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Science and Engineering

Software Defined Materials for Antenna Applications

Yang Hao

Queen Mary University of London Science and Engineering

Content

- Enabling Fundamental Material Sciences
- Innovative Antenna Solutions Inspired by Discovery Research
- Summary and Recommendations
- Capabilities & Facilities for 5G/6G & Beyond (Bonus Slides)

Fundamental Limit of Antenna and Arrays

- **History**
  - 6G and millimeter wave technologies can date back to the 1900s
  - QMUL's 100GHz active antenna array was funded by EPSRC in 2000
- **Challenges**
  - Both Antennas and Arrays have fundamental limits of operation
  - Size and bandwidth is unlikely an issue at millimeter frequencies
  - Costs and material availability become an issue

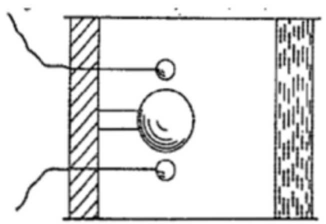


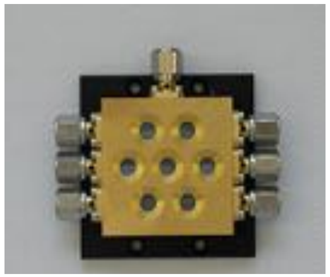
Fig. 6. Bose's Sulphur Lens (1895).

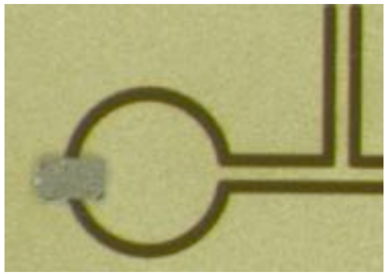
$$\eta^{\mathrm{TE}} := \frac{|\ln|\Gamma_{Z,\max}||\,(BW-1)}{2\pi^2\mu_s\left(\frac{d}{\lambda_{\mathrm{hf}}}\right)\cos\theta_1} \leq 1.$$

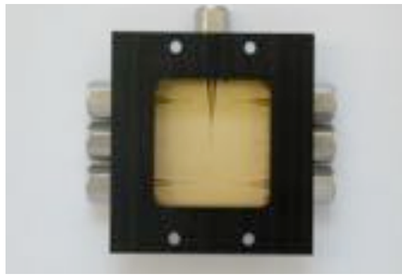
From Harrington,

$$G = (ka)^2 + ka$$

k is wave number







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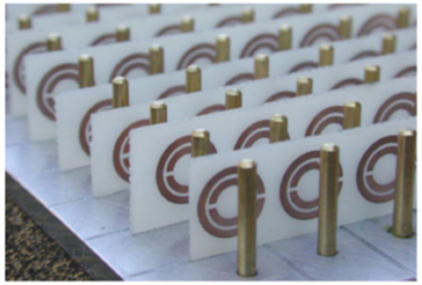
Discovery Research of Metamaterials and Transformation Optics

- **History**
  - Metamaterials (MTMs) is artificially designed materials with the history date back in 1960s
  - Transformation Optics (TO) is the underlying tool for invisibility cloak design
- **Challenges**
  - MTMs and TO are enabling tools rather solutions
  - They open up more degrees of freedom in design space
  - They enable multiscale and multi-disciplinary solutions to challenging engineering problems



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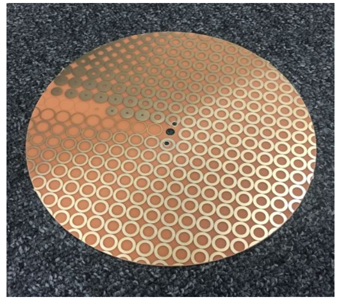

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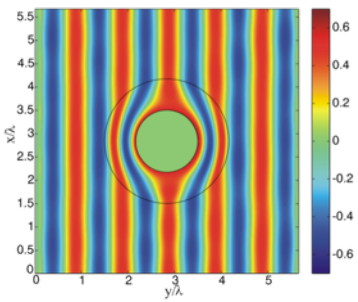

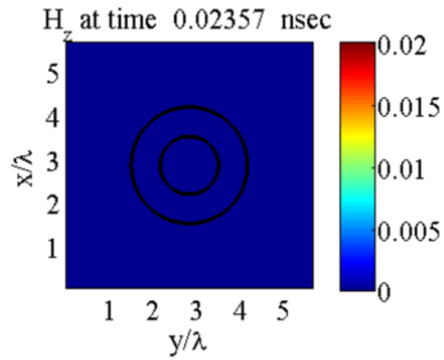

Y Hao, R Mittra, FDTD modeling of metamaterials: Theory and applications, Artech House, 2008

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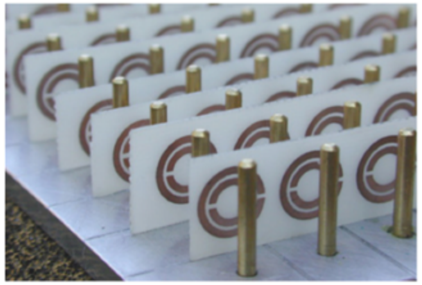

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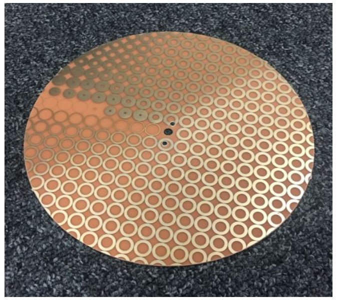

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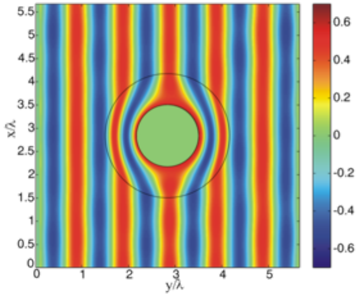

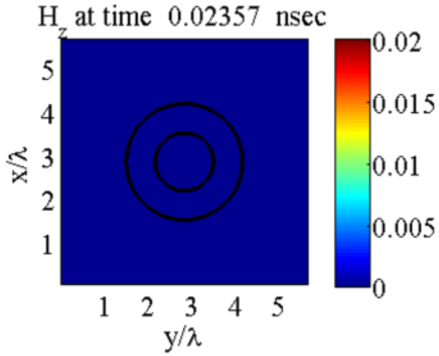

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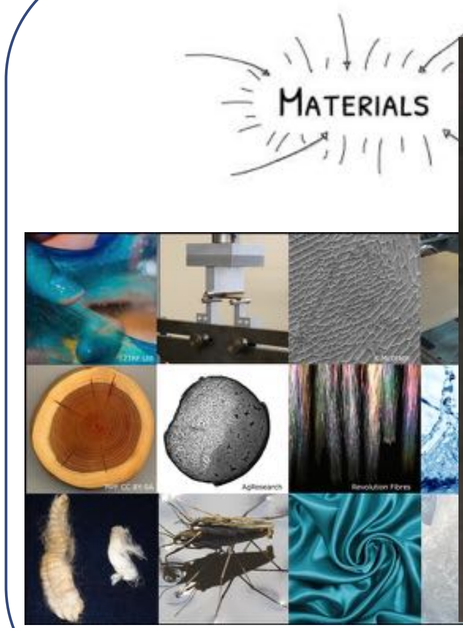
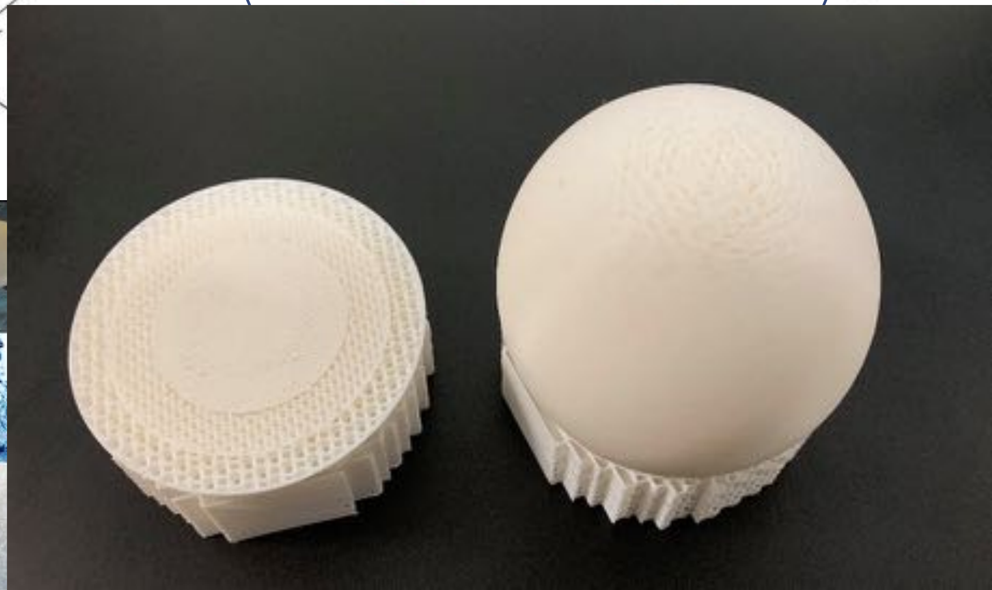
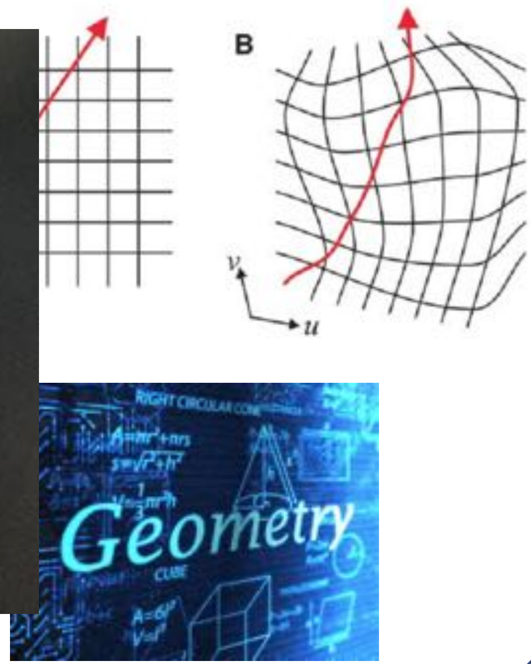
Innovative Antenna Solutions Inspired by Discovery Science







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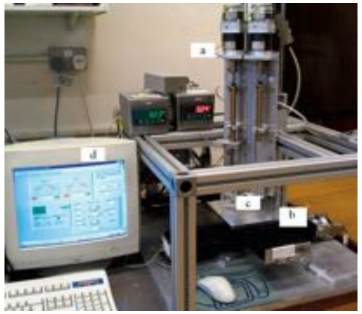
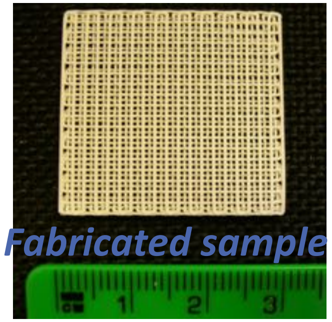
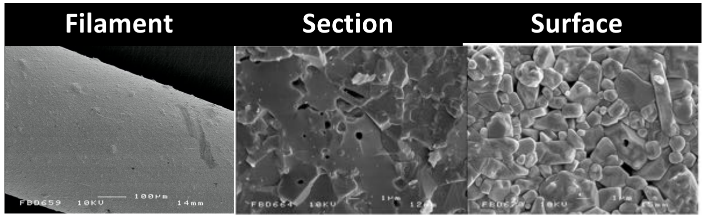
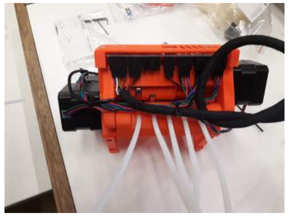
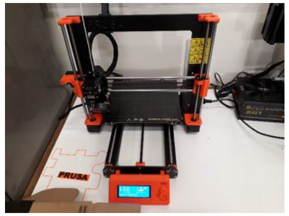




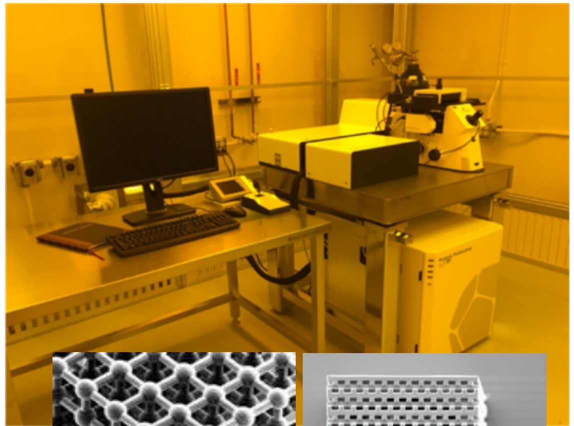


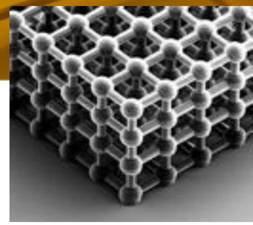
Y. Lee, X. Lu, Y. Hao, et al, "Low-Profile Directive Millimeter-Wave Antennas Using Free-Formed Three-Dimensional (3-D) Electromagnetic Bandgap Structures," in IEEE Transactions on Antennas and Propagation, vol. 57, no. 10, pp. 2893-2903, Oct. 2009, doi: 10.1109/TAP.2009.2029299.

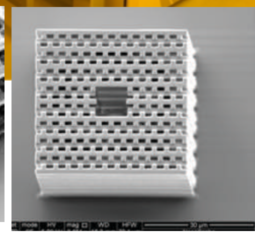




Prussa i3 mk3s MMU2s (approx. $1200)







- 3D laser lithography system
- Resolutions down to 100 nm (highest resolution commercially available)
- Print areas as large as 100 x 100 mm
- 2-photon exposure of common positive-tone photoresists

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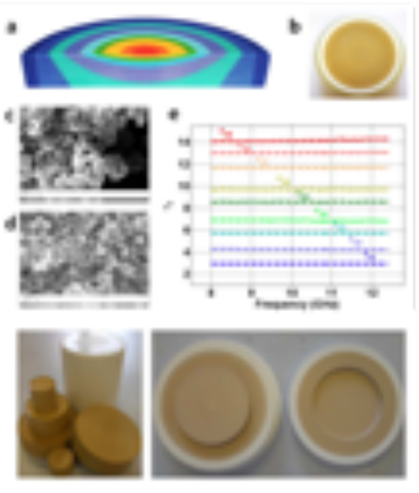

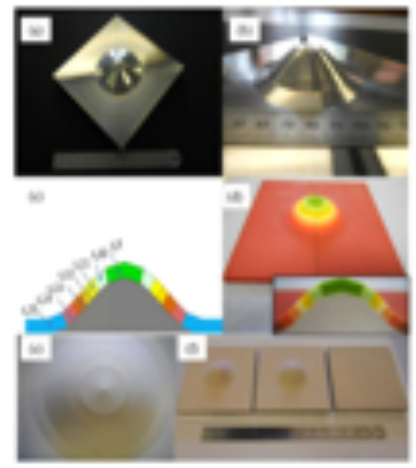

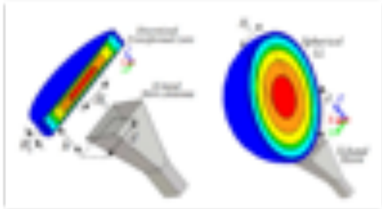

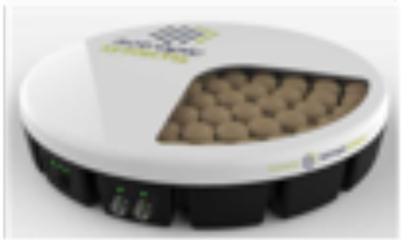

BAE SYSTEMS
[dstl]
QINETIQ
THALES
Plextek
AGC
isotropic systems

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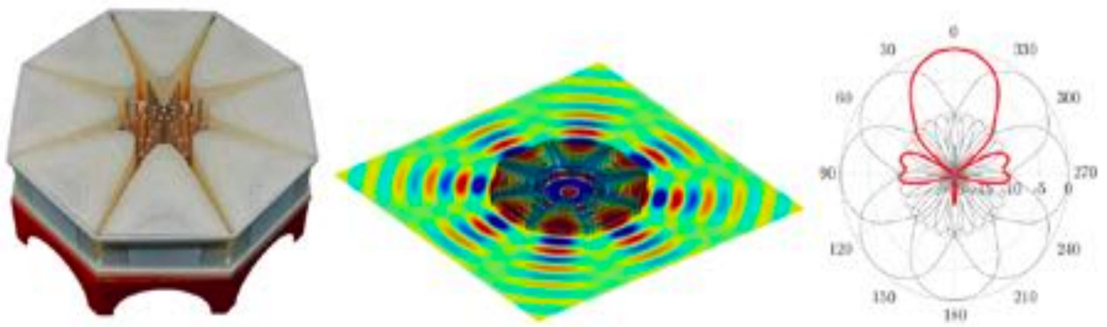
MANET Antennas



- **History**
  - TO lens have been applied to MANET antenna designs for anti-jamming etc.
  - 3D Printed Multi-Beam Antenna for 360° coverage
  - Multi-beam radiation emerging from a single feed
  - Optimised single sector radiation pattern
- **Challenges**
  - Industrial take-up of technology
  - Size, weight reduction
  - Cost benefits benchmarking against other technologies

6G/Future Generation Wireless Demo

- **History**
  - Flat Luneburg Lens developed under EPSRC QUEST Programme Grant
  - Demonstration of 8K video over 60GHz link without compression in 2017
- **Challenges**
  - Industrial take-up of technology
  - System integration
  - Applications and commercial exploitation
  - Likely in VR, IoT, automotive and others

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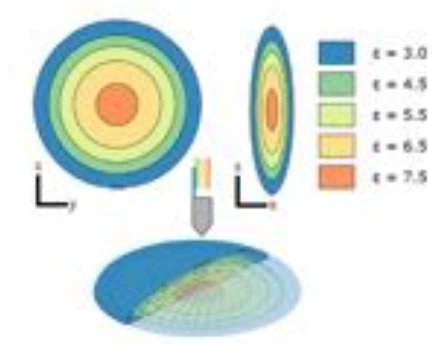
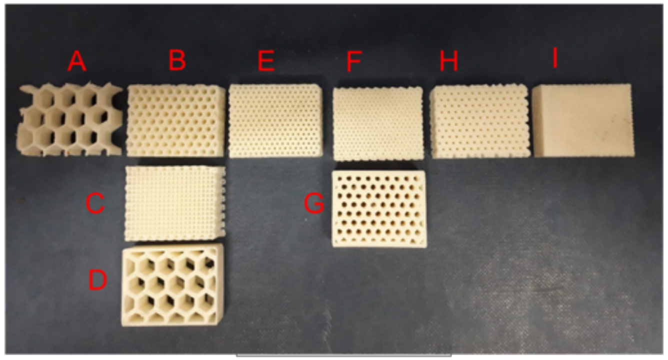
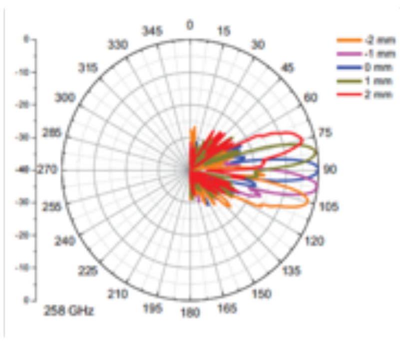
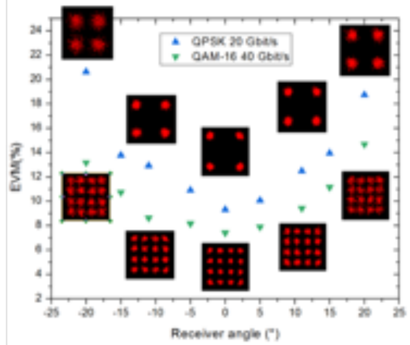
300GHz Wireless Demo with TeraLINK

- **History**
  - Sub-THz wireless communications have been demonstrated in 2019 under the ERC Chist-ERA funding
  - 40Gbps 16-QAM has been demonstrated with scanning up to 25 degrees
- **Challenges**
  - Low cost power amplification
  - Fully integrated optoelectronic solutions
  - Massive MIMO arrays



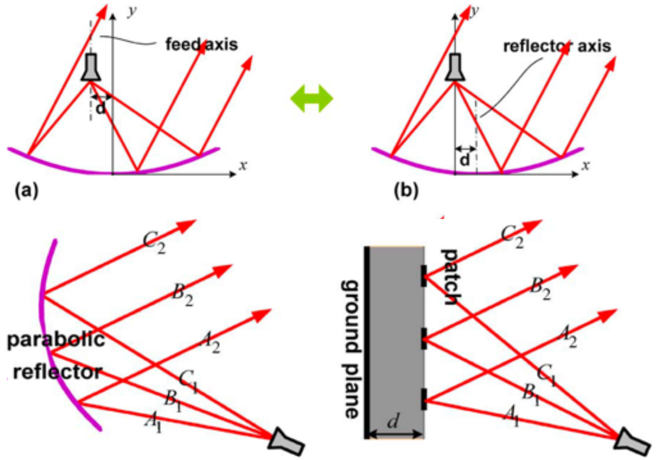


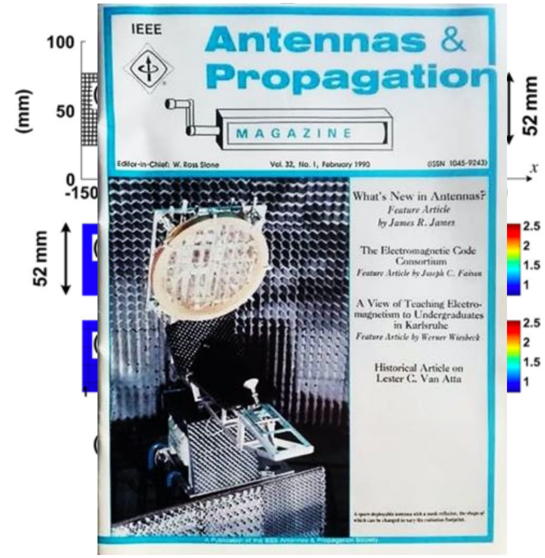


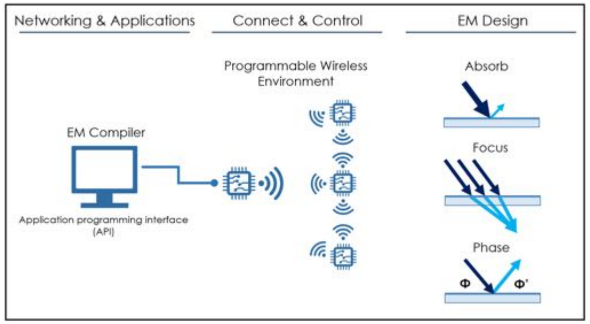


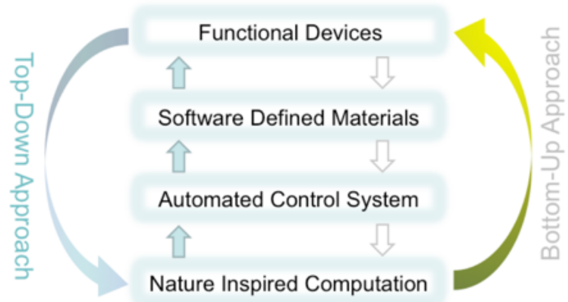
Software Defined Materials/MTSs

- **History**
  - Tunable materials are needed to design intelligent surfaces and materials which can be controlled and updated by software
  - EPSRC funded £2M ANIMATE project funded in 2018 looking into a cross-disciplinary approach tackling software defined materials and MTSs
- **Challenges**
  - No suitable tunable materials available considering loss, tunability and biasing network









R. Yang, W. Tang and Y. Hao, in *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 1290-1294, 2011, doi: 10.1109/LAWP.2011.2176461.

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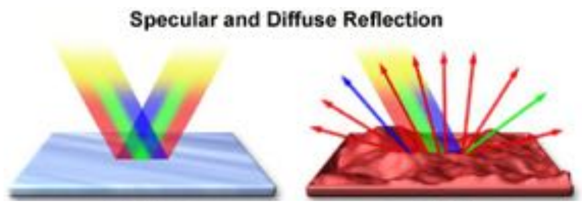
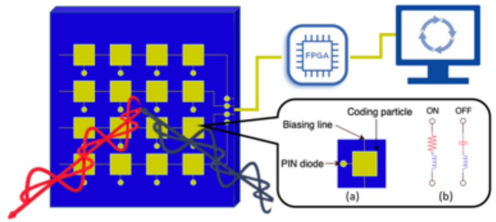
Software Defined Materials/MTSs



Problem Statement

Solutions



System Architecture

- **Benefits**
  - Many different terminologies including RIS, digital coding, LIS, STAR.
  - Claimed benefits include: RIS-aided mmWave Systems, maximized spectrum efficiency through multi-cells, Simultaneous Wireless Information and Power Transfer (SWIPT), Added Physical Layer Security (PLS), Cognitive Radio (CR) Networks.
- **Challenges**
  - No current solutions are “intelligent”.
  - No tangible benefits for RF/Microwaves.
  - Over-optimistic performance and over-engineered designs.
  - Not really solving problems at mmwaves and THz

QMUL ANIMATE Solutions

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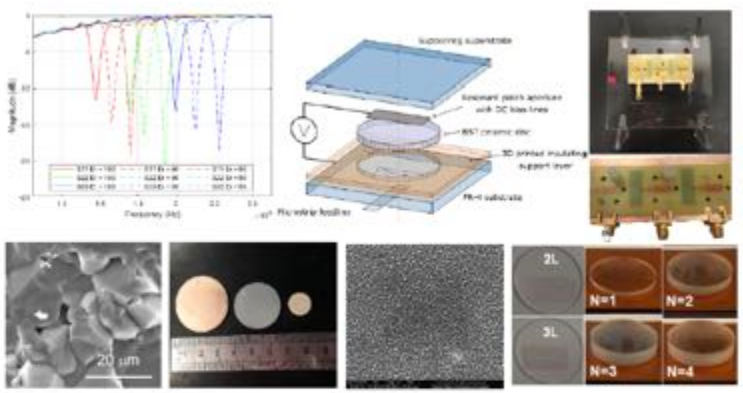
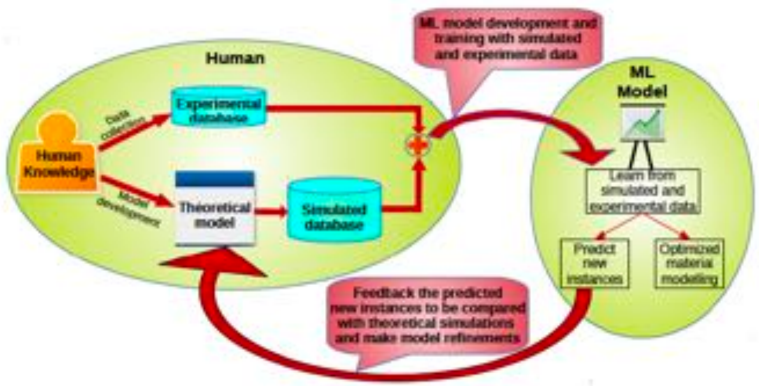
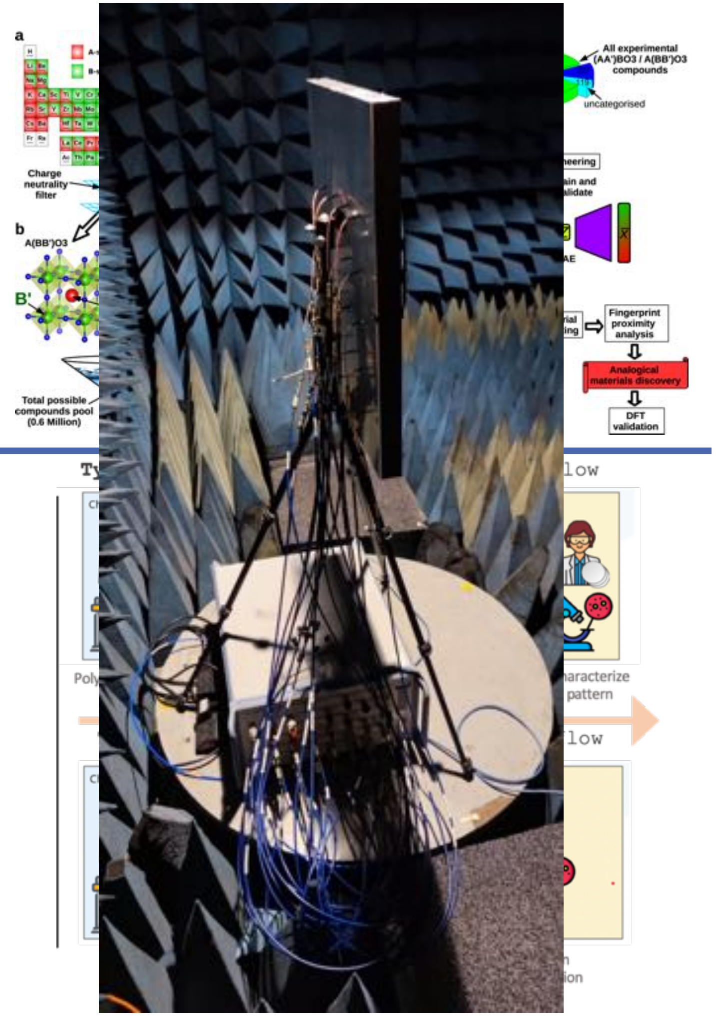
- New tunable material discovery from AI/ML
- Human-Machine Interactive Learning for new antennas
- Research lab automation for high throughput material discovery
- Functional device system demonstration for applications in wireless communications, security imaging, IoT, autonomous systems, space etc.







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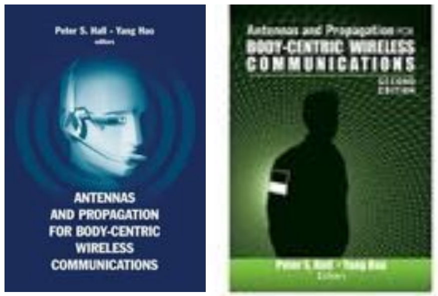
Summary and Recommendations

- **Summary**
  - UK has strong research bases and is leading in discovery science
  - Research culture is changing with strong academic and business partnership, spinout activities
  - A joined-up agenda from the government, university and industry is needed, involving multi-disciplinary teams and international partners to tackle 6G and future communication challenges

Body-Centric Wireless Communications

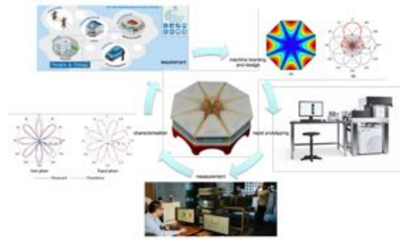


- Lots of academic impact
- Strong industrial Collaboration
- No spinout from universities

Metamaterials and TO

- £5M QUEST created the critical mass for research
- Oxford, Exeter, QMUL all have follow-on activities including CDTs, industrial collaborations
- ISL spinout led by VC fund

Design by Science



- Close the loop between design and prototyping
- Moving towards design automation
- Net Zero and sustainability
- New spinout from PDRA
- Henry Giddens

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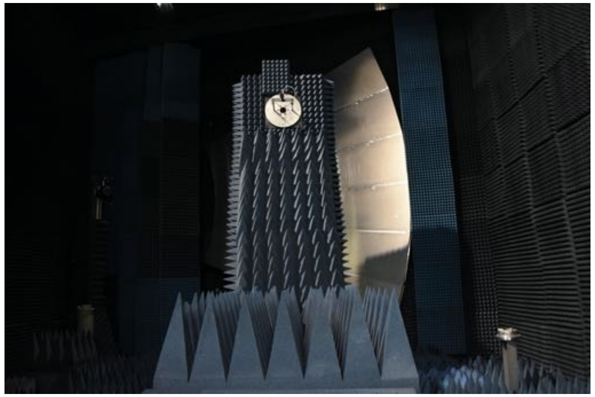
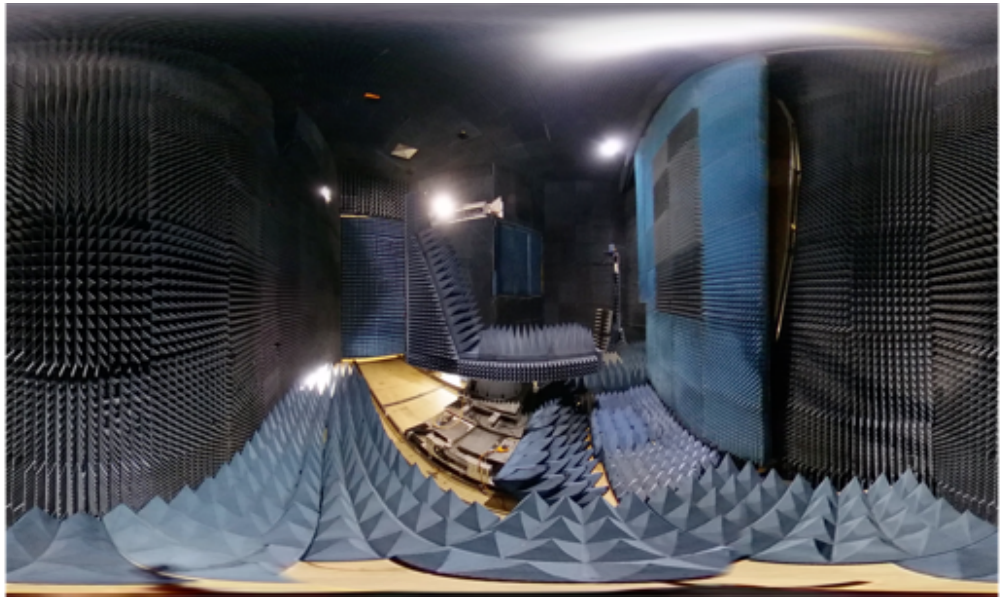
130+ of E&E Engineering

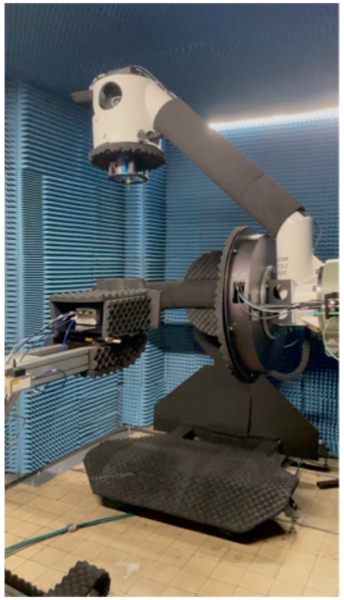
- Electrical Engineering was first taught at East London College in October 1888.
- The Antennas & EM research Group was set up in 1966 by Prof Peter Clarricoats (FRS, FREng).
- The Group has 15 members and around 60 researchers with support of ~£3m in infrastructure and core equipment funds focused on mm-wave and THz. The Antennas Measurement Lab covers frequencies up to 4 THz with 4 Anechoic Chambers and comprehensive suite of equipment for antenna characterization, radio channel assessment, and material engineering down to the nano-scale.



SPHERICAL NEAR-FIELD / FAR-FIELD ANTENNA TEST SYSTEM: This NSI system, installed within the CATR chamber and sharing the same antenna under test turntable system offers the ability to test large antennas up to 2m in diameter and up to 40GHz by measuring the amplitude and phase in the “near-field” and then computing the traditional “far-field” pattern



THE NSI 700-S360 COMPACT ANTENNA MULTI-TEST SYSTEM represents the most advanced antenna measurement system facility available at frequencies up to 500GHz. It consists of a dual-axis, “theta over phi”, positioning arrangement with a 5-axis laser alignment procedure. Unique to this product is the capability to mount a test antenna on a stationary mm-wave probe station while completing a full 4π steradian closed spherical surface measurement of on-chip antennas.



QMUL 5G & Beyond Interests

Traceable Characterisation of Antennas and Channels

- Over-the-air testing for sub 6GHz and mm-wave
- Testing and novel designed extended to mm-wave and sub-THz (up to 500 GHz)
- Including novel reconfigurable and adaptive materials

  - Numerical analysis of materials-influenced antenna arrays
  - Experimental assessment of reconfigurable antenna arrays (mainly integrated)
  - Radio channel characterisation up to sub-THz
  - Repeatability and scalability through design and fabrication

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Multi-scale Numerical Analysis

- **Focus**
  - Multi-scale and multi-physics numerical simulations of antenna arrays up to sub-THz (500 GHz)
  - Integration of reconfigurable enabled pixel-like material matrix
- **Outcomes**
  - Numerically driven reference design and lumped element equivalent circuitry for the reconfigurability aspects
- **Available Infrastructure**
  - High performance computing clusters
  - Suite of commercial software packages (CST, AWR, ADS, etc.)

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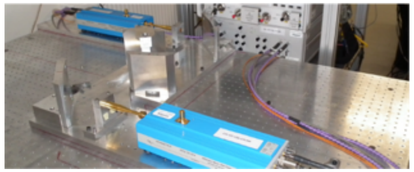
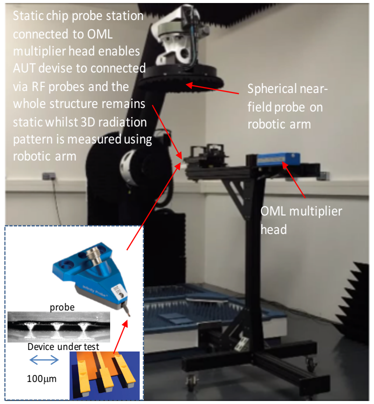
Sub-THz Antenna Array Designs and Characterisation

- **Focus**
  - Develop experimental methodology and guidelines for assessing sub-THz wideband antenna array structures
  - Figure-of-merit in assessing new array requirements
- **Outcomes**
  - Characterisation methodology and protocol for high gain and compact sub-THz arrays
  - Parameters and features for optimisation of array
- **Available Infrastructure**
  - The NSI 700-S360 compact antenna multi-test system
  - Keysight transceiver pair of 325 – 500 GHz frequency extender modules for our 4-port Vector Network Analyser (overall capability 10 MHz to 500 GHz)





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Sub-THz Radio Channel Characterisation

- **Focus**
  - Channel modelling and characterisation at mm-wave and sub-THz (30 GHz and up to 500 GHz)
  - Radio link performance in presence adaptive and reconfigurable front-ends
- **Outcomes**
  - Radio channel parameters and models
  - Influence on over-the-air testing
  - Intelligent antenna arrays
- **Available Infrastructure**
  - Anechoic chambers covering up to 320 GHz
  - New transceiver pair of 325 – 500 GHz frequency extender modules for our 4-port Vector Network Analyser

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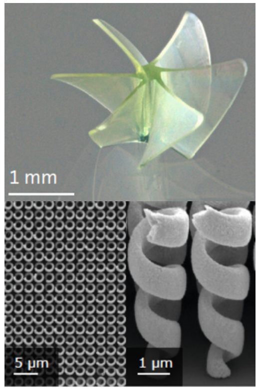
Closing the Gap between Design and Fabrication

- **Focus**
  - Assessing fabrication uncertainty on antenna and channel performance
  - Dispersive behavior considering wideband nature of proposed structures
- **Outcomes**
  - Uncertainty analysis of element and array
  - Evaluation through numerical analysis and simulations
- **Available Infrastructure**
  - Time domain spectroscopy (both transmission and reflection)
  - The NSI 700-S360 compact antenna multi-test system
  - The Nanoscribe 3D laser lithography system



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