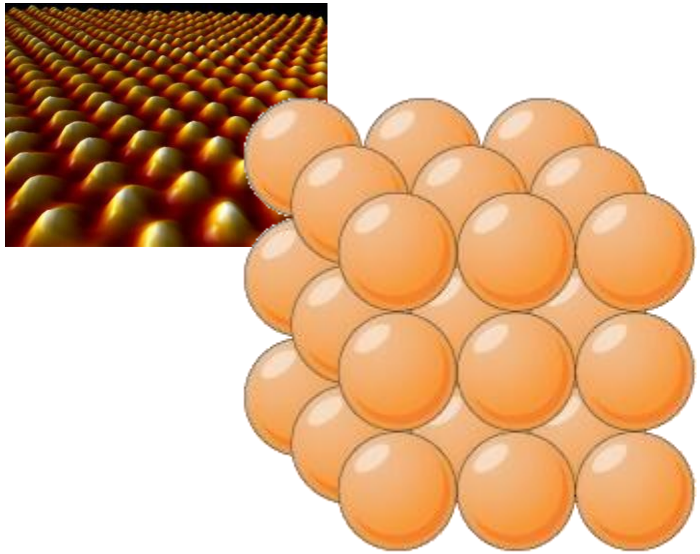
…but representing the work of a host of others

DCMS / SPF workshop on *6G: Technology Enablers for Spectrum & Energy Efficient Wireless Access*

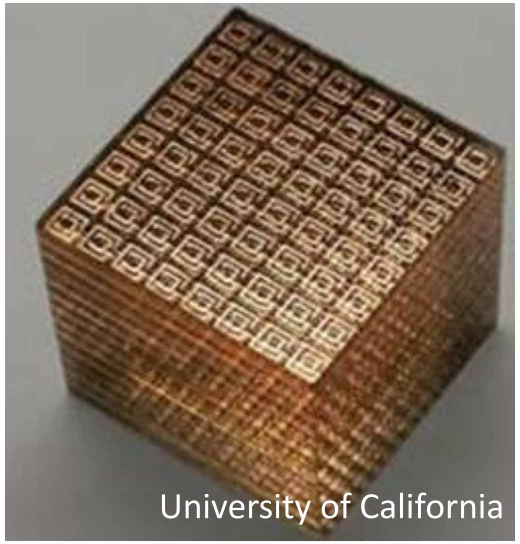
Metamaterials - definition

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**.”



Atoms make a **Material**



Meta-atoms make a **Metamaterial**

UNIVERSITY OF EXETER

Centre for Metamaterial Research and Innovation

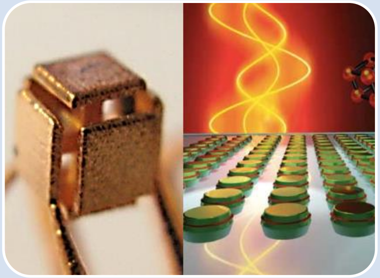
EPSRC Centre for Doctoral Training in Metamaterials XM²

www.metamaterials.center

Metamaterials - definition

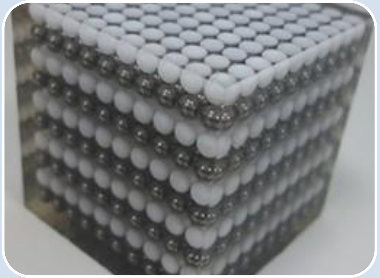
As defined by the recent National Security and Investment Bill:

“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**.”



Electromagnetic

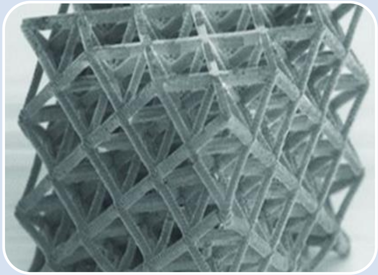
- THz, Microwave, RF, Optics
- Permittivity, Permeability, Refractive index, Chirality
- Wave speed, loss



Acoustic

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

Haberman and Guild; *Physics Today*



Mechanical

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

Zheng et al.; *Science*

Thermal

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

Schittny et al.; *Phys. Rev. Lett.*

UKRI Engineering and Physical Sciences Research Council

UNIVERSITY OF EXETER

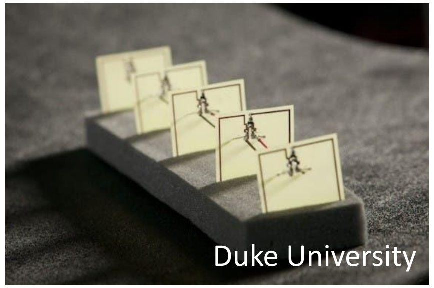
Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials XM²

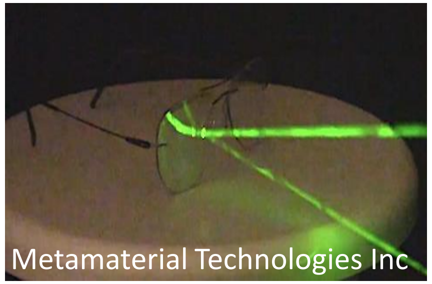
www.metamaterials.center

Technology Enabler

Metamaterials can be used to deliver:



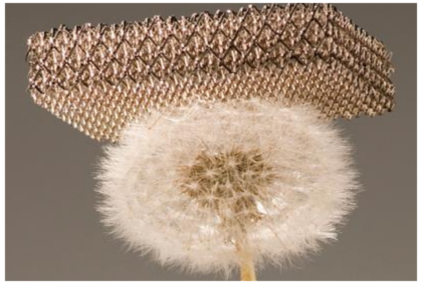
Energy harvesting



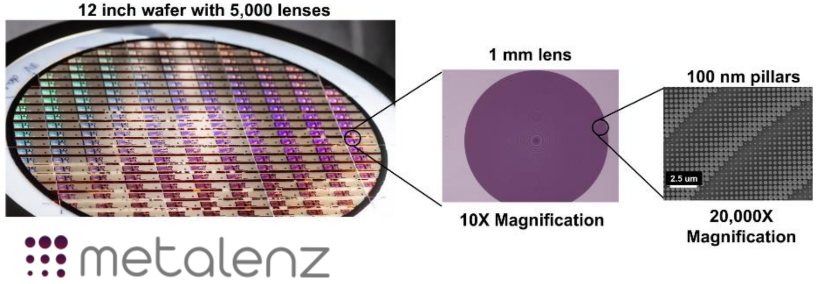
Optical / Light control

Wireless energy transfer

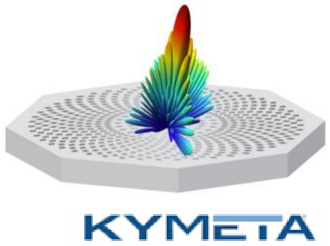
Noise control



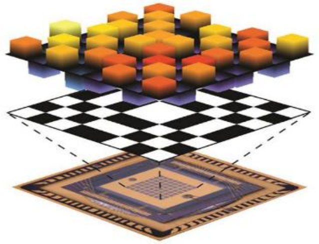
Strength without weight



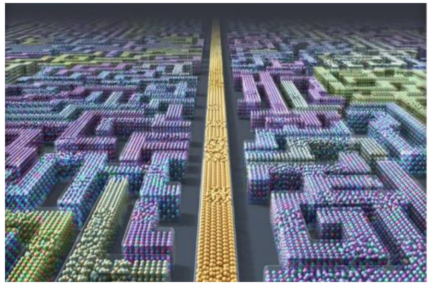
Better (thinner) and cheaper camera lenses



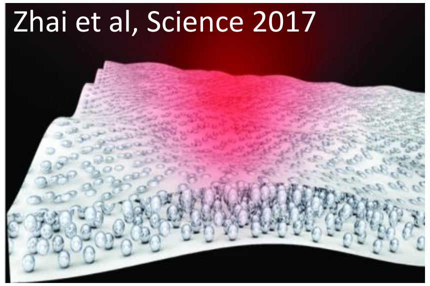
Thinner, smaller, lighter, efficient antennas



Improved imaging / sensing using light & sound



Fast, efficient computing



Heat control

Vibration reduction

Engineering and Physical Sciences Research Council

UNIVERSITY OF EXETER

Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials XM²

www.metamaterials.center

Technology Enabler

WaveOptics

ZDNet

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.

CNBC MARKETS BUSINESS INVESTING TECH POLITICS CNBC TV WATCHLIST PRO

Snap buys WaveOptics, a company that makes parts for augmented reality glasses, in $500 million deal

PUBLISHED FRI, MAY 21 2021-9:26 AM EDT | UPDATED 21 MIN AGO

Todd Haselton
@ROBOTODD

SHARE

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.

In this article

SNAP +0.50 (+0.88%)

Evan Spiegel, CEO of Snap, announces new Spectacles AR glasses that let you overlay digital objects on the real world.
Source: SNAP Inc.

UKRI Engineering and Physical Sciences Research Council

Alastair Hibbins, University of Exeter
Ian Youngs, Dstl
Owen Lozman, M.Ventures
Anja Roeding, UK Metamaterials Network

UNIVERSITY OF EXETER

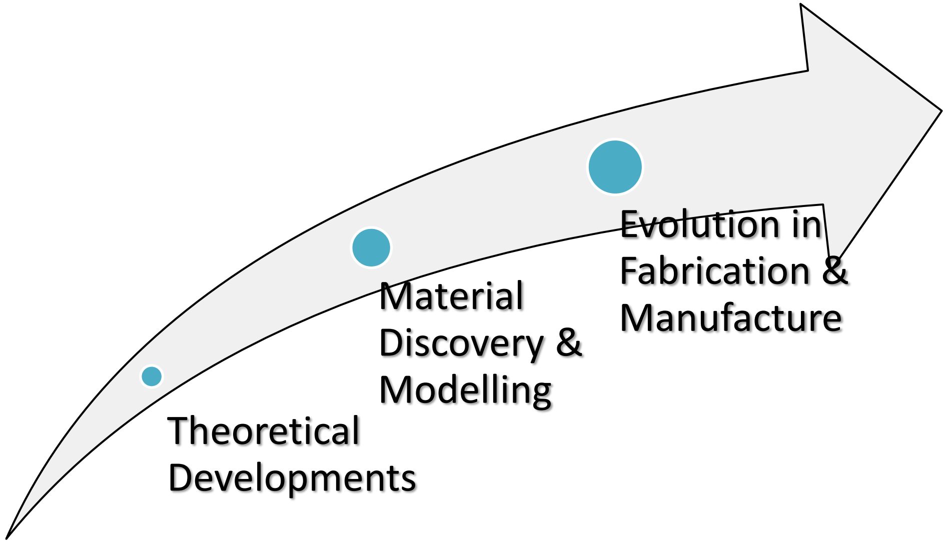
Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials XM^2

www.metamaterials.center

EPSRC Big Idea

EPSRC Advanced Materials Theme (Danny Smith)



Metamaterials Revolution:

Next generation control of energy & information

$£$£

Global Metamaterial Device Market

Zero ⇨ $11bn in 10 years

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**.

UKRI Engineering and Physical Sciences Research Council

UNIVERSITY OF EXETER

Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials XM^2

www.metamaterials.center

UK META MATERIALS NETWORK

Facts & figures

Key challenges identified by the community

Visibility of metamaterials research

Visibility of industry challenges

Bridging the valley of death

Manufacturing

- **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

UKRI Engineering and Physical Sciences Research Council

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)

?

UNIVERSITY OF EXETER
Centre for Metamaterial Research and Innovation
EPSRC Centre for Doctoral Training in Metamaterials XM²
www.metamaterials.center
UKRI Engineering and Physical Sciences Research Council

Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials

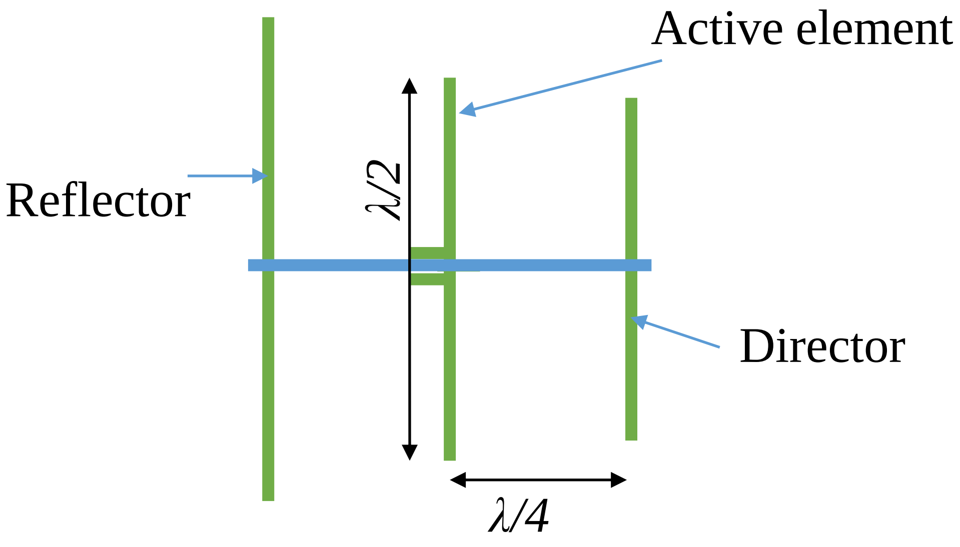
www.metamaterials.center

Pavel Petrov, Prof Alastair Hibbins, Prof Sir Roy Sambles

Dstl

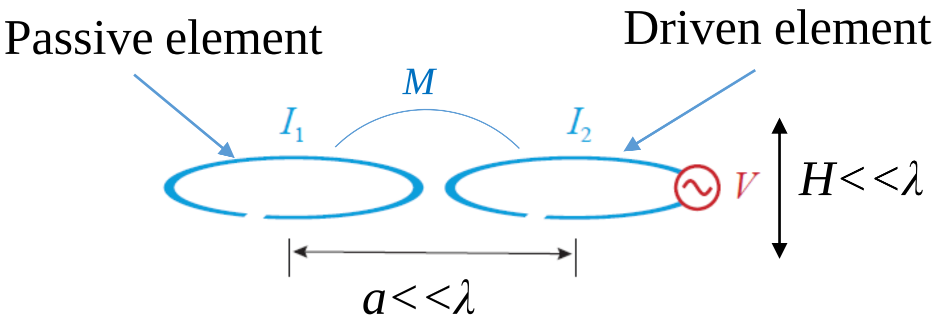
Superdirective antennas

Conventional superdirective antennas: Yagi-type



- Phase difference is governed by retardation effect
- Size = λ/2
- Directivity = 5.75 = 7.6 dBi

Meta-atom inspired superdirective antennas

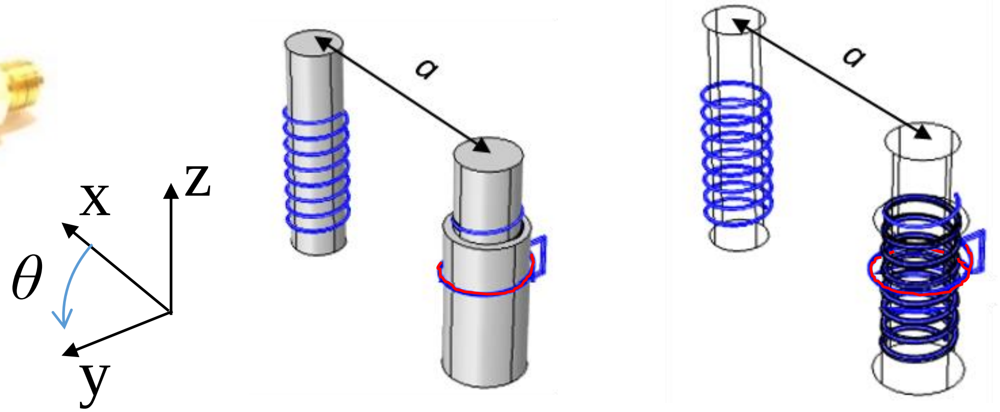


- Phase difference is governed by coupling between elements
- Size << λ, the smaller the better
- Directivity = 5.25 = 7.2 dBi

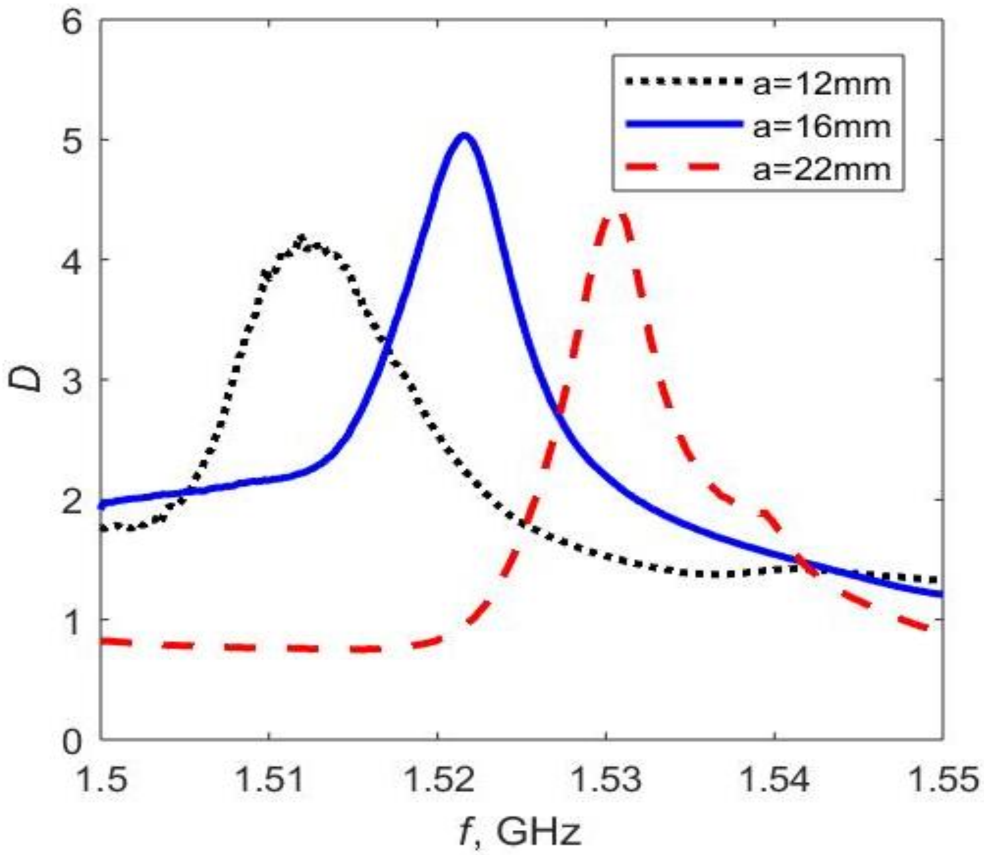
UNIVERSITY OF EXETER
Centre for Metamaterial Research and Innovation
EPSRC Centre for Doctoral Training in Metamaterials XM²
www.metamaterials.center

Pavel Petrov, Prof Alastair Hibbins, Prof Sir Roy Sambles

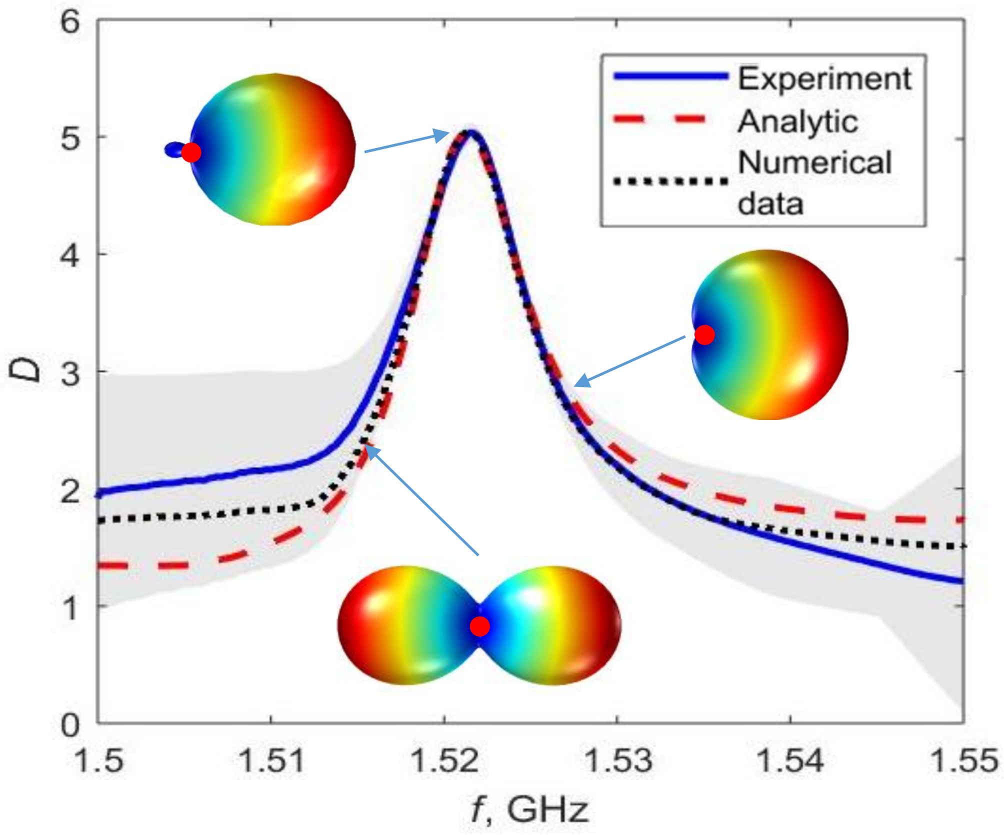
Dstl



Experimental frequency dependence of *D*



Frequency dependence of *D*, *a* = 16 mm

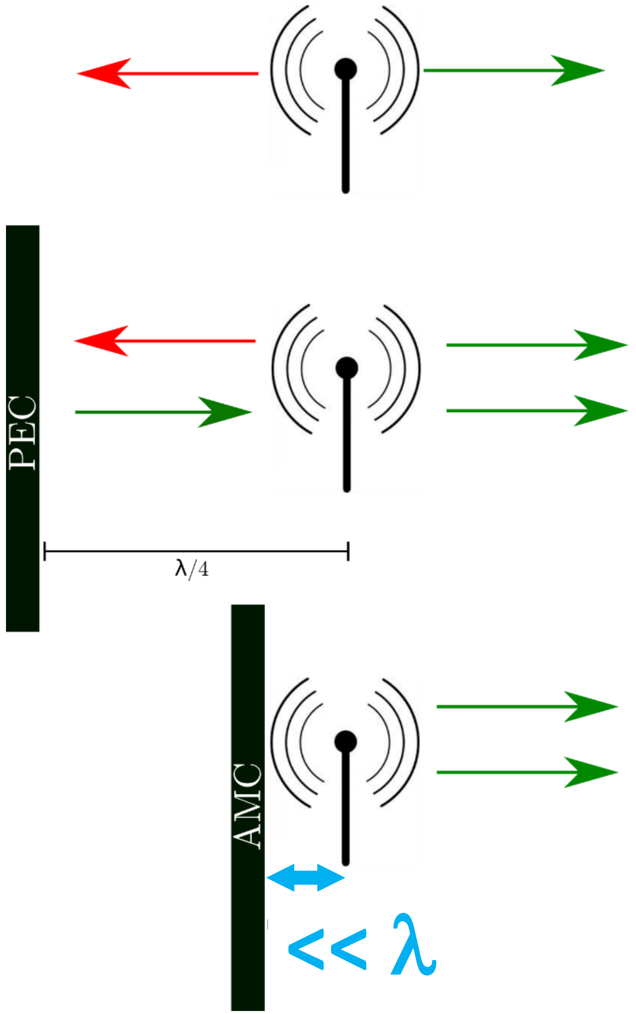


Artificial Magnetic Conductors

- 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



UNIVERSITY OF EXETER
Centre for Metamaterial Research and Innovation
EPSRC Centre for Doctoral Training in Metamaterials XM²
www.metamaterials.center
UKRI Engineering and Physical Sciences Research Council

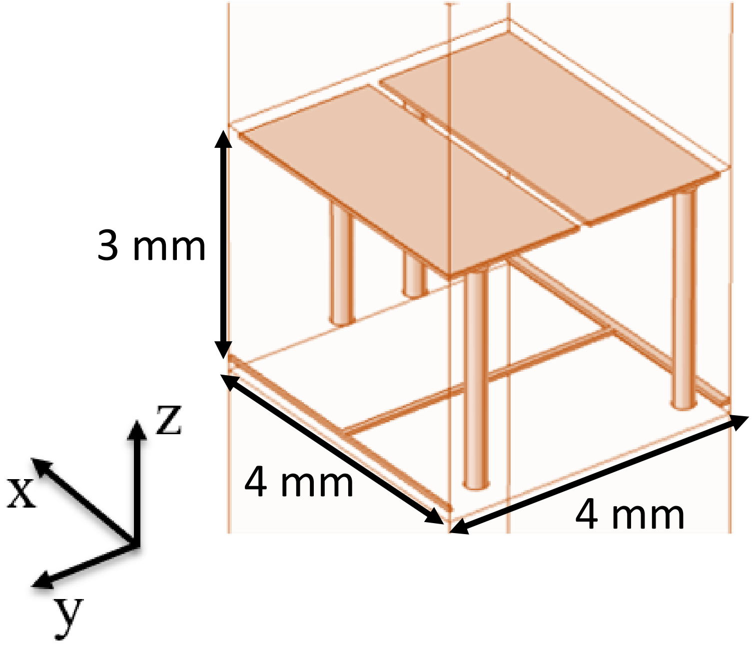
UNIVERSITY OF EXETER
Centre for Metamaterial Research and Innovation
EPSRC Centre for Doctoral Training in Metamaterials XM2
www.metamaterials.center

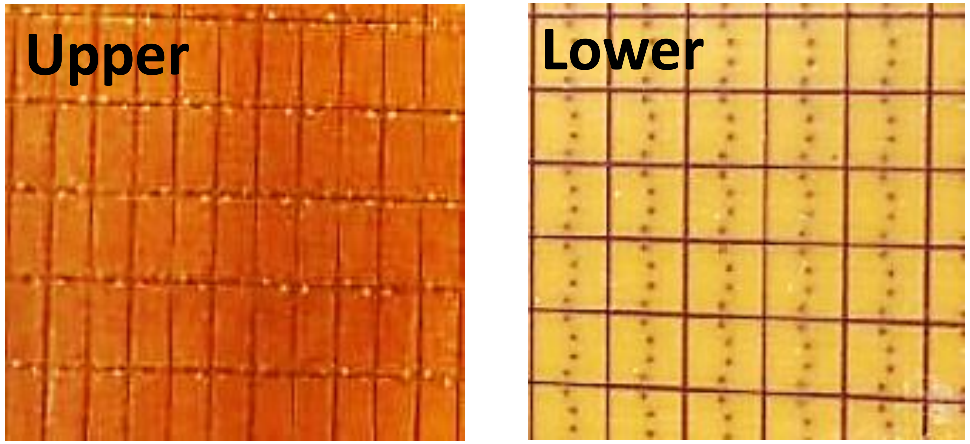
Pavel Petrov, Prof Alastair Hibbins, Prof Sir Roy Sambles

Dstl

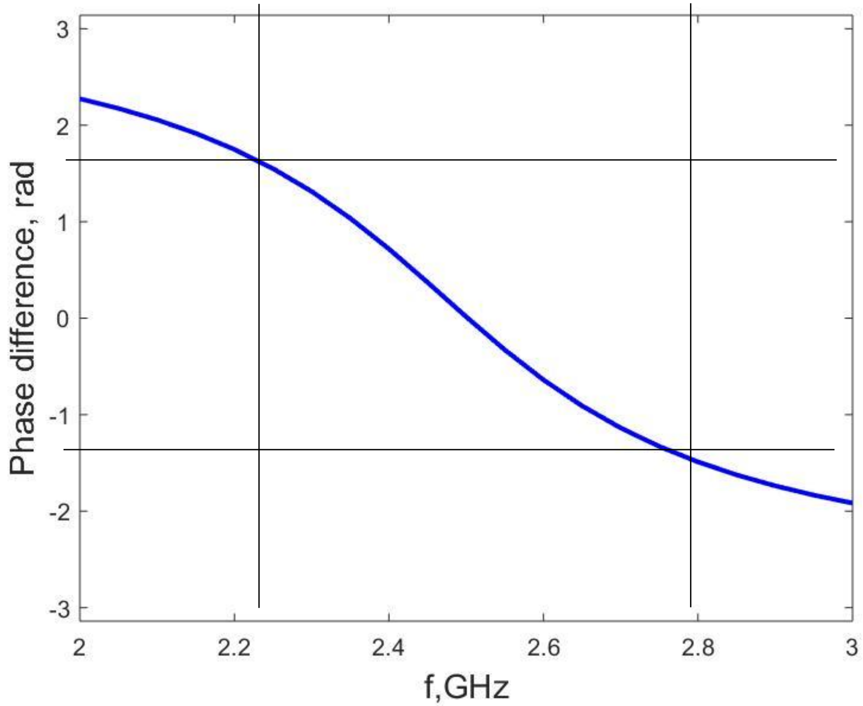
UKRI Engineering and Physical Sciences Research Council

Artificial Magnetic Conductors - 1





Phase difference between incident and reflected signals



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

UNIVERSITY OF EXETER
Centre for Metamaterial Research and Innovation
EPSRC Centre for Doctoral Training in Metamaterials XM2
www.metamaterials.center

Dr Cameron Gallagher, Prof Alastair Hibbins, Prof Sir Roy Sambles, Dr Mike Sloan

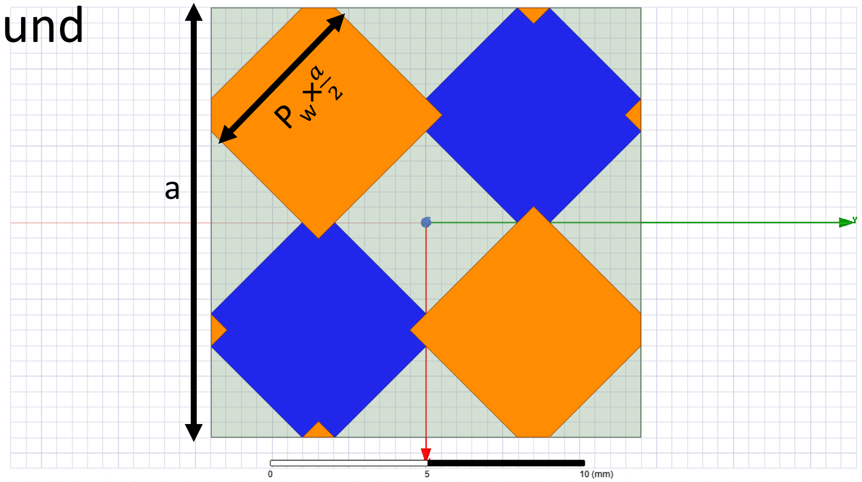
Technical Composite Systems

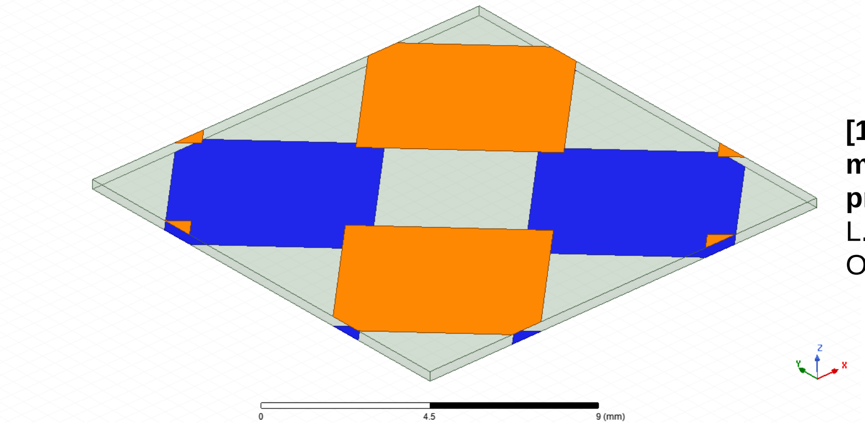
"Composite Baseplates for Aerospace Antennas"

NATEP
UKRI
Engineering and Physical Sciences Research Council

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,

Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials

www.metamaterials.center

Dr Cameron Gallagher, Prof Alastair Hibbins, Prof Sir Roy Sambles, Dr Mike Sloan

Technical Composite Systems

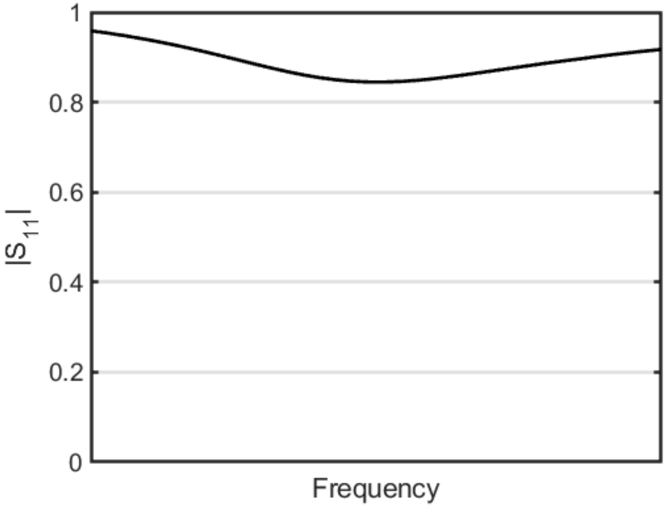
“Composite Baseplates for Aerospace Antennas”

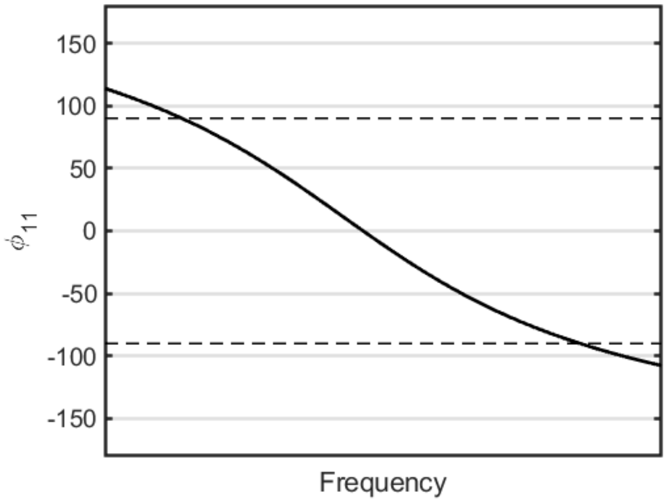
NATEP

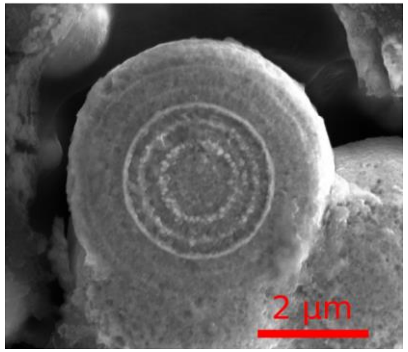
Engineering and Physical Sciences Research Council

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







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

[2] A Broadband Stripline Technique for Characterizing Relative Permittivity and Permeability
C. P. Gallagher, N. Cole, P. P. Savage, C. Mckeever, J. R. Sambles and A. P. Hibbins, (2019)

Centre for Metamaterial Research and Innovation

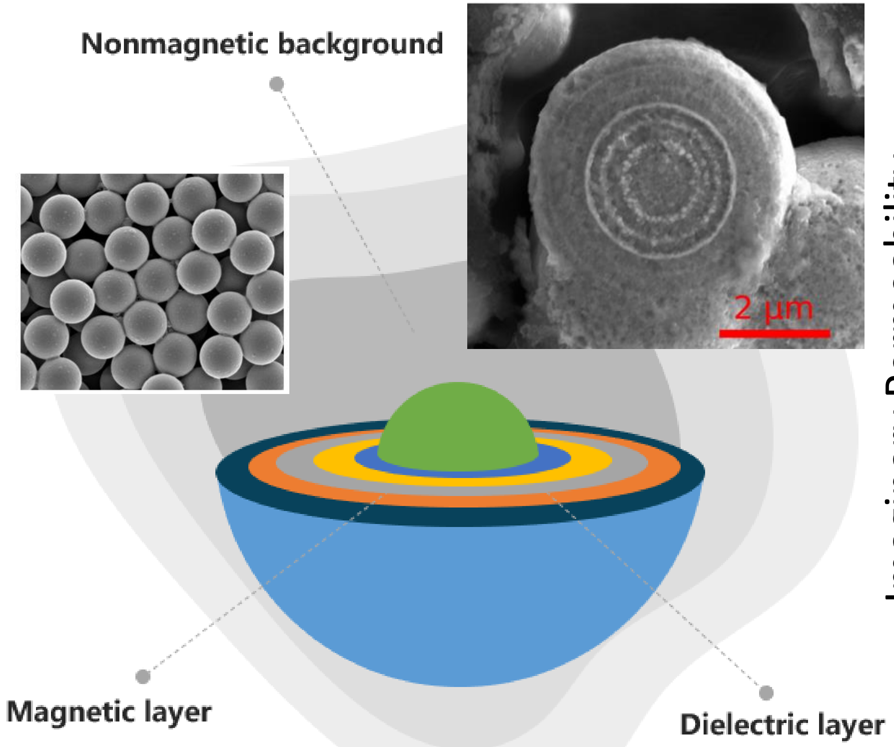
EPSRC Centre for Doctoral Training in Metamaterials XM²

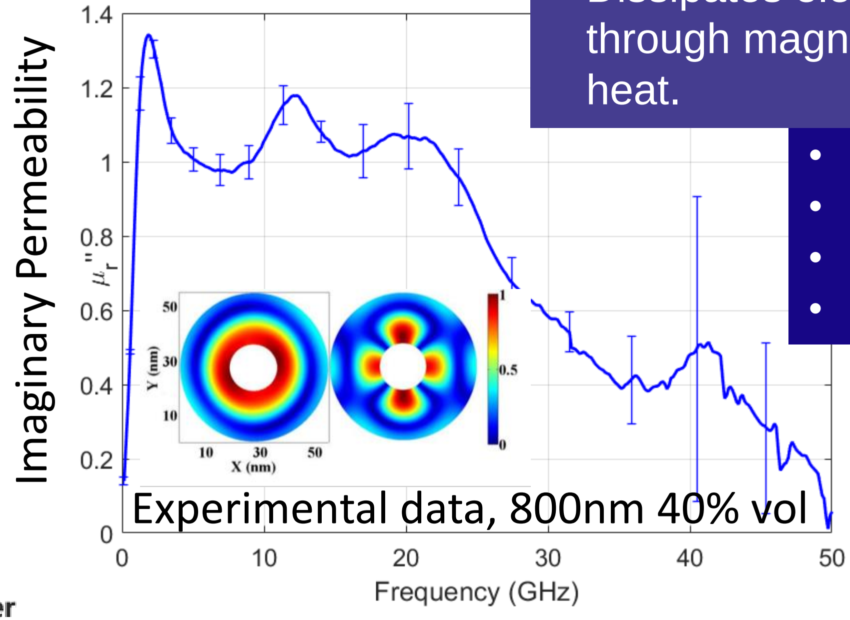
www.metamaterials.center

Prof. Feodor Ogrin, Prof Mustafa Aziz, Prof Sir Roy Sambles, Prof Alastair Hibbins, Dr Cameron Gallagher, Dr Cononor McKeever

Magnetic Metamaterials

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





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

Maxwell's equations:
Solved using the FDTD method

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E}$$

$$\varepsilon \frac{\partial \boldsymbol{E}}{\partial t} = \nabla \times \boldsymbol{H} - \sigma \boldsymbol{E}$$

Micromagnetics of material:
Landau-Lifshitz-Gilbert (LLG) equation

$$\frac{d\boldsymbol{M}}{dt} = -|\gamma| \boldsymbol{M} \times \boldsymbol{H}_{eff}(\boldsymbol{M}) + \frac{\alpha}{|\boldsymbol{M}|}\left(\boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt}\right)$$

$$\boldsymbol{B} = \mu_0(\boldsymbol{M}+\boldsymbol{H})$$

MAXLLG.

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

Engineering and Physical Sciences Research Council

Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials

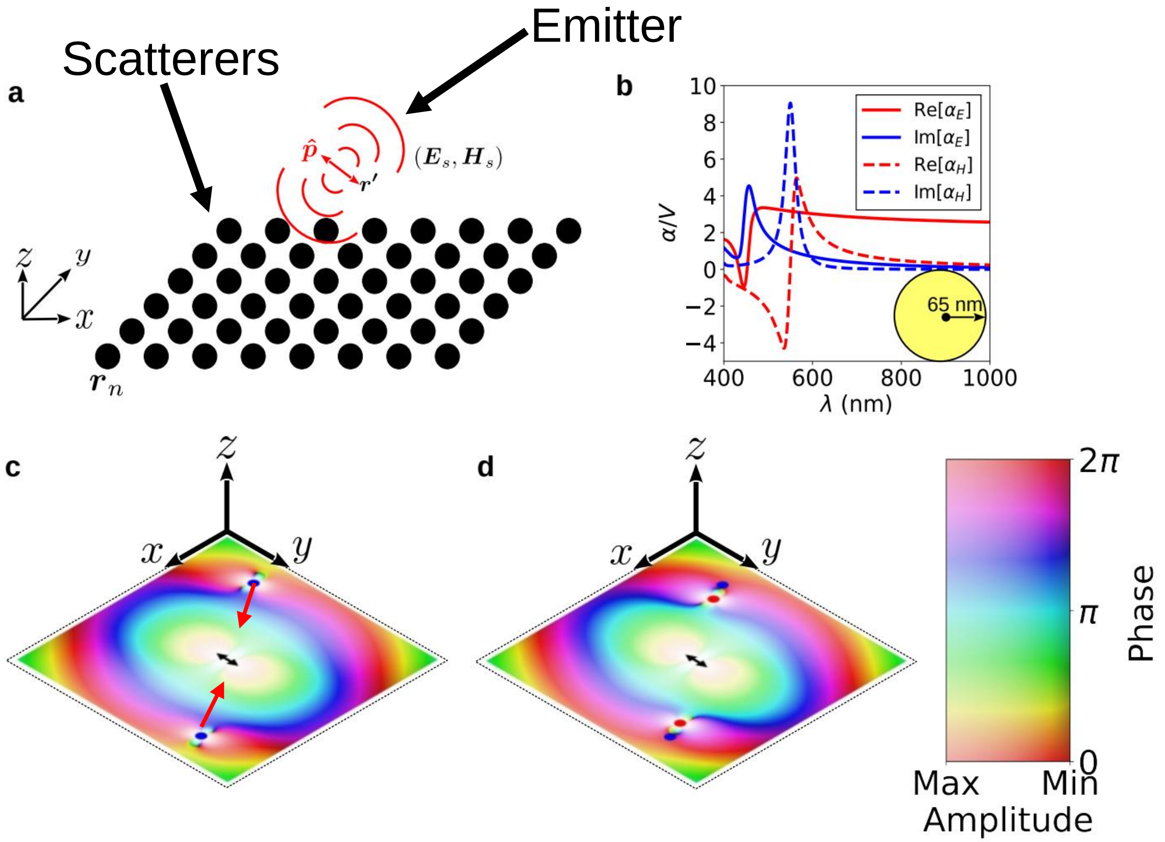
www.metamaterials.center

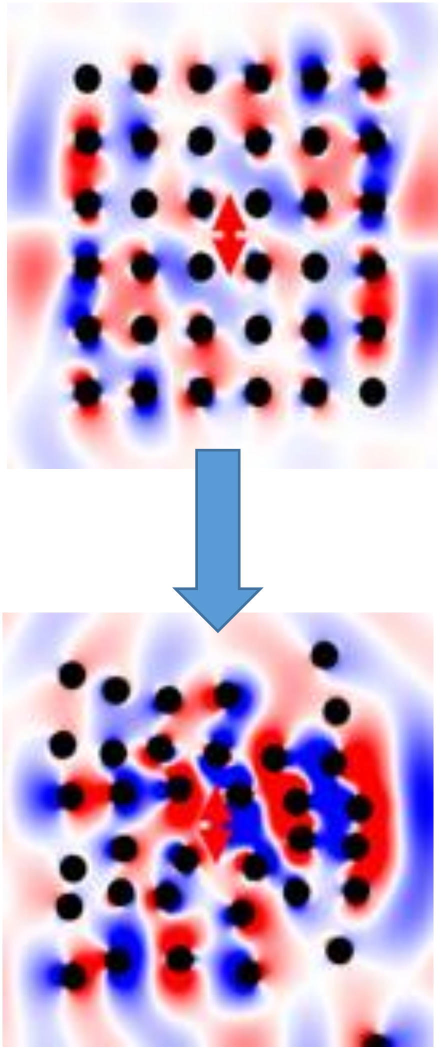
James Capers, Dr Simon Horsley, Prof Alastair Hibbins

Dstl

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:

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

UNIVERSITY OF EXETER

Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials XM²

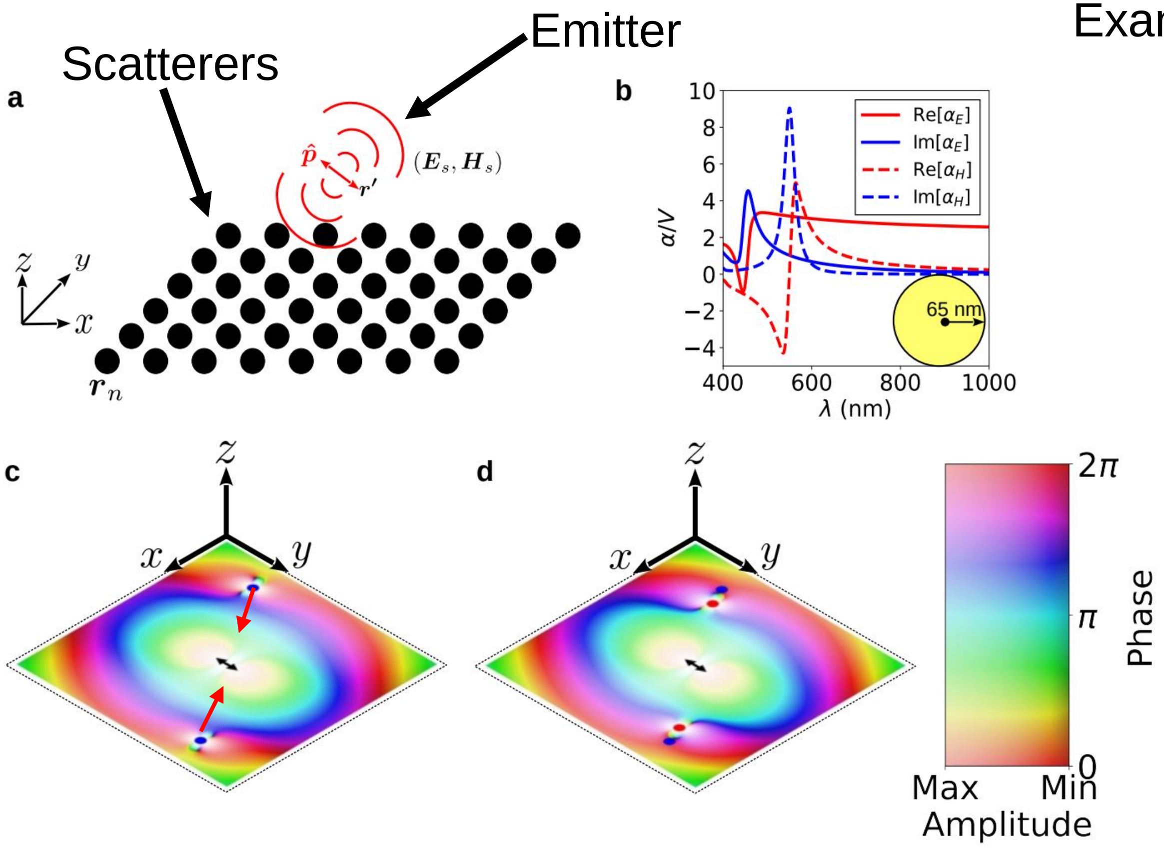
www.metamaterials.center

James Capers, Dr Simon Horsley, Prof Alastair Hibbins

Dstl

Metamaterials for Shaping Radiation

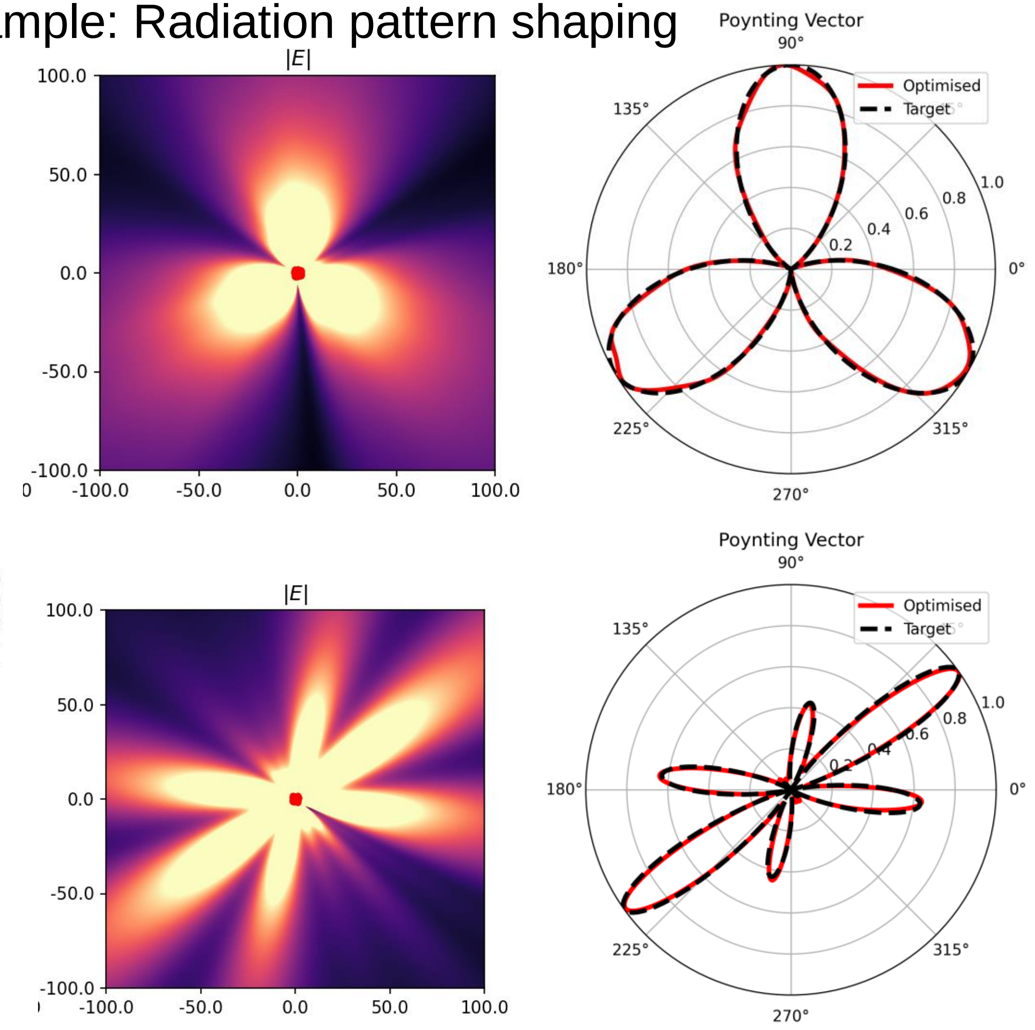
- Analytic coupled-dipole model to describe the effect of several scatterers upon the emitter
- Efficient optimisation algorithm to adjust scatterer locations to enhance power emission and design directivity.



Iterative design method based on perturbation theory:

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

Example: Radiation pattern shaping



UKRI Engineering and Physical Sciences Research Council

Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials

www.metamaterials.center

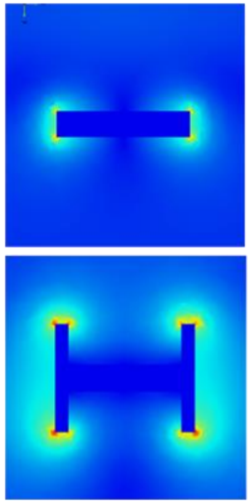
Dr Alexander Powell, Prof Alastair Hibbins, Prof Roy Sambles

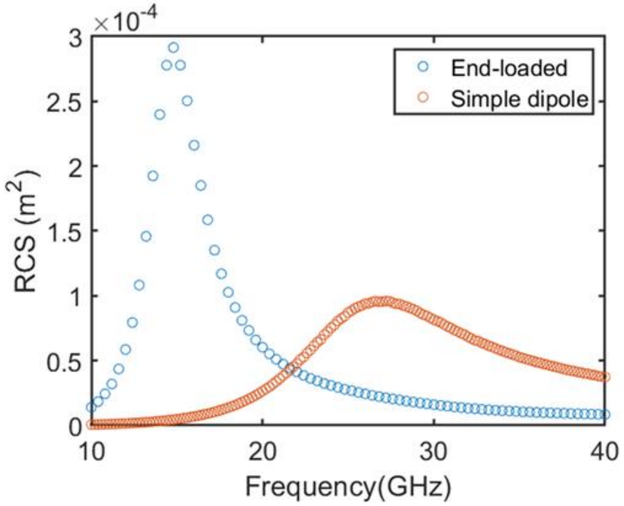
NPL

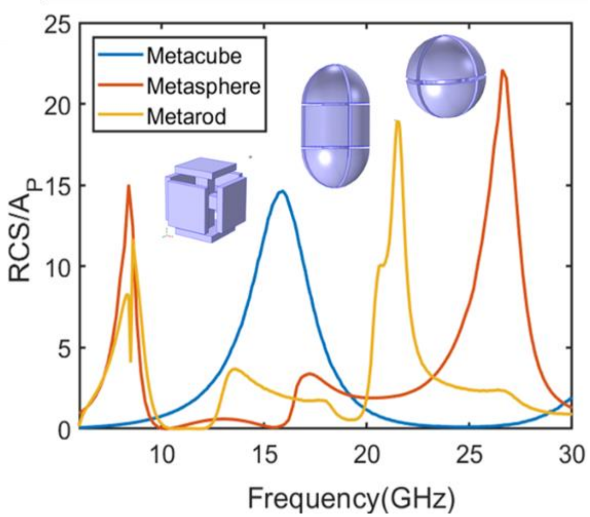
Metallic superscatterers

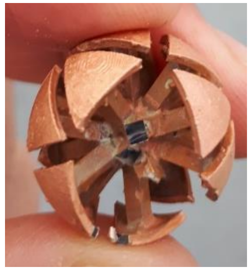
- Adding plates to the end of the dipole can make a small antenna have the power and frequency of a much larger one.

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









Strong, omnidirectional radar backscatter from subwavelength, 3D printed metacubes, IET Microw. Antennas Propag., 14: 1862-1868 (2020)

UNIVERSITY OF EXETER

Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials XM²

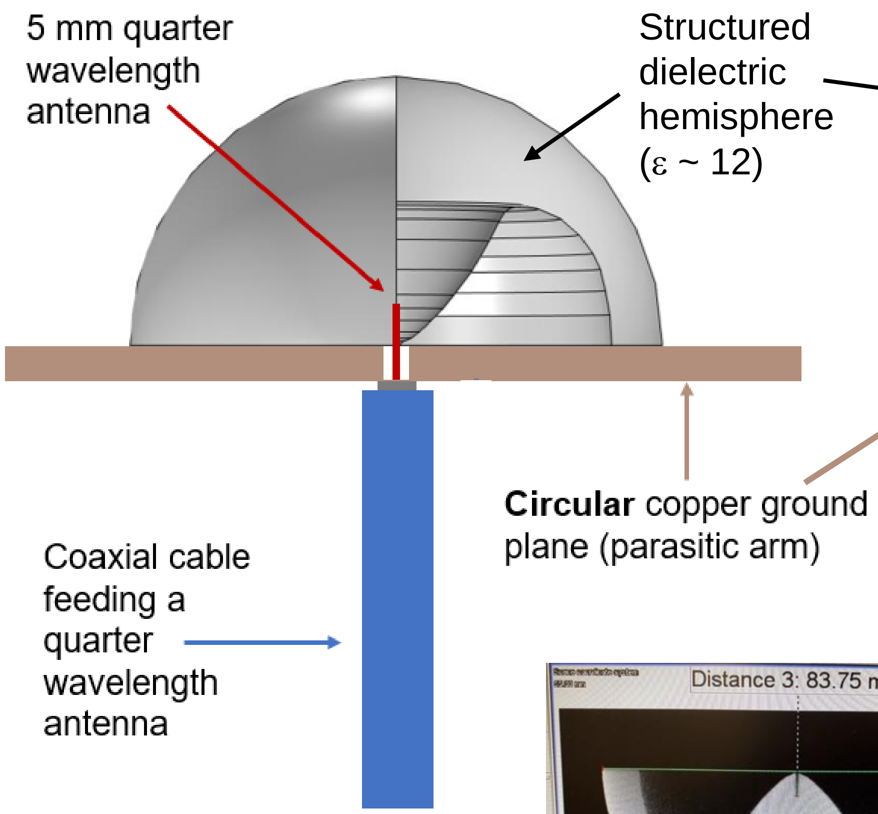
www.metamaterials.center

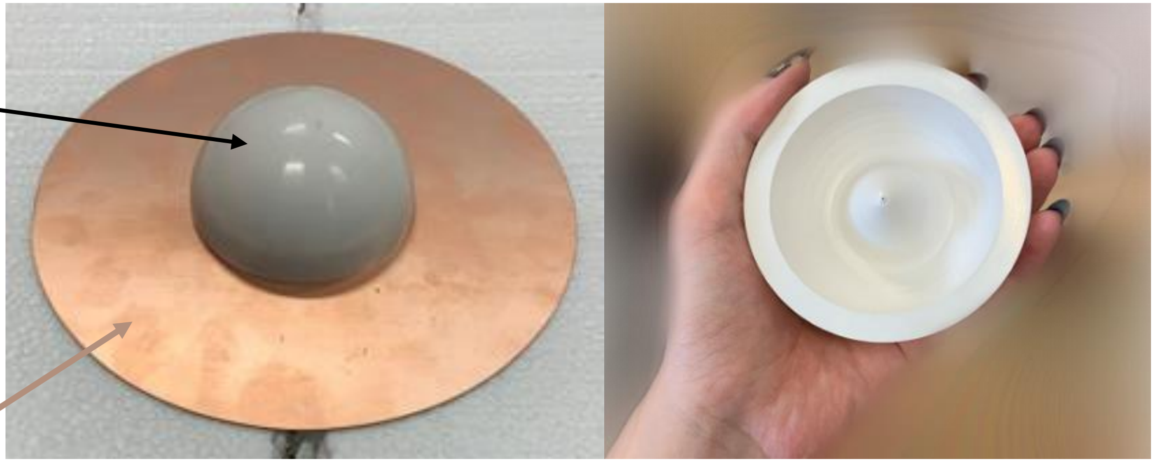
Leanne Stanfield, Prof Alastair Hibbins; Prof Sir Roy Sambles; Dr Alex Powell; Dr Simon Horsley;

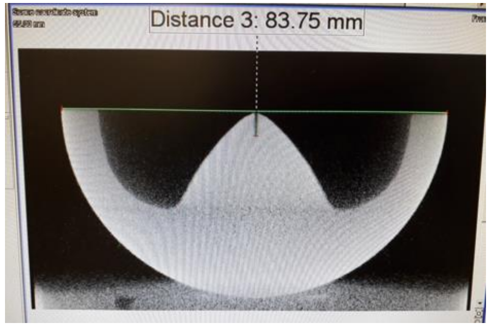
Leonardo

Enhancing efficiency of small antennas

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







X-ray tomography

- 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

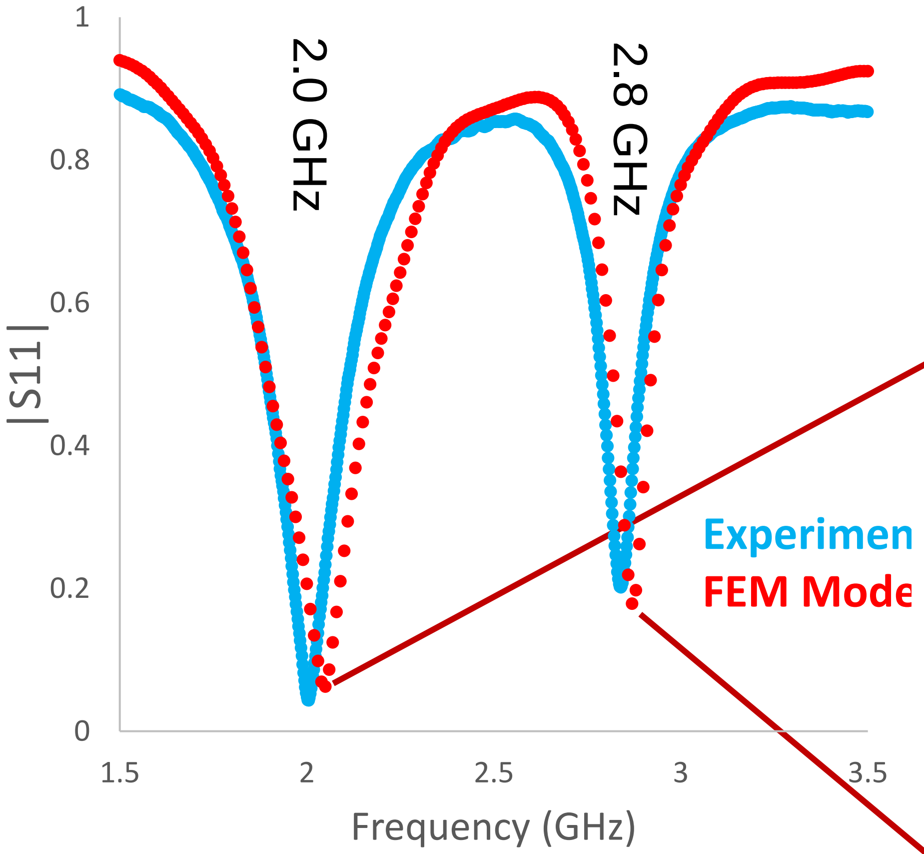
Engineering and Physical Sciences Research Council

Enhancing efficiency of small antennas

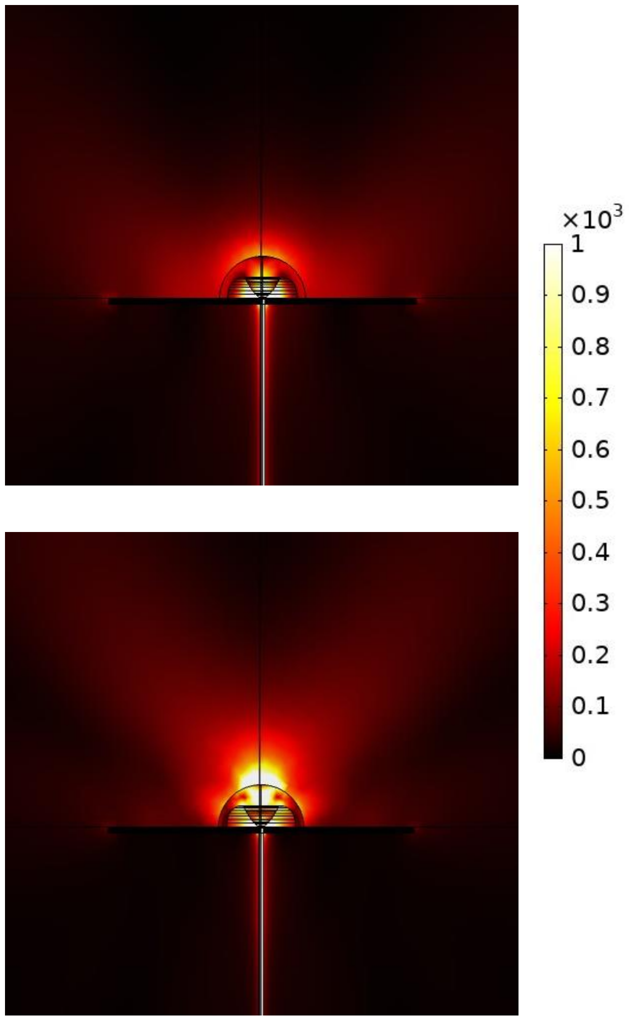
UNIVERSITY OF EXETER
Centre for Metamaterial Research and Innovation
EPSRC Centre for Doctoral Training in Metamaterials XM2
www.metamaterials.center

Leanne Stanfield, Prof Alastair Hibbins; Prof Sir Roy Sambles; Dr Alex Powell; Dr Simon Horsley;

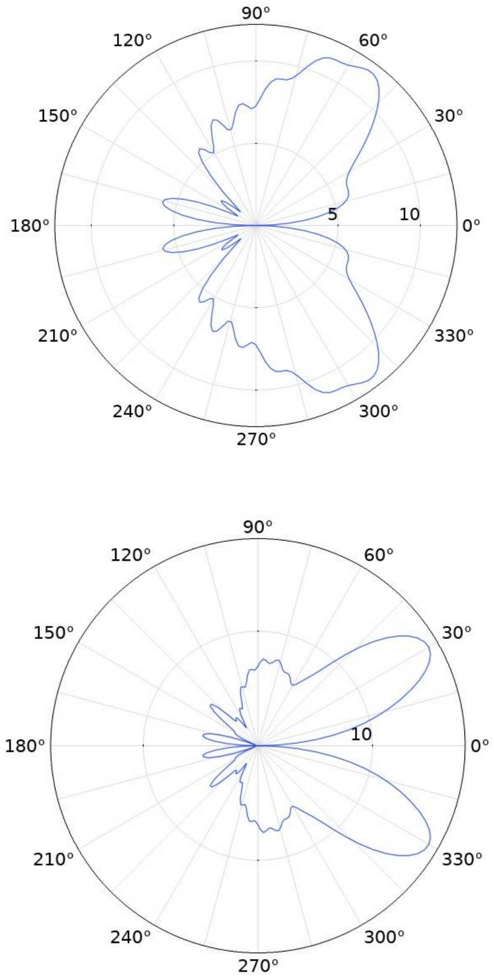
Leonardo



Normalised electric field (Vm $^{-1}$)



Farfield radiation pattern



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

Engineering and Physical Sciences Research Council

Dynamically reconfigurable spatial modulators

UNIVERSITY OF EXETER

Centre for Metamaterial Research and Innovation

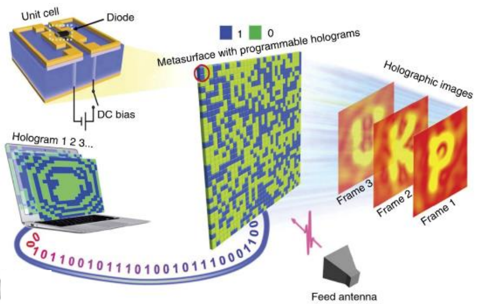
EPSRC Centre for Doctoral Training in Metamaterials XM²

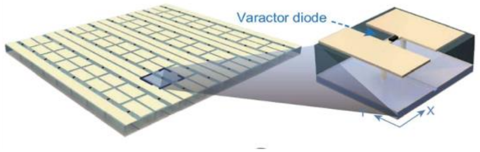
www.metamaterials.center

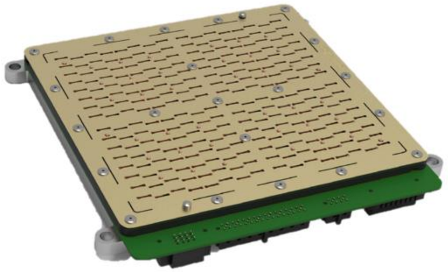
Dr Ian Hooper, Dr Lauren Barr, Prof Euan Hendry

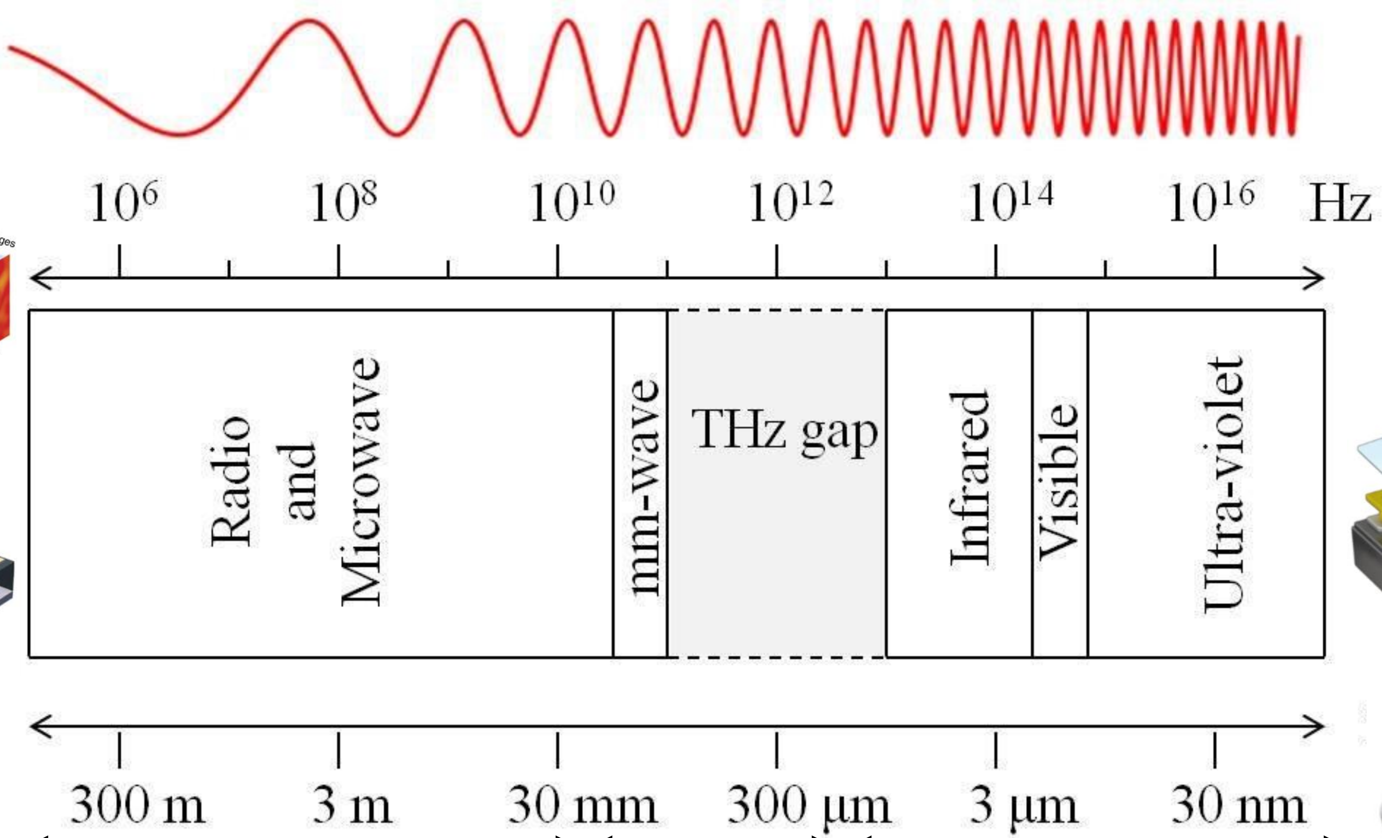
University of Warwick

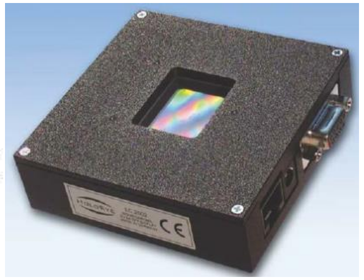
QinetiQ

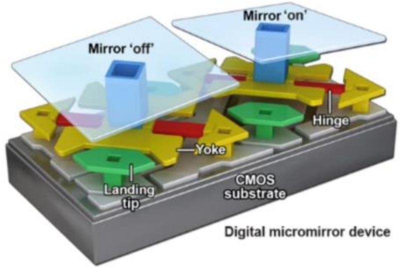


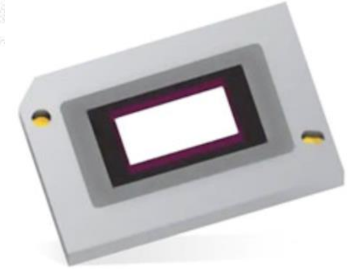












Electronics:
- Varactors, Diodes
- Phased arrays, etc.

???

- LC devices
- DMDs
- Phase change materials

Engineering and Physical Sciences Research Council

One approach - Si-based photomodulators

Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials

www.metamaterials.center

Dr Ian Hooper, Dr Lauren Barr, Prof Euan Hendry

University of Warwick

QinetiQ

Photoexcite charge carriers in Si

↓

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

↓

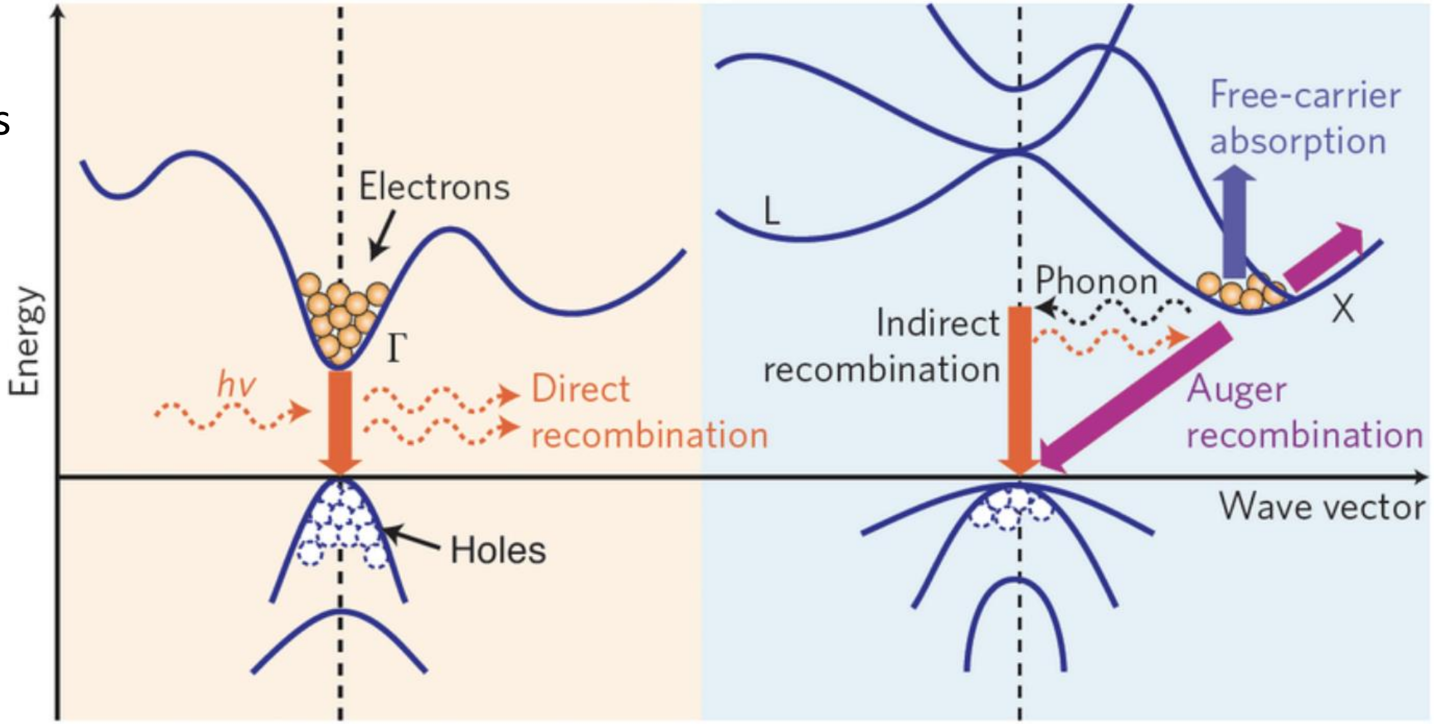
Change the conductivity – change the transmission of radiation through the wafer

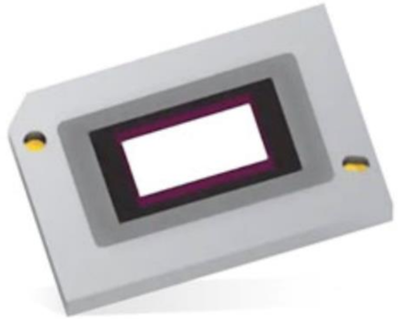
↓

Can easily spatially pattern the photoexcitation to produce a conductivity profile

↓

A spatial AND temporal modulator





Engineering and Physical Sciences Research Council

UNIVERSITY OF EXETER

Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials XM²

www.metamaterials.center

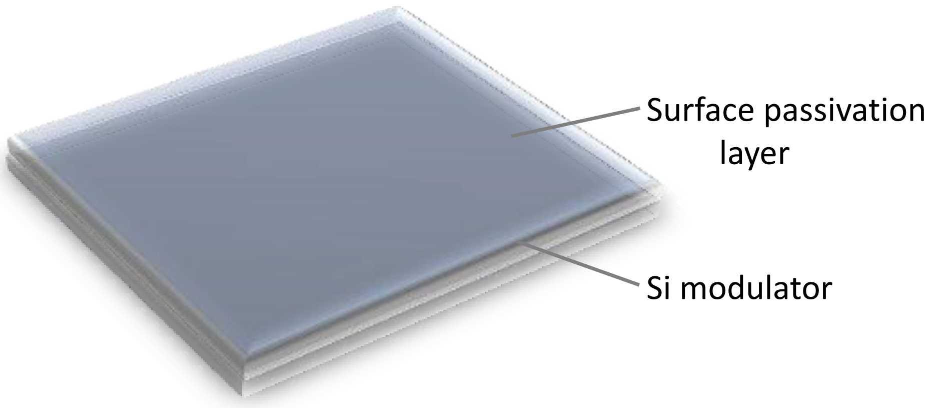
Dr Ian Hooper, Dr Lauren Barr, Prof Euan Hendry

University of Warwick

QinetiQ

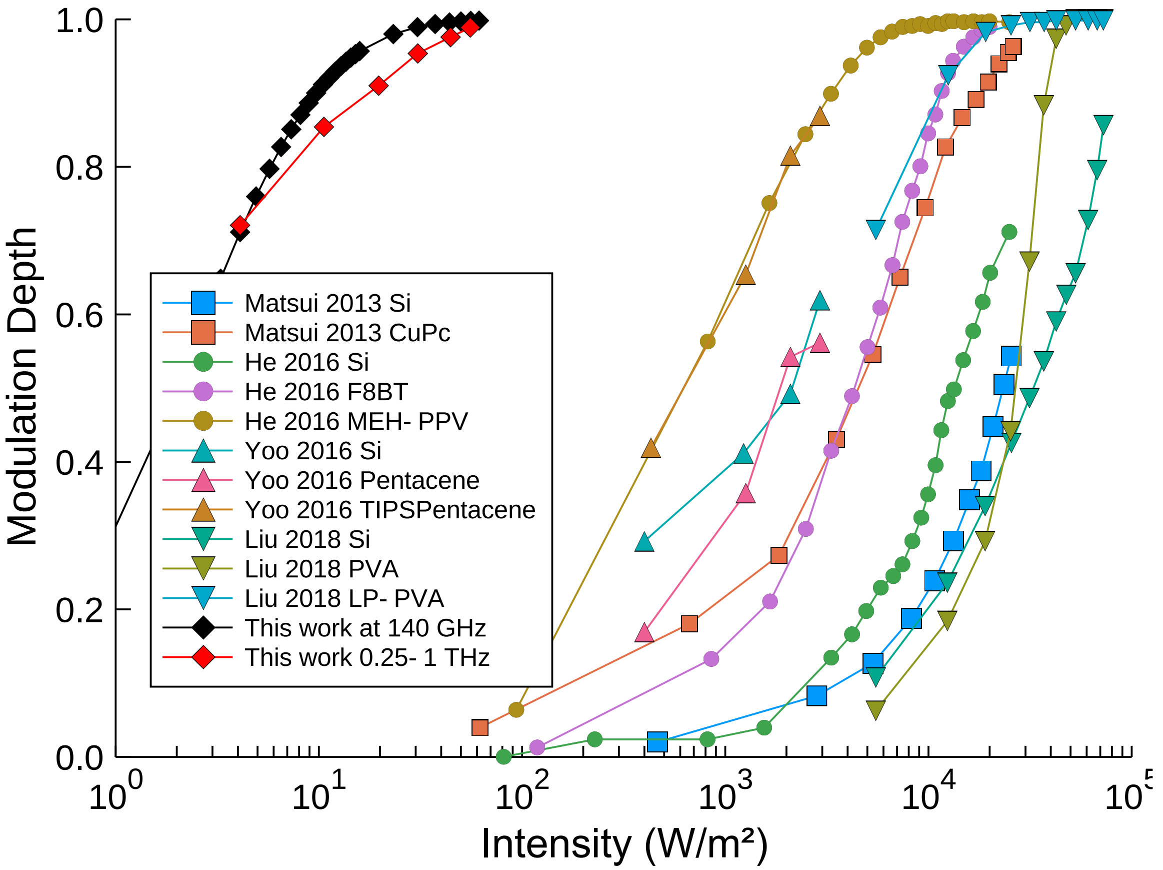
Enhancing efficiency…

I. R. Hooper, N. E. Grant, L. E. Barr, S. M. Hornett, J. D. Murphy, and E. Hendry, High efficiency photomodulators for mm-wave and THz radiation, Sci Rep, 9:18304 (2019).



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)



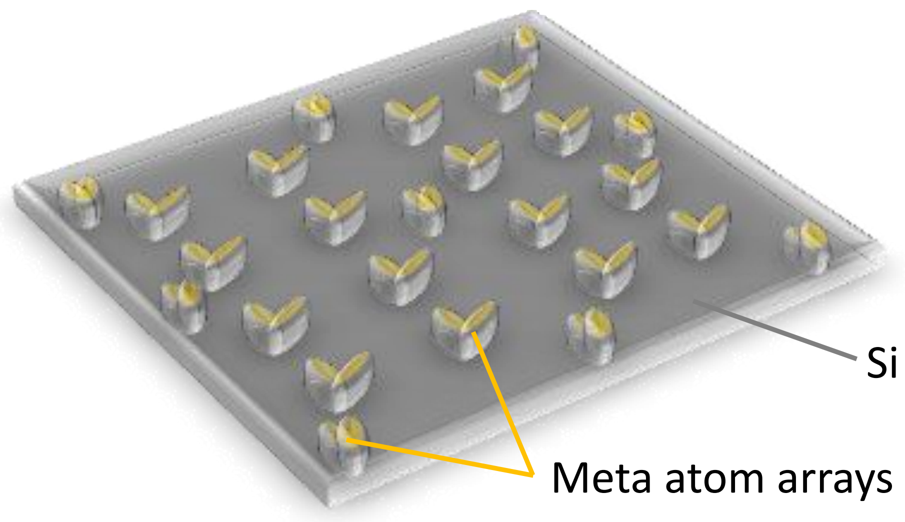
3-4 orders of magnitude increase in efficiency

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

Engineering and Physical Sciences Research Council

… But at a cost

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

UNIVERSITY OF EXETER
Centre for Metamaterial Research and Innovation
EPSRC Centre for Doctoral Training in Metamaterials XM^2
www.metamaterials.center

Dr Ian Hooper, Dr Lauren Barr, Prof Euan Hendry

University of Warwick

QinetiQ

UKRI Engineering and Physical Sciences Research Council

UNIVERSITY OF EXETER

Centre for Metamaterial Research and Innovation

EPSRC Centre for Doctoral Training in Metamaterials XM²

www.metamaterials.center

UK META MATERIALS NETWORK

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 Kisil, Manchester; TBC)
- **Biophotonics applications** (A Clark, Glasgow; M Kenney, Nottingham)
- **Manufacturing and scale up** (C Dancer, Warwick; N Grant, Warwick)
- **Multifunctional and mechanical metamaterials** (F Scarpa, Bristol; TBC)
- **Wireless and microwave applications** (L Ford, Sheffield; S Henthorn, Sheffield)
- **Acoustic Metamaterials** (G Memoli, Sussex T Starkey, Exeter)

acoustics.ac.uk

THE UK ACOUSTICS NETWORK

Forums

- **Early Career Researchers** (A Gower, Sheffield; O Lozman, M.Ventures)
- **Horizon scanning / disruptive concepts** (A Souslov, Bath; N Meinzer, Nature)
- **Industry** (A Alexeev, Waveoptics; N Crew, Airbus)
- **Outreach & Education** (R Assier, Manchester; A Roeding, Exeter)

ktn

S Morris, KTN

UKRI Engineering and Physical Sciences Research Council

Join the Network and Expert Database: www.metamaterials.network