EPSRC BIG IDEAS SUBMISSION FORM

Q1. BIG IDEA TITLE

The UK Metamaterials Revolution: Innovative solutions to global challenges in energy, communication, health and security.

Q2. PITCH

Recent advances in fundamental physics, engineering and advanced manufacturing have brought us to the cusp of delivering a range of materials that offer game changing control of energy and light. This opens up a new landscape of potential impacts benefiting UK strategic advantage.

Metamaterials have a crucial future role to play in combatting the climate emergency. They will be used for

- reducing power consumption (e.g., low power computing and communications),
- making electrochemically based technologies more efficient, economically viable and environmentally friendly for batteries, fuel cells, capacitors, solar cells and water desalination
- improving circularity (new catalytic materials and substitutes for scarce elements),
- providing carbon neutral feedstocks (new catalytic materials)
- complete environmental control for improved yields from agriculture, digital farming (sensing and intervention), crops resilient to disease and drought
- In a warming environment, passive, radiative cooling surfaces for efficient next-gen air-conditioning and refrigeration systems
- net-zero building design (including thermal management)
- reducing the embodied carbon in many consumer goods (replacing high carbon materials).

The fundamental nature of this research means that it is imperative that it is done now so that the resulting materials can be in production in time to have full market penetration ahead of 2050.

This Research and Innovation will also have profound impacts across health and wellbeing, ICT, and national security. This Big Idea is achievable through the convergence of complementary advances in fundamental physics, engineering and advanced manufacturing, allied to the training of highly skilled people, the acceleration of technology transfer and the scale up of Metamaterial manufacture and metrology.

Q3. WHAT IS THE 'BIG IDEA'?

GIVE A DESCRIPTION OF THE PROPOSED OPPORTUNITY, IN NON-TECHNICAL LANGUAGE HOW COULD THIS BIG IDEA HAVE THE ABILITY TO ENTHUSE THE GOVERNMENT AND THE PUBLIC? HIGHLIGHT THE TRANSFORMATIONAL ASPIRATIONS OF THE IDEA EXPLAIN HOW THIS IDEA IS 'BIG', HOW IT MOVES FROM BEYOND AN INDIVIDUAL RESEARCH PROJECT/PROPOSAL TO A LARGER ENDEAVOUR.

Materials underpin almost every aspect of human existence, from protecting us to feeding us; from enabling communication to the supply of energy; from constructing transport infrastructure to housing and keeping us warm. UK leadership in, and resilient access to current and future materials directly dictates our national prosperity, our security and our quality of life.

Conventionally, particular materials, whether they are first generation natural materials, purified and refined natural materials or synthetic materials such as nylon or carbon composites, are selected from a diverse array of options for specific uses because of their individual fixed characteristics and defined behaviours.

A new class of materials, '**Metamaterials**', enormously expands what materials can do for us, realising that in addition to chemical composition, the fine structure of a conventional material can be designed at the outset to engineer bespoke and disruptively advantageous characteristics and functionality. This concept of **function-through-structure** has achieved huge traction in recent years particularly in microwave, optics and acoustics, and is poised to radically transform the design, manufacture and functionality of everyday products.

The Metamaterials Revolution builds on a world-leading base of UK academic strength and recent seminal advances in UK expertise in pioneering fundamental physics, methods for the accelerated discovery of new Metamaterial designs, and breakthroughs in fabrication techniques. Metamaterials are both a **Technology and Market Enabler**, and the beyond-state-of-the-art opportunities they offer are universally relevant to applications associated with the control of vibrational, thermal, acoustic or electromagnetic energy, and associated communication and processing of information.

Metamaterials have the potential to disruptively enhance the technology associated with hardware and physical components, revolutionise the processes we use to control and interact with our surroundings, and reduce the burden we make on the environment. Ground-breaking applications range from *ultrafast and energy-efficient computing and electronics*, to *thinner, smaller, and lighter antennas*; from *holographic displays* to *lightweight, but extraordinarily strong materials;* from *noise control* to *high resolution imaging and enhanced sensing*; from *clean energy production* to *energy-efficient cooling*.[1]

The **UK Metamaterials Revolution** focusses on the development and execution of a strategy, which will exploit the significant potential that the UK has to establish a thriving innovation driven, research and industrial base. The **transformative challenge** is to demystify Metamaterials technology, deliver the application of Metamaterials across a wide range of markets sectors to increase device functionality and practicality, create a clear path to scale up in manufacture, and train a highly productive pool of skilled people, while providing a reduction in the environmental burden and financial cost compared to conventional technologies.

A *revolution* is required to ensure that the UK HMG, industry, and academia reacts coherently and collectively to this unfolding technological shift in established market sectors important to the UK economy (e.g., 6G communication technologies, and beyond). The potential to mobilise is reflected by the large number of organisations engaged since 2020/21 launch of the combined EPSRC[2] and KTN[3] Networks to form the UK Metamaterials community (www.Metamaterials.network). Over 300 individuals representing 84 organisations across HEIs (39), Industry (35), RTOs (4), Government (4) and other (2) organisations have already proactively registered as experts or end-users, and a further 105 distinct organisations have engaged with the events (with over 750 individual delegates), demonstrating a hugely positive potential, combining breadth of demand, expertise and capability in the field (Appendix 1: stakeholder organisation summary).

In a post-Brexit and post-Covid UK, our nation needs to build and deliver impact from sovereign capabilities where we are world leading. Metamaterial science provides a timely opportunity of this class. We provide a summary of funding landscape in Q6, but this is almost entirely in the EPSRC space: it is based around large programme-grant-style investments, and there has been no coherence nor coordination of strategic direction. The UK needs a strategy and a **National Metamaterials Programme** to maintain our academic leadership in discovery science on the global stage, and to ensure that the nation's prosperity and security can fully benefit from this foundational investment.

Through an extensive period of consultation with academic, industry and Government stakeholders, we have identified **five core themes that form the scope of this Big Idea**, which are:

(i) a programme supporting fundamental research across physics, engineering and advanced manufacturing ,
(ii) a UKRI Metamaterials Observatory for national leadership, to drive and invest in national priorities,
(iii) a programme of innovation acceleration developing disruptive technologies,
(iv) a programme for training of highly productive people, and
(v) an investment in infrastructure for manufacturing, testing and standards.

[1] Links to tangible benefits are described in detail in response to Q4.
[2] EPSRC UK Metamaterials Network, EP/V002198/1
[3] KTN Commercialising Metamaterials Network, https://ktn-uk.org/materials/Metamaterials/

Together these strands, which are discussed in more detail in Q7, will support the effort across academia and business, the development of a highly productive technical workforce and national infrastructure to provide significant return on investment for UK plc. In this way, the UK Metamaterials Revolution will secure and strengthen our international standing to benefit from the 36.7% (CAGR) anticipated growth in the Metamaterials market[4], prosperity and jobs, and attract international investment.

Market intelligence suggests that the UK is positioned to provide high-growth potential within this overall global context. The current market for metamaterials is estimated to be £27M, with projected CAGR growth estimated to be 65% over the next 5 years – reaching a market size of £144M by 2026[4]. We estimate that this would be equivalent to growth in associated Gross Value Added (GVA) of around £48M over the next 5-year period[5]. The UK is projected to be the highest growth market within Europe, exceeding projected growth in both Germany and France. The latest market intelligence suggests that the UK could constitute around 14% of total global growth and nearly half of the projected European growth over the next 5 years.

These market projections are largely 'policy neutral'. They do not encapsulate the impact of any support landscape that may be put in place to support the development of UK metamaterials capability. For each additional 1% of projected global growth that the UK could capture over the near-term, this would be equivalent to an additional ~£8.3M output per year (or ~£3.5M in GVA). Clearly, the potential for strong returns (economic benefits) – even in the near-term – against public investment is significant. Even small increases in the UK share of projected growth in the metamaterial market could reap significant economic benefits. **As an illustration, if the UK were to offer an intervention, and as a result, able to generate higher growth and achieve 18% of global market share by 2026 (from a projected 14%) this would be worth an additional £45M in annual output by 2026. Considered over a 5-year period, this would equate to an additional £135M (non-discounted) in metamaterial-related UK output, or £55M equivalent GVA over this period (non-discounted).** When considered on a cumulative basis, potential benefits could quickly build over time if the support landscape positions the UK more competitively. Given that these are near-term projections/illustrations, then over the longer-term benefits could accumulate quickly – dependent on the strength of global demand, the ability of technology development to respond to that demand (supply) and UK's relative competitive position. This bid focuses on strengthening the latter, allowing it to exploit the opportunities as they arise.

Q4. WHY DOES THIS MATTER, AND WHAT IMPACT WOULD IT HAVE IF SUCCESSFUL?

WHAT WOULD THE 'BIG WIN' BE FOR THE UK IF THE IDEA IS REALISED AND WHAT OTHER BENEFITS CAN BE REALISED (BOTH SCIENTIFICALLY AND NON-SCIENTIFICALLY)? HOW IS THIS IDEA LIKELY TO LEAD TO SIGNIFICANT IMPACT E.G. THROUGH PEOPLE, KNOWLEDGE, SOCIETY, ECONOMY?

Note: Many of the opportunities and case studies described in this section and throughout the document have been contributed by the participants of the stakeholder-mapping activities that we have undertaken through the Metamaterial Network 'expert database', EPSRC UK Metamaterials Network events, KTN Commercialising Metamaterial Innovations events, and the extensive consultation meetings held with key opinion leaders from government, academia and industrial end-users. See *Appendix 2* *for more details.*

The scope of the UK Metamaterials Revolution spans numerous UKRI councils and multiple Governmental departments and drives cross-disciplinary thinking. The opportunities are manifold and ubiquitous. **The Metamaterials Revolution is an exemplar opportunity aligned to the Prime Minister's ambition for the UK to be "a Science and Tech Superpower by 2030"** with "S&T as an integral element of our national security and international policy" (Integrated Review of Security, Defence, Development and Foreign Policy, 2021).

[4] Markets and Markets, Metamaterial Market, https://www.marketsandmarkets.com/Market-Reports/Metamaterials-market-139795737.htm

[5] This has been derived by estimating the average Turnover: GVA ratio within those sectors that the CMRI industry partners working within – taken from the ONS Annual Business Survey

Moreover, at home, it supports the Government's plans to support economic growth through infrastructure, skills and innovation ("Build Back Better: our plan for growth", 2021). Metamaterials are recognised as playing an enormous part in safeguarding national security (National Security and Investment Bill, 2021) because of the importance of winning in the contested electromagnetic operating environment, underpinning success in all other operating environments (air, land, sea and space), including cyber.

The 'Big Win' for the UK will be to forge a pipeline of highly innovative technologies based on Metamaterials, backing an acceleration and long-term growth in this area, encouraging international investment and creating 1000's of highly productive high-tech design and manufacturing jobs. The Metamaterial market is predicted to grow at a CAGR of 36.7% over the next 5 years[4] and expected to reach $1,457M by 2026. As highlighted above, the UK is well positioned to benefit from this projected growth – with latest market intelligence-based projections indicating that it has the potential to be one of the fastest growing markets globally, and the fastest growth market within Europe. However, it is important that the UK positions itself to counter the competition that is developing elsewhere. For example, North America is expected to constitute approximately 55% of overall global growth over the next 5 years. This is just the tip of the iceberg: the technology will feed next generation and beyond products in economically important market sectors, with alignment to major national and international challenges (e.g. Net Zero). In this way the UK will drive to maximise its market share and technological impact on the world, whilst securing technological advantage and resilience in support of defence and national security in the short, medium and longer term. **Metamaterials is a top-table example of a ripe emerging technology opportunity across the full spectrum of UK policy aims identified by the *Integrated Review* and the *Plan for Growth*.**

Given appropriate investment, the UK can look forward to benefitting from the full potential of Metamaterials-enabled technologies and devices, benefiting a broad and impactful list of realistically achievable moon-shots with a strong overlap with global and national priorities. An extensive list of these moon-shots, collected via a comprehensive programme of stake-holder engagement undertaken during 2021, is summarised in Appendix 3. Examples include: securing the UK's food self-sufficiency; meeting carbon emissions targets and avoiding the continued depletion of natural resources and ongoing harm to the environment; and catapulting the shift towards safe, and emission free autonomous transportation.

> "BT's big infrastructure investments in the UK are the optical fibre network and the 4G/5G mobile network. Our main infrastructure concerns are to drive up these networks' capacity and coverage and to drive down energy consumption. The Big Idea goals are of direct interest to us, as applied to these fixed and mobile telecom networks."
>
> Fraser Burton, BT Research and Technology

In summary, Metamaterials provide the opportunity to address problems and deliver solutions that have not yet been considered. Strategic leadership and investment via a **National Observatory** to drive a vibrant UK Metamaterials sector is critical, overseeing the entire value chain, stimulating innovation, and accelerating progress in terms of the UK's economic, societal, and security position in the world.

Moreover, for the UK to be internationally competitive and credible as a science and technology superpower, it needs to broaden and dramatically increase the pace of uptake, demystifying this technology for industry, and lowering the perceived risk of adoption caused by gaps in skills, engineering, manufacturing and metrology capabilities (as evidenced repeatedly and strongly through the extensive consultation activities that have been conducted). A strategic investment in Metamaterials will see the UK at the leading edge of innovation in this disruptive and transformative field, fuelling these many application sectors.

Q5. WHY IS THE IDEA TIMELY NOW?

WHAT HAS CHANGED (IN THE DEVELOPMENT OF THE SCIENCE, IN THE RESEARCH LANDSCAPE, AND/OR THE POLITICAL LANDSCAPE) TO MAKE THE REALISATION OF THIS IDEA MORE ATTRACTIVE /

LIKELY OR POSSIBLE NOW? WHAT ARE THE RISKS FOR THE UK OF NOT SUPPORTING THIS OPPORTUNITY NOW?

Researchers from the UK have pioneered Metamaterials science over the past 20 years, with the earliest work focusing on artificial metallic behaviour, structurally induced magnetism, and 'negative index', where light bends or refracts in unusual and unexpected ways. The concept of an 'invisibility' cloak was perhaps the most famous indication of the disruptive properties that Metamaterials offer, which, while difficult to realise in its originally devised configuration, inaugurated a new Metamaterial design-led approach enabling almost unlimited possibilities for the bespoke control of wave propagation. The field expanded from the microwave regime, where lab-scale structures are relatively easy to fabricate, to photonics, thermal, acoustic, mechanical and even electrochemical and hydrodynamics. Now is the time for the UK to turn that work into new products and services that could change our lives, drive significant economic growth, and safeguard our environment and security.

The Metamaterials field continues to reveal novel fundamental science breakthroughs and drives step-change in our understanding, with implications for disruptive technologies. Seminal academic studies recently published illustrate the **strong international competition that the UK faces from North America and Asia**, which include: enabling the link between nanophotonics and spin electronics in topological insulators for ultrasensitive detection[6], metalens-array-based quantum sources[7], controlling thermal emission for radiative cooling and waste-heat recovery[8], and nano-architected low weight, high stiffness carbon materials for protective coatings and armour[9]. However, the UK has excelled across history for its creativity in physics, and in terms of scientific papers published in Metamaterials, we maintain a strong position (albeit it far behind China and the US, Appendix 4). Therefore, there is no doubt that we must continue to **invest in discovery science** in Metamaterials so that we can continue to reveal disruptive advances and concepts, stoking the innovation pipeline.

However, the UK is clearly lagging in the translation of the science into patents and commercial value. So, if we are to achieve credibility as a science and technology superpower, we must also invest **in more applied science and engineering research** to build the bridge to industry uptake, supported by policy coherence and direction from across HMG. **The UK is capable and fit to seize this opportunity**: there are strong indicators that commercial exploitation can flourish through examples of start-ups and spin-outs from universities and growing wider industry interest and uptake:

- Examples of academic push translating into embryonic businesses include: Sonobex (acoustic panels for noise reduction), Metaboards (wireless power and data transfer), KEF (metamaterial absorption technology for loudspeakers) and Mediwise (wireless medical diagnostics and monitoring, recently acquired by Metamaterial Technologies Inc), and VividQ (holographic displays).
- Examples of early stage industry pull include, WaveOptics (Waveguides for Artificial Reality, see Case Study box), Qioptiq (complex optronic modules, systems and products for defence and aerospace), Plextek (antennas), Teraview (terahertz imaging and spectroscopy for inspection and pharmaceuticals), Oneweb, Isotropic Systems and Phasor Solutions (satellite communications); QinetiQ (stealth), Artemis Optical (optical coatings to combat laser threats), META (photonics) and Leonardo MW (miniaturization of antennas and microwave components).

[6] Sun et al., Science Advances (2021), https://doi.org/10.1126/sciadv.abe5748
[7] Li et al., Science (2020), https://doi.org/10.1126/science.aba9779
[8] Xu et al., Science (2021), https://doi.org/10.1126/science.abc5381
[9] Portela et al., Nature Materials (2021), https://doi.org/10.1038/s41563-021-01033-z

CASE STUDY: Metamaterial enhanced Augmented Reality wearables and displays

The presence and impact of Metamaterials will be typically 'hidden inside the system' and cascade through the combination of multiple Metamaterials enabled components in a system or product, leading to unexpected and disruptive outcomes for the market and user.

An immediate high priority application for Metamaterials is in holography for Augmented Reality wearables and automotive head up displays (HUD). In both applications, the system needs the following multiple attributes, all being uniquely enabled by Metamaterial components within the system:

- Accurate 3D imagery - provided by the phase modulating Metamaterial
- High Field of View – possible in Metamaterials due to sub-wavelength feature sizes
- Extremely compact form factor display – Metamaterial displays would be relatively small and extremely power efficient, enabling consumer form factor wearables such as smart glasses and small volume HUDs, suitable for mid and low-end vehicles.
- High framerate and effective resolution – Metamaterials can give a much larger space/bandwidth product allowing for much higher quality and high contrast holographic images, a requirement for consumer AR and the automotive industry

The market for Augmented Reality (AR) smartglasses display hardware is forecast to be worth $8bn by 2025, and that for automotive HUDs market, $7.5bn. If this is expanded to general consumer display applications e.g. holodeck displays, smartphones etc, then the market is $293bn. This is a key area of investment for most major consumer electronics brands, big tech firms and automotive OEMs such as Google, Apple, Facebook, Samsung, Sony, General Motors, Nippon Seiki, etc. This is just one example, in one market! (At the time of writing, it has just been announced that the social media giant Snap Inc. is to acquire Oxford-based Wave-Optics who exploit Metamaterial technology within their waveguide components for AR devices, for $500M.)

The strategic imperative to act now also arises from rapid research advances that have recently further cemented the UK's potential for impactful innovation and growth. These are

(i) Development of novel theories, e.g., the seminal work on topological physics, and space-time modulated Metamaterials from Imperial College London[10];
(ii) Step change in efficient simulation, such as advanced mathematical modelling methods for acoustics and thermal systems[11], and optimisation methods, such as adjoint inverse design methods[12];
(iii) Emerging capability in advanced manufacturing fabrication (e.g. driven by the HVM and Semiconductor catapults, the Henry Royce Institute and University centres such as Nottingham's Centre for Additive Manufacturing, and Warwick's WMG);
(iv) A richness of societal, industrial, and national security challenges including supporting a reduction in emissions, sustainable resource management, access to new markets and security of supply.

[10] Examples include "Broadband Nonreciprocal Amplification in Luminal Metamaterials", Physical Review Letters (2019); "Negative Refraction in Time-Varying Strongly Coupled Plasmonic-Antenna–Epsilon-Near-Zero Systems" Physical Review Letters (2020) and "Homogenization theory of space-time Metamaterials", Physical Review D (2021).
[11] For example, "The Development of Novel High-Performance Advanced Microstructured Materials and their Associated Continuum Models", Professor W Parnell, University of Manchester (EPSRC Fellowship EP/S019804/1)
[12] For example, "Designing Collective Non-local Responses of Metasurfaces", Capers et al., University of Exeter, https://arxiv.org/pdf/2011.13274.pdf

Prioritising and investing in Metamaterials today helps the UK meet many of the recently set Government targets, so the UK becomes a S&T superpower, attracts talent to the research sector through relevant training, better attracts domestic investment (and utilises HMC VC mechanisms), mindfully encourages international investment, creates highly productive jobs in research and enterprise, and reaches the 2.4% R&D target.

Furthermore, Metamaterials will contribute to the UK's *Ten Point Plan for a Green Industrial Revolution* by developing new technologies to reduce our imprint on the environment, such as metasurface coatings on wind turbine blades to reduce radar clutter; pushes towards efficient, autonomous connected vehicles; reducing the greenhouse gas and noise emissions from air and maritime transport, and creating passive systems for energy efficient cooling of buildings. Metamaterials represent a critical and transformative implementation of *Advanced Materials*, highlighted explicitly within the UK Government's recent policy paper "*UK Innovation Strategy: Leading the future by creating it"*[13], and there are hotspots of excellence in research and innovation across academia and business in every part of the UK (see Appendix 1, table 1.1).

Progress in the USA and China already demonstrate strong market potential for Metamaterials but their strategic importance to the prosperity and security of each leading nation, <u>means that the UK cannot rely upon the sharing of international expertise and market access.</u> Other nations are using Government funding to drive disruptive science, with China (world-leading for patents, Appendix 4) demonstrating a particularly strong quest to become a global innovation powerhouse. Indeed they have been playing an increasingly active role in setting international standards (Belt and Road Initiative) to monetize technological innovation and shape new technologies. **The risk of doing nothing is clear for the UK and the West - the future technologies and standards that underpin our economy and security will no longer be within our own control**, described as a "moment of reckoning" by GCHQ Director Jeremy Fleming[14]. As a specific example, the debacle over the removal of Huawei's 5G technology from the UK. The Prime Minster wrote "We made no particular effort to develop 5G, for instance, and we have paid a price"[15] – it is predicted to cost £2bn in hardware replacement alone, but the delay to the 5G roll-out is predicted to represent a loss to the UK economy of up to £36bn over 5 years[16].

The UK has a lot to do, highlighted by North America's successful capture of nearly 70% of the current Metamaterial market in 2021[4]. Whilst market-intelligence based projections suggest that Europe and particularly the UK has the potential to erode this market dominance, the appropriate support needs to be put in place. It may not be a coincidence that recent commercial activity in the US has followed a manufacturing sector analysis[17] and analysis of the competition risks from China[18]. Today, US industry perhaps understands the benefits of Metamaterials better than any other nation: during 2021 we have seen the acquirement of Oxford-based WaveOptics by Snap ($500M), the first NASDAQ-listing of a Metamaterials company (META) and a Bill Gates backed venture-fund ($100M) launched to invest in start-ups commercialising Metamaterials (MetaVC). In addition, there is clear industry recognition of the opportunity (e.g. AMS, ST-Micro, Intel, Applied Materials, UMC). The potential winnings are huge: market surveys are predicting that, in as little as 10 years, the Metamaterial market will grow to $5bn-$10bn[19] and based on this, we conservatively estimate that Metamaterial-enabled hardware will be worth beyond $50bn by 2030. The UK could capture a significant

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[13] Department for Business, Energy & Industrial Strategy, page 86, July 2021 (https://www.gov.uk/government/publications/uk-innovation-strategy-leading-the-future-by-creating-it)
[14] Vincent Briscoe Annual Security Lecture 2021, https://www.gchq.gov.uk/news/2021-vincent-briscoe-lecture
[15] "We're restoring Britain's place as a scientific superpower" https://www.gov.uk/government/speeches/prime-ministers-article-in-the-daily-telegraph-21-june-2021
[16] "The real cost of removing Huawei from the UK 5G roll-out", https://www.trippassociates.co.uk/the-real-cost-of-removing-huawei-from-the-uk-5g-roll-out/
[17] Metamaterials Manufacturing: Pathway to Industrial Competitiveness, MForesight, 2018, http://mforesight.org/projects-events/metamaterials/
[18] US-China Economic and Security Review Commission, 2019 Annual Report to Congress, Chapter 3, Section 2: Emerging Technologies and Military-Civil Fusion: Artificial Intelligence, *New Materials*, and New Energy, https://www.uscc.gov/annual-report/2019-annual-report-congress
[19] For example, Lux Research 2019 (http://ex.ac.uk/bSc); Market Research Engine 2019 (http://ex.ac.uk/bSd)

percentage of that, if we are able to avoid selling off spinouts to foreign investors, who subsequently move production overseas.

The UK has one of the world's largest technology ecosystems with thousands of tech start-ups, built around a strong entrepreneurial culture. But without creating a strong research and innovation ecosystem in Metamaterials now, the UK will not be in a position to access new markets and may lose its share of important existing markets at an unexpected rate.

Q6. WHAT IS THE CURRENT INVESTMENT LANDSCAPE, BOTH IN THE UK AND GLOBALLY AND HOW DOES THE IDEA RELATE TO THESE OTHER PRIORITIES IN THE UK LANDSCAPE?

DOES THE UK CURRENTLY HAVE THE CAPACITY AND INFRASTRUCTURE NEEDED TO ADDRESS THIS OPPORTUNITY? DESCRIBE THE INTERNATIONAL INVESTMENT LANDSCAPE AND THE UK'S POSITION IN RELATION TO THIS OPPORTUNITY HOW DOES THE IDEA FIT WITH OTHER CURRENT UK STRATEGIC INVESTMENTS AND PRIORITIES?

UK academic institutions excel in the global landscape in terms of fundamental Metamaterials science (Appendix 4), supported by relatively large (£1M+) investments from EPSRC in areas that include biomolecules and plasmonic Metamaterials[20], 3D Metamaterials[21], photonic metadevices and metasystems[22], biological Metamaterials for noise control[23], as well as closely related programmes that include key Metamaterial aspects, e.g. photonic manufacturing[24] nanophotonics metrology[25], and the electromagnetic and acoustic materials Prosperity Partnership[26] with QinetiQ. Furthermore the UK is making initial steps to train and upskill its workforce (e.g., via the EPSRC Centres of Doctoral Training at Exeter[27] and Birmingham[28] and the recent KTN[3] and EPSRC[2] Metamaterial Networks). In total, UKRI has funded projects associated with Metamaterials of value £49M, with £42M from EPSRC and £1M from Innovate UK[29].

Our academic institutions are hugely productive and creative, providing a pipeline of qualified work force through PhDs, generating papers that position the UK 3rd globally (Appendix 4), but they are of-course focused on low-TRL work. Our RTOs (Research and Technology Organisations), on the other hand, such as NPL and TWI are technology/product focussed and while they recognise and are aware of the benefits of Metamaterials (e.g., for efficient 5G antenna systems, or metasurfaces to reduce radar clutter from wind turbines), they lack critical mass to accelerate innovation and commercialisation, and the ability to validate performance of Metamaterial devices.

Given the maturity of some aspects of Metamaterial science, and its huge potential for disruptive evolution of technology, its noteworthy that its commercial exploitation has been weak in comparison to the US (£1M funded through Innovate, $27M via the US seed fund schemes, since 2016). In contrast to what is emerging in the US (see Q5), the opportunity to fully exploit the growing Metamaterials market is not recognized and understood in the UK, and so is not connected: the outcome is left to chance and the academic strengths are open to exploitation by global competitors. **The start-ups that we should be nurturing ourselves are instead relying on foreign investment - meaning the UK does not fully realise the economic impact of its investment in academic strength.**

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[20] Meta-Smart: Merging de novo designed biomolecules with plasmonic Metamaterials for new technologies, EP/S029168/1
[21] SYnthesizing 3D METAmaterials for RF, microwave and THz applications (SYMETA), EP/N010493/1
[22] The Physics and Technology of Photonic Metadevices and Metasystems, EP/M009122/1
[23] Biological Metamaterials for enhanced noise control technology, EP/T002654/1
[24] National Hub in High Value Photonic Manufacturing, EP/N00762X/1
[25] Next Generation Metrology Driven by Nanophotonics, EP/T02643X/1
[26] TEAM-A: The tailored electromagnetic and acoustic materials accelerator, EP/R004781/1
[27] EPSRC Centre for Doctoral Training in Electromagnetic Metamaterials, EP/L015331/1
[28] EPSRC Centre for Doctoral Training in Topological Design, EP/S02297X/1
[29] As a comparison, in the US, the figure is $133M (NSF $106M, with $27M from the SBIR/STTR seed funds).

The EPSRC and KTN Metamaterial Networks were established because a community with critical mass was recognised in the bid submissions, and these networks are now demonstrably mobilising the existing community to address grand challenges, enable upscaling and accelerate towards the initial commercial opportunities. In this way they are validating the value proposition, and revealing the detailed evidence supporting further coordinated and targeted interventions. Their early activities have confirmed that the UK will be unable to maximize future opportunities and strengthen the value of its academic excellence without a very significant coordinated effort accompanied by an uplift in investment in people and facilities. Key messages identified from community engagement activities have highlighted a lack of understanding by end-users of the functionality and performance-benefits that Metamaterials can offer, the need to develop Metamaterials manufacturing technology at scale, the need for metrology and standards, and the difficulty in accessing the ability to model Metamaterial performance. To address the first, the KTN Metamaterial Network are running a number of focus groups to demystify Metamaterials across targeted application and technology sectors (e.g., Sensing; Aerospace and Aviation; Automotive), and are engaging the leading bodies and organisations in these areas to connect Metamaterials to their present needs and challenges (Appendix 5 – KTN report).

> "The main challenge for UK plc is to make people aware of what Metamaterials are and can potentially do – there is little appetite for risky unknowns"
>
> Prof Chris Lawrence, R&D Lead, QinetiQ

The UK Government recognised the importance of the science and technology of advanced materials and their manufacturing by establishing the £235M **Henry Royce Institute**, the £128M (core grant) **High Value Manufacturing Catapult** (HVMC) and the £50M **Compound Semiconductor Applications Catapult**, however there is currently no unifying strand to target Metamaterial development, training, scale-up facilities or metrology. The challenges facing successful scale-up within UK borders are particularly difficult, not simply for mass-production of devices, but for the production of large area Metamaterials, and Metamaterials suitable for integration in the net shape of real products and situations.

BEIS see emerging technologies around Advanced Materials including Metamaterials as a key part of the UK's future Innovation Strategy and MOD identified Advanced Materials as one of seven key technology families in the Defence Technology Framework 2019, with Metamaterials recognised as playing an enormous part in safeguarding national security (National Security and Investment Bill, 2021). The MOD Science and Technology Strategy describes how the UK must integrate emerging technologies into generation-after-next (GAN) capabilities to give our nation a decisive edge in the future, and an ambition of this Big idea is to ensure the UK has access to supply chains supporting these GAN outputs, because of the clear dual-use nature of Metamaterial-enabled technology.

Beyond the UK, the commercial significance of Metamaterial devices is underlined with some 25 Metamaterials product developers having received >$300 million in recent investment[30]. Very recently, Meta Materials Inc., a developer of high-performance functional materials and nanocomposites, became the first NASDAQ-listed Metamaterials company, and Metalenz, a start-up from Harvard, gained $10M investment to develop wafer-thin chips for the control of light (and a subsequent $7M upfront for manufacturing contract with the European semiconductor foundry, ST-Micro). While the first examples of UK Metamaterial innovations are starting to gain commercial traction[31], it is informative to understand that internationally, state-funded labs and industry

[30] As of 2018, https://www.prnewswire.com/news-releases/global-market-for-Metamaterials-to-2030-300728569.html. A review of public, venture-backed startup investments shows on investigation close to 60 companies (activities in larger companies is not searchable) [Pitchbook search carried out using the term "Metamaterial" in Q1 2020].

[31] e.g. Metaboards wireless energy transfer, Sonobex acoustic absorbers, TeraView THz imaging and sensing, META's laser glare protection and glucose monitoring products.

are taking the lead, with the US and China dominating in terms of publications, citations, and intellectual property. The Chinese government has funded the world's first large-scale Metamaterial fabrication facility[32], with capacity for 100,000 m^2 of Metamaterial plates annually, serving aerospace, communication, satellite and military applications. This and other interventions (e.g., semiconductor development fund) shows the extent to which state financial resources are being utilized in China's quest to become a global innovation powerhouse. China's rapid acceleration to dominate Metamaterials publications infers intent too in this emerging opportunity, noting also the relevance to future generations of telecommunications technologies beyond 5G and exploiting Low Earth Orbit links.

Q7. WHAT WILL IT TAKE TO DELIVER THIS BIG IDEA?

WILL THIS IDEA GALVANISE COMMUNITIES TO WORK TOGETHER TO REALISE THE OPPORTUNITY PRESENTED? HIGHLIGHT THE UNDERPINNING RESEARCH CHALLENGES THAT ARE REQUIRED TO SUPPORT THE REALISATION OF THIS OPPORTUNITY WHO ELSE WOULD BE INTERESTED IN SUPPORTING THE INITIAL DEVELOPMENT OF THIS IDEA? WHAT ARE THE POTENTIAL PATHWAYS AND MECHANISMS TO ACHIEVING THE IMPACT DESCRIBED PREVIOUSLY? GIVE AN INITIAL INDICATION OF THE EXPECTED TIME TO DELIVERY (IN YEARS) AND SCALE OF INVESTMENT REQUIRED TO DELIVER THIS IDEA.

The Metamaterial Revolution brings together common concepts, understanding, and expertise from across multiple domains and length scales to enhance UK sustainability, prosperity and security in the transport, communication, electronics and photonics, infrastructure, energy and healthcare sectors. **Delivering the Revolution will require substantial programmes of investment, spanning disciplines and funding councils, encompassing training and technology translation, with investment from cross-Government, industry and academic sources to continue fundamental research and commence much more applied research.**

Metamaterial research and innovation bridges the (i) *Physical Sciences*, (ii) *Engineering*, and (iii) *Manufacturing the Future* themes within EPSRC with a core requirement for world-class capability in modelling and simulation methods, and with infrastructure for material and device fabrication, and metrology. However with relevant topics and associated applications as wide ranging as control of turbulence, diagnostic healthcare imaging, analogue computing, AI-inspired Metamaterial design, energy harvesting, autonomous systems, efficient sensors, protection of sovereign assets, electronic-human interfacing, wireless communication, and quantum devices, **Metamaterials have relevance to all of EPSRC's research themes**.

The high level of engagement and enthusiasm demonstrated by participants of the UK Metamaterials Network are proof that the UK community is ready to galvanise around this opportunity. The industry partners within the Network are highly significant commercial entities in their own right – with an estimated combined annual operating revenue of around £77bn (equivalent to ~£32bn in GVA per annum) and employing approximately 296,000 people[33]. Metamaterials currently only represents a very small fraction of this commercial activity, but clearly through their engagement and involvement in the Network the industry partners recognise the potential offered through metamaterial development – either through direct development or applications within their core business. The combination of research expertise, the mobility of SME partners and the commercial reach (and potential demand for applications) of the large industry partners will provide impetus for the development of the UK sector.

We have consulted with researchers and stakeholders widely, through workshops, seminars and interviews, encompassing industry, government, UKRI, RTO's and academia (Appendix 1 and 2). The key message is clear: **Metamaterials are a disruptive technology enabler** – they provide a new degree of freedom to manipulate the way we create materials, devices and coatings to interact with the energy and information in the world around us. The Metamaterials Revolution focusses on the development of a strategy and implementation of an action

32 http://www.kuang-chi.com/en/

33 Estimated using latest annual financial figures taken from FAME UK – Bureau Van Dijk

plan capable of exploiting the significant potential within the UK to establish a thriving research and industrial base. The **transformative challenge** is to demystify Metamaterials technology, deliver the application of Metamaterials across a wide range of markets sectors to increase device functionality and practicality, create a clear path to scale up in manufacture, and train a highly productive pool of skilled people, while providing a reduction in the environmental burden and financial cost compared to conventional technologies.

This Big Idea will deliver the Metamaterial Revolution via three key strands, embedded within a creative and agile research environment that allows fundamental science and engineering to flourish and which is essential to allow for a full pipeline of new and future technologies to feed commercial exploitation in later years.

The first strand is **Research and Communication**, in terms of understanding the value proposition that Metamaterials provide, i.e. continuing to invest in fundamental science and then promoting to end users the advances that the Metamaterial technology offers, as well as bringing together the UK academic community to discover practical solutions for the challenges they face.

The second strand is **Training and Infrastructure**. The complex and diverse Metamaterials supply chain represents such a paradigm shift that specific focus is needed to create an effective industry pull, which is only achievable through the role of trained people. Here the UK needs to develop diverse talent pool of scientists and engineers to play leading roles in industry and academia, trained to discover and exploit novel functionality across the breadth of Metamaterial opportunities, while also of creative and entrepreneurial mindset to solve impactful challenges and develop new high-value products and devices. This strand also includes *Manufacturing Innovation and Metrology*. There is much to be done to document the UK capability across industry, RTO, governmental agencies and industry, to identify the gaps and unearth new opportunities to develop the state-of-the-art. In Metrology, there is currently no representation of Metamaterials within the UK's National Measurement System (NMS), and so a focus on the development of Metamaterial measurement methods and standards that designers need to shape new technologies and engineer competitive products is essential

> "There is a need is to bridge the gap in funding between concept and prototype. Many of the businesses that would benefit from Metamaterials, and which have R&D budget, require compelling demonstrations [in order] to invest. On the other hand, without initial investment, it is difficult to produce the required demonstrations. To enable scale-up to industrial level, we require methods to efficiently and cheaply prototype new consumer/mass market devices to quickly test new ideas and showcase to relevant businesses"
>
> Darran Milne, CEO @ VividQ

The third strand is **Strategic Leadership**. Delivery of the Metamaterials Revolution will be based around strategic leadership and a purposeful innovation ecosystem, drawing upon existing centres of excellence and creating new academic-industry-government partnerships establishing and exercising critical mass in the regions. Investment needs to be targeted here with an emphasis on linking the continued discovery of new physics, the translation of this science into engineering and manufacturing, the application of the technology to devices, the scale up, and commercial exploitation of systems and products.

Mechanisms for delivering the vision for the Revolution during the first 5 years include:

- A programme of **Core Research** (£40M) to advance capability and understanding across fundamental science, engineering, digitalisation of design and advanced manufacturing, funded through Fellowships, Centres of Excellence and targeted calls.
- A UKRI **Metamaterials Observatory** (£40M from Government/ARIA/MOD). The Observatory will provide strategic leadership of a vibrant UK Metamaterials community to meet the needs of national priorities and security and overseeing the entire value chain. It will coordinate direct investment to

accelerate progress towards disruptive technologies and moonshots of national importance (e.g. see Appendix 3).

- **Industrial Take-Up Acceleration** via a £60M fund (1:1 match to encourage early stage institutional or strategic investment), to support SMEs and start-ups, and a Metamaterial Innovation and Knowledge Centre (IKC) to drive rapid translation of disruptive research across the TRL "valley-of-death".
- **Developing the Future Workforce** in Metamaterial science, technology translation, and advanced manufacturing (£20M). From PhDs in CDTs with embedded entrepreneurship, to Enterprise Fellowships (similar to those of the Quantum Technology Enterprise Centre) and conversion courses for product-design and upskilling industry R&D engineers.
- Investment in **Infrastructure** (£40M) targeting (i) manufacturing across length scales, linking with the Henry Royce Institute and the HVM Catapult to focus on sample fabrication, prototyping and UK-based scale-up; and (ii) characterisation and metrology, setting standards and benchmarking, linking with NPL to develop a national centre to provide the expertise and facilities needed for academia and industry to test, validate, and accelerate early take-up in new technologies.

The cross-disciplinary nature of this challenge requires a strategic collaborative approach ideally suited to and coordinated by UKRI, with support from cross-government sources, industry and academia. Our model proposes a new normal, spanning TRLs across R&D and Innovation, aligned with a cultural change to enhance national strategic advantage in concert with being a global S&T superpower. It will require significant resource; we estimate ca. £200M over the first 5 years from UKRI, and Government (e.g. ARIA, MOD) as the primary funders, with match from industry and HEIs. It will establish and drive the purposeful ecosystem to embed the path, capabilities and intent into the DNA of the UK research and industrial base, supporting the effort across academia and business, and the development of a highly productive technical workforce and national infrastructure to provide a strong return of investment.

Q8. WHICH OF THE FOLLOWING DOES THIS IDEA FIT WITH? (YOU MAY SELECT MULTIPLE BOXES):

☒Industrial Strategy Challenge Fund

☒Fundamental Research

☒Multidisciplinary

If multidisciplinary: what are the relevant disciplines? Is it multidisciplinary just across the EPS disciplines or across other Research Council remits too? (maximum 50 words)

The most relevant EPSRC themes are Engineering, ICT, Manufacturing the future, Physical sciences, with links also to AI and robotics, Energy, Healthcare technologies, Mathematical sciences and Quantum technologies.

In terms of EPSRC research areas, the key ones include: condensed matter: electronic structure, Condensed matter: magnetism and magnetic materials, Continuum mechanics, Displays, Engineering design, Fluid dynamics and aerodynamics, Graphene and carbon nanotechnology, Light matter interaction and optical phenomena, Manufacturing technologies, Mathematical physics, Music and acoustic technology, Optical communications, Optical devices and subsystems, Photonic materials, RF and microwave communications, RF and microwave devices, Sensors and instrumentation, Solar technology, and Spintronics.

This Big Idea is also closely allied to the Innovate UK priority area "Mobility, manufacturing and materials", and existing Industry Strategy Challenge Funds[34] .

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[34] Driverless cars, Faraday battery challenge, From data to early diagnosis and precision medicine, Healthy ageing, Leading-edge healthcare, Manufacturing and future materials, Prospering from the energy revolution, Quantum technologies

There is also strong relevance across BBSRC, MRC, STFC, and ESRC.

Q9. WHO HAS BEEN INVOLVED IN THE DEVELOPMENT OF THIS BIG IDEA?

This document has been developed by Prof Alastair Hibbins and Dr Anja Roeding (University of Exeter), Dr Owen Lozman (M Ventures, Amsterdam) and Prof Ian Youngs (Dstl). Following submission of the original version considered by SET-B in September 2020, they welcomed the opportunity to review an updated submission, advising that the team should clarify the scope, undertake a mapping exercise of existing work and relevant stakeholders, identify the high priority application areas and link the theory of the area to manufacturing and engineering. In producing the current document we have consulted widely by crowdsourcing information from the membership database of the EPSRC Metamaterials Network, and we held a number of workshops and discussion meetings (Appendix 2.1) as part of the EPSRC and KTN network programmes. A number of influential figures agreed to review this document, and they are named in Appendix 2.2.

Q10. LEAD CONTACT DETAILS

Details	Academic Lead	EPSRC Lead
Name:	**Prof Alastair Hibbins**	**Dr Alexander Broomsgrove**
Department:	**Physics & Astronomy**	**Advanced Materials**
Organisation:	**University of Exeter**	**EPSRC**
Email Address:	**a.p.hibbins@exeter.ac.uk**	**Alexander.broomsgrove@epsrc.ukri.org**

Q11. IS THERE ANY ADDITIONAL INFORMATION THAT IS RELEVANT TO YOUR APPLICATION THAT EPSRC STAFF AND THOSE WHO ARE PART OF THE DECISION-MAKING PROCESS SHOULD BE MADE AWARE OF, SUCH AS A CONFLICT OF INTEREST OR RELATED SUBMISSIONS.

The Big Idea was mentioned to the Institute of Physics for consideration as part of their “Transformative Physics Research” call.

NOTE FROM EPSRC ADVANCED MATERIALS TEAM

This paper has been shared across EPSRC and with BBSRC, ESRC, Innovate UK and across DSTL (See Appendix 6 for a supporting statement).

EPSRC: James Draycott, Lydia Gardner, Jim Fleming

ESRC: Sarah Keynes, Louise Richards, Susie Stevenson

BBSRC: Lee Beniston, Dave O’Gorman, Laura Pritchard

Innovate: David Elson, Neil Witten

- ESRC have highlighted links to their Living with Technology strategic programme and have highlighted potential to align with SPF NICER programme and NET Zero priorities. ESRC see regulation and market models as key angles from a social science perspective with investigations into management practices, business models, financing and regulations, standards, policy implications with the opportunity for co-innovation with users.

- Innovate UK have noted this as an area of interest as it develops, with specific links to the KTN Special Interest Group on Metamaterial Innovations.

- BBSRC have noted interest and are keen to engage with EPSRC while proposals are developed.

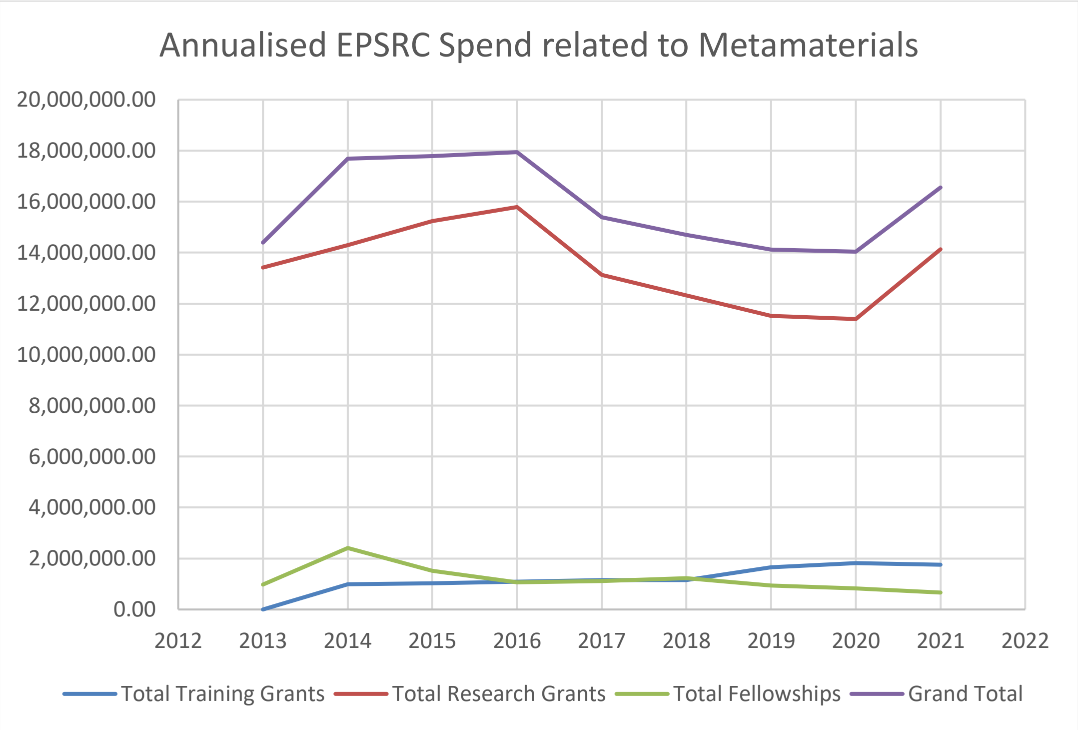
- Although this paper has not been shared with departments more widely, there may be cross departmental support from the Home Office, Department of Housing, Communities and Local Government, Department for Business, Energy & Industrial Strategy, the Department of Transport, Foreign, Commonwealth and Development Office and the Centre for the Protection of National Infrastructure.

The potential for Metamaterials to deliver advances across a wide range of application areas (Appendix 2.3) means that capability in this area has the potential to address pressing research challenges across both UKRI and a number of government departments:

  - ***Ministry of Defence*****,** who seek for Defence Primes to exploit Metamaterials in sensing, communications and advanced electronic defence systems, understanding appropriate supply chains which would grow most successfully through dual-use and civil applications;
  - ***Home Office*** (e.g. security and anti-counterfeiting);
  - ***Ministry of Housing, Communities & Local Government*** (e.g. modern housing);
  - ***Department for Transport*** (e.g. environmental noise).
  - ***Foreign, Commonwealth and Development Office*** in relation to: UN Sustainable Development Goals, Net Zero, Multi-lateral Export Control Regimes, Counter Proliferation and other fora relating to international norms and behaviours.

Across the UKRI landscape: *EPSRC* and *Innovate* UK are links; *BBSRC* (e.g. Physics of Life); *ESRC* (e.g. quality of living and working environments, productivity, green economy); *MRC* (e.g. disease diagnosis); STFC (e.g. astronomical imaging).

The chart below shows annualised EPSRC spend on Metamaterials related research (found by search for grants in the portfolio with the key word metamaterials in title, abstract, objectives and beneficiaries within the EPSRC dataset). The graph shows a very flat profile for what is a fast-emerging area of research as evidenced by the rapid increase in publications and patents shown in Appendix 4. There are currently 53 active research grants that mention metamaterials and of these only 14 have a reporting value greater than £1M this is insufficient to create more than pockets of progress in the landscape.



APPENDIX

APPENDIX 1 - STAKEHOLDERS

Table 1: Stakeholder organisations registered with the publicly available UK Metamaterials Network database (data as of 1 July 2021)

Organisation type	Organisation name
Academia	Bangor University
Academia	Cardiff University
Academia	Durham University
Academia	Henry Royce Institute
Academia	Heriot-Watt University
Academia	Imperial College London
Academia	King's College London
Academia	Lancaster University
Academia	Loughborough University
Academia	Manchester Metropolitan University
Academia	Newcastle University
Academia	Northumbria University
Academia	Queen Mary University of London
Academia	Queen's University Belfast
Academia	Robert Gordon University
Academia	Sheffield Hallam University
Academia	University of Bath
Academia	University of Birmingham
Academia	University of Bolton
Academia	University of Bristol
Academia	University of Cambridge
Academia	University of Durham
Academia	University of Edinburgh
Academia	University of Exeter
Academia	University of Glasgow
Academia	University of Huddersfield
Academia	University of Hull
Academia	University of Kent
Academia	University of Liverpool
Academia	University of Manchester
Academia	University of Nottingham
Academia	University of Oxford
Academia	University of Salford
Academia	University of Sheffield
Academia	University of Southampton
Academia	University of St Andrews
Academia	University of Surrey
Academia	University of Warwick
Academia	University of Wolverhampton
Academia	University of York
GPO*	AWE
GPO*	DSTL
GPO*	KTN
GPO*	Met Office
Industry	Advanced Material Development
Industry	Ampode
Industry	Atlas Elektronik UK
Industry	BAE Systems
Industry	BT
Industry	Cadence
Industry	CDT Ltd
Industry	Chelton

Table 2: Additional stakeholders registered for KTN Metamaterials events in 2020/21

Organisation
2x3D Ltd
4D-Dynamics.Net
7Th Design & Invention
Aci, Lsbu
Ad Network
Adaptive Communications Team Ltd
Added Scientific Limited
Advanced Propulsion Centre UK Ltd
Advancing Innovations Ltd
Aedstem Limited
Aerospace Engineering
Airbus Limited
Alta Innovations
Andrew Griffiths Limited
Ansys UK Limited
Anywherehplc
AR UK
Artemis Optical Limited
Artis
Bailrigg Diagnostics Limited
Bank of England
Barron Gould Limited
Bcast Ltd
BDE Space limited
BEKO Plc
Bespoke Orthopedics
Biaccon
BIC Innovation Ltd.
Big Urban Data Centre
Biotec Ltd
Boult Wade Tennant Llp
C1 Net (BBSRC-NIBB)
Cambridge Display Technology Limited
Cambridge Enterprise Limited
Christ Lefteri Design Limited
Cip Technologies Ltd
CSA Catapult Limited
Corporate Intelligence Ltd
Crover Ltd
CSMA Limited
Dassault Systems UK Ltd
e4 Structures ltd
East Midlands Transport Inet
Elif Global Packaging
E-Step Limited
Fiberlean
Finden Ltd
Flamingo Engineering Limited
GKN Aerospace Systems
Hamamatsu Photonics UK Limited
Health Enterprise East Limited
High Value Manufacturing (HVM) Catapult

Industry	Darwin Innovation Group
Industry	Electrosciences ltd
Industry	Excelitas
Industry	GE
Industry	Hamlyns Technology Ltd
Industry	Hy-Met Limited
Industry	Jaguar Land Rover
Industry	Leonardo UK Ltd
Industry	M Ventures (Merck)
Industry	MBDA UK
Industry	META
Industry	Metaboards
Industry	Metamaterial Inc (META)
Industry	Murata
Industry	Optomel Ltd
Industry	Oxford Instruments Plasma Technology
Industry	PepsiCo
Industry	Pilkington (NSG Group)
Industry	PlanOpSim NV
Industry	Plextek
Industry	PragmatIC
Industry	Pyreos Ltd
Industry	QinetiQ
Industry	Sumitomo Chemical
Industry	Synopsys
Industry	Technical Composite Systems Ltd
Industry	Vickers Venture Partners
Other	Business West
Other	Potter Clarkson LLP
RTO*	Centre for Process Innovation (CPI Ltd)
RTO*	Metaboards
RTO*	National Physical Laboratory
RTO*	TWI Ltd

*RTO = Research and Technology Organisations, GPO = Government or policy organization

Figure 1: Visualisation of the UK Metamaterials network member locations. Blue: academia, red: industry; green/yellow/grey: other. (As of 15 July 2021)

Honeywell Limited
Horiba
Huawei R&D Centre in UK
Iconiq Innovation Ltd
Immaterial Labs Ltd.
Immortalight
Inclusive Designs Ltd
Innomarket
Innovlab Ltd
Institute for Capitalising on Creativity
Intellidigest Ltd
Invest Northern Ireland
IQ Capital
IQE Plc
Iris Advanced Engineering
Ixion Limited
Just Great Products Limited
Lumentum Inc
Malvern Optical Limited
Marine Resource Management Ltd
MAS Design Products Ltd
Materials Industry Consulting Limited
Metasonixx
National Composites Centre
Nicholas Jones Associates Ltd
Nuclear AMRC
Opsec Ltd
Optical Ink
Optomel Limited
Oxford RF Solutions Ltd
Petec
Plant Integrity Ltd
Praxis Networks Limited
Precision Acoustics
PRFI Limited
Pyreos
Rheon Labs
Rothamsted Research
Satellite Applications Catapult
Scottish Enterprise
Semitronics Limtes
SETSquared Partnership
Sony Computer Entertainment
Stellar Advanced Concepts Ltd
Synbiosys
Tata Steel UK Ltd
The Imagination Factory Ltd
The Last Puzzle Piece Limited
Transtekniq Limited
Vendevco Ltd
Wave Optics Limited
Welbury Consulting
Welwyn Business Services Ltd

2.1 SCIENTIFIC COMMUNITY EVENTS

In June/July 2021, the UK Metamaterials Network ran multiple events to discuss challenges and opportunities for Metamaterials in the UK.

Some specific and overarching challenges highlighted by the community are:

Manufacturing: lack of infrastructure to manufacture (e.g. nanoimprint at large scale; tuneable surfaces; additive manufacturing at scale as well as manufacturing for large area MM with complex shapes); lack of capacity to build prototypes to give confidence of proof-of-concept; lack of feasibility studies; lack of confidence in the effectiveness of the existing Catapults; need for insights to integrating MM into established products/manufacture

Measurements: lack of standards for e.g. free-space calibration >110GHz; mitigating magnetic effects); lack of a central database and point of contact to list and facilitate access to existing measurement facilities and their specifics (minimising duplication, enabling collaboration) across the UK

Innovation: A barrier to academic/industry engagement and innovation are classification/IP restrictions; lack of shared language and understanding in the field; lack of industry staff upskilling opportunities within academia; facilitation of engagement to other life sciences and medical;

Table 3: Examples of community engagement events (along with the number of contributors) that were used to identify capabilities and barriers for Metamaterials innovation and exploitation in the UK up to June 2021.

Activity type	**Activity title / details**	**Delegates**
Briefing	Defining a value proposition for Metamaterials	62
Webinar	Scaling up and commercialising Metamaterials	78
Workshop	Metamaterials Applications and Manufacturing	98
Webinar	Metamaterials Applications and Manufacturing	135
Webinar	Metamaterials for design	68
Showcase event	Flexible and conformable metasurfaces	63
Showcase event	Metamaterials session at Defence Materials Forum	91
Showcase / group work	Metamaterials manufacturing on the micrometer to millimeter length scale	59
Showcase / group work	Metamaterials manufacturing on the millimetre length scale and above	49
Discussion group	Microwave/wireless Metamaterials measurement capabilities and challenges	30
Discussion group	Metamaterials for rf low observability	25
Discussion group	Tuneable metasurfaces in the microwave to thz domain	48
Discussion group	Microwave scatterers for radiation shaping and chipless identification	46

2.2 KEY CONSULTEES FOR THE BIG IDEA

Table 4: Key Consultees for the Big Idea.

Organisation	Consultee	Role
BT Group plc	Fraser Burton	Head of University Partnerships
Centre for Process Innovation	Alf Smith	Business Development Manager
Harvard University	Federico Capasso	Professor of Applied Physics
Hebrew University	Uriel Levy	Professor of Applied Physics
Henry Royce Institute	Dave Knowles	CEO
HVM Catapult	Mike Hinton	Director of Research and Technology Partnerships
Intel Capital	Jennifer Ard	Managing Director
IOP	Louis Barson	Director of Science, Innovation and Skills
Leonardo	John Innes	Vice President of Technology; Chairman of the Scottish Space Leadership Council
Lumotive	Gleb Akslrod	CTO
Metaboards	Dennis O'Donovan	VP Operations and Supply Chain
Metalenz	Rob Devlin	CEO
Metamaterials Inc	Jonathan Waldern	CTO
MetOffice	Ed Stone	Observations Scientist
National Physical Laboratory	Fernando Castro	Head of Science (Materials)
Rolls-Royce	Al Lambourne	Materials Research Engineer
Rolls-Royce	Neil Glover	Head of Materials
VividQ	Darren Milne	CEO

2.3 CROWD-SOURCING OF METAMATERIALS APPLICATIONS AND MARKET SECTORS

The data below is the result of an analysis of approximately 140 individual user responses from UK Metamaterials Network members. The individual submitted these responses as part of their profile entries on the publicly available UK Metamaterials 'expert database'.

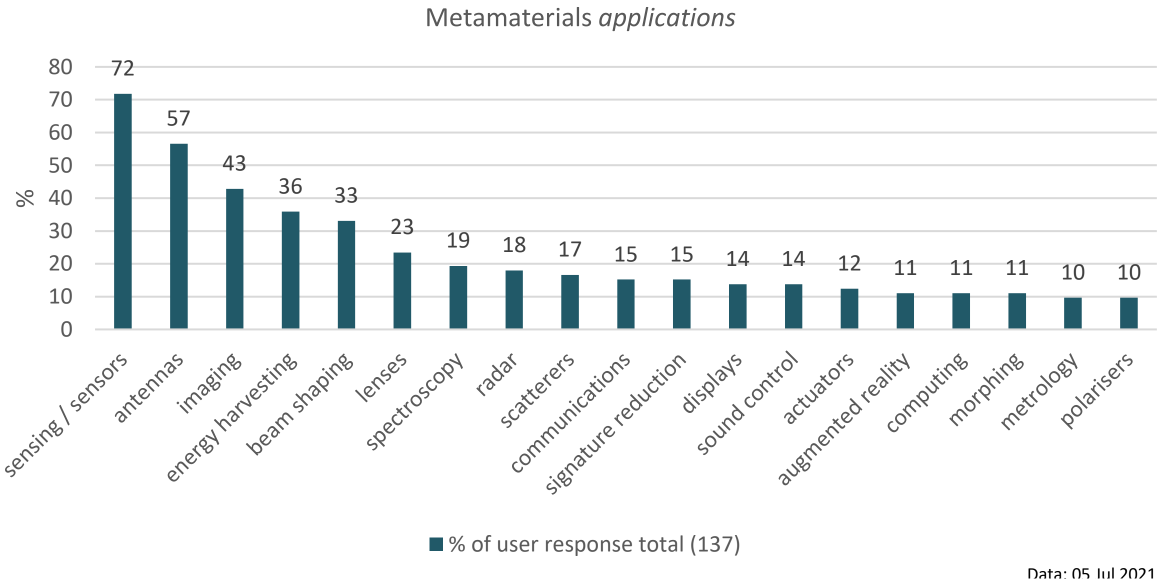


Figure 2: A summary of the broad variety of applications for Metamaterials collected from a survey of 137 members of the UK Metamaterials network.

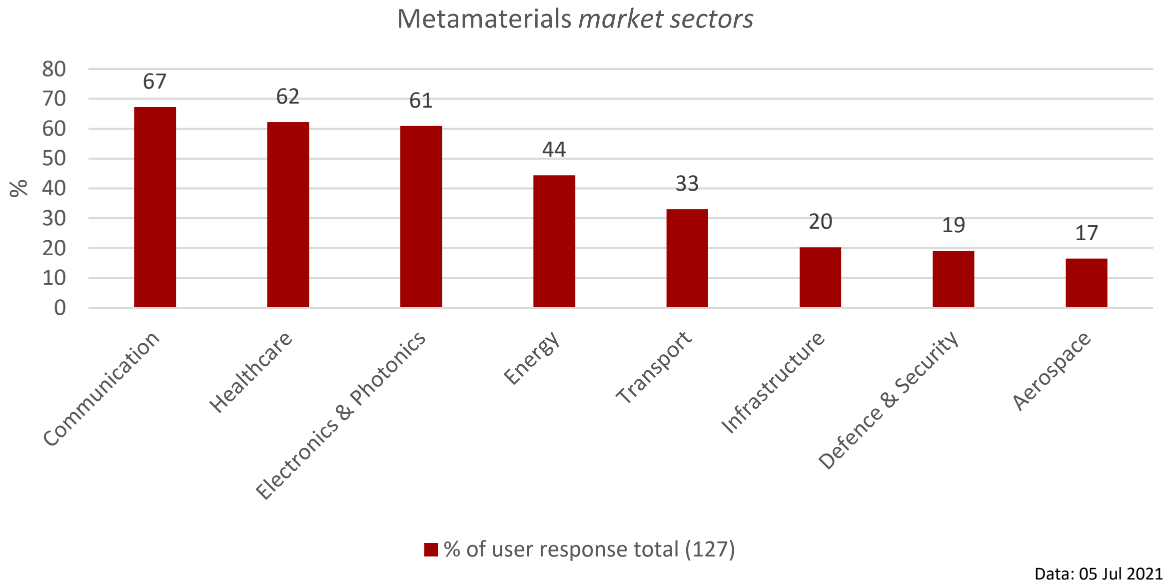


Figure 3: A summary of the market sectors corresponding to the applications described in Figure 2.

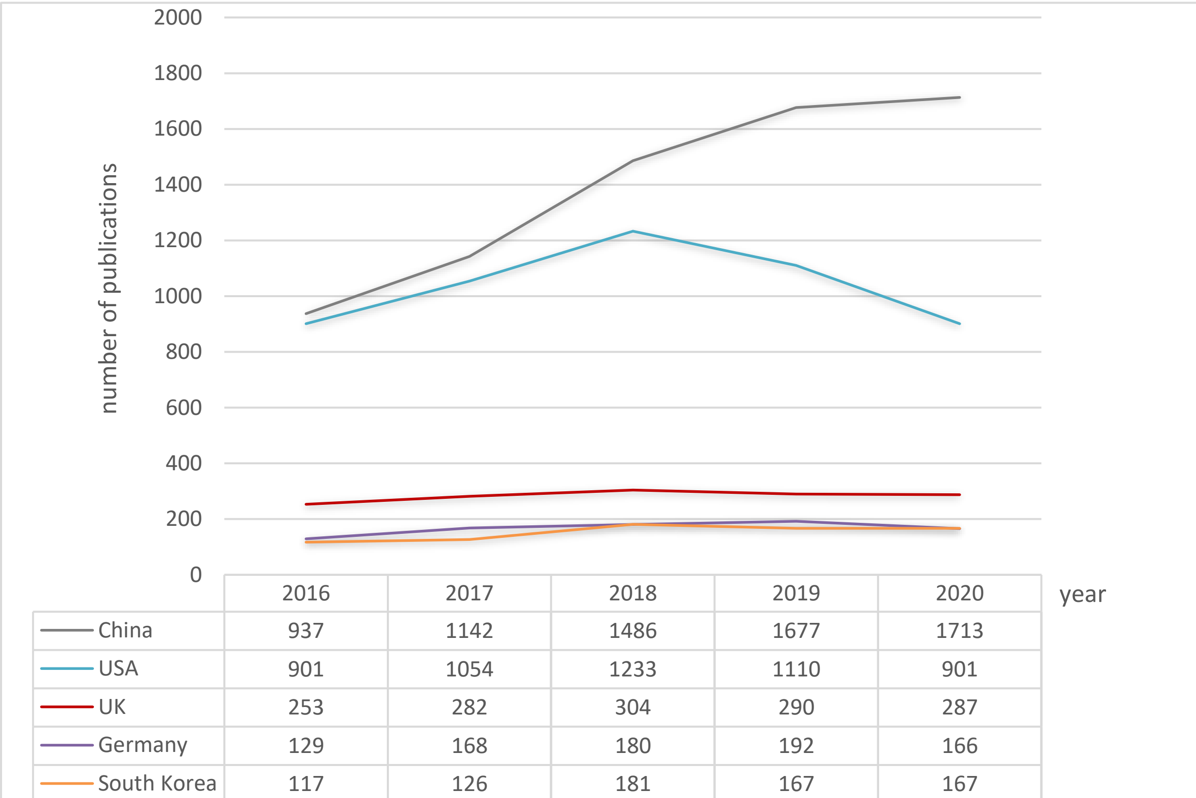
APPENDIX 3 – CURATED LIST OF "MOON SHOTS" FROM THE PARTICIPANTS OF INTERVIEWS AND WORKSHOPS LISTED IN APPENDIX 1

- Large-scale passive cooling of buildings as global temperatures rise,
- Efficient desalination of sea-water as fresh-water resources dwindle,
- Efficient and robust antennas and photovoltaics for space-based solar power,
- Robust resonators in the ocean to deflect tsunami.
- Meeting carbon emissions targets and avoiding the continued depletion of natural resources and ongoing harm to the environment through pressures on energy and resource usage. For example
    - Metamaterials that improve efficiency in photovoltaics,
    - mechanical Metamaterials providing alternatives to conventional raw materials, providing strength without weight,
    - energy harvesting from the environment, e.g., flow, or ocean-wave energy converters
    - reduction of energy usage and noise associated with transportation, e.g., mechanical Metamaterials that reduce the underwater noise radiation and greenhouse gas emissions in shipping [UK Marine Strategy (2019) and International Maritime Organization (2018)], or the 75% reduction in CO_2 emission and 65% perceived noise emission of aircraft by 2050 (ACARE Flightpath 2050).
- Mitigating the exponential demands on energy and infrastructure to control, process and store data – some predictions estimate that ICT will account for over 20% of global electricity usage by 2030 (Nature 2018). Metamaterials can offer low energy technology alternatives, for example
    - Metamaterial based ultrafast detectors, optical switching, and routing using plasmonics and Metamaterial-devices for efficient neuromorphic, analogue computing.
- Resolving the congested and contested electromagnetic environment and the ability to transfer information and energy, for example,
    - helping the UK achieve its target for a universal broadband service, through advanced antennas systems for 5G and beyond (Universal Service Obligation (USO) for Broadband, 2020)
    - benefitting secure and resilient wireless communication, through beam forming, reconfigurability, filters and access to less congested bands.
- Catapulting the shift towards safe, and low emission connected autonomous transportation, as well as navigation and reconnaissance,

    - integrated 5G antennas (in headlights, mirrors, windows etc);
    - metasurface and flat optics for improved LiDAR performance;
    - mechanical Metamaterials for light-weighting.
- Enabling ubiquitous Real World Evidence to improve healthcare outcomes, For example
    - Monitoring and treatment for an aging population with advances in imaging and targeted therapy, for example
    - resonant particles for targeted treatment and electromagnetic Metamaterials for improved imaging;
    - Metamaterial textiles for wireless body sensor network;
    - mechanical Metamaterials for smart bandages for facilitating and monitoring the wound-healing process.
- Securing the UK's food self-sufficiency and ambition to provide its citizens with cheap and healthy food; to reverse the decline and increasing UK food security against a backdrop of climate change and vagaries of our long global supply chain (UK Government commissioned National Food Strategy 2019 and 2021). For example,
    - reconfigurable Metamaterials to provide complete environmental control (heat, sound, moisture, light, vibration) for farming;
    - low power and light-weight, multifunctional, Metamaterial-based sensors (e.g. moisture, pH, IR) for Precision Agriculture
    - mechanical Metamaterials for controlled delivery of fertilisers.
    - Mechanical Metamaterials to enable sustainably grown animal and plant based proteins to replace traditional farm grown foods.
- Ensuring the sovereign need to maintain strategic advantage in national security and defence as our adversaries rapidly progress in controlling information and energy. As described by the Defence Technology Framework (MOD 2019), illustrative applications include "totally new approaches to traditional physical challenges – such as the use of Metamaterials to improve both sensing and camouflage…, or through adding functionality or reconfigurability into existing structures." Further examples include,
    - RF and acoustic Metamaterials for signature control;
    - resilient and secure operation, e.g. protection against electromagnetic pulse (also see above), and enhanced electronic warfare;
    - the design of functional devices, e.g. for surveillance and sensing, for use in remote, harsh and hostile environments, such as mechanical Metamaterials that offer an autonomous and purely mechanical operation (without electronics) or devices that use energy scavenging process for a power source.

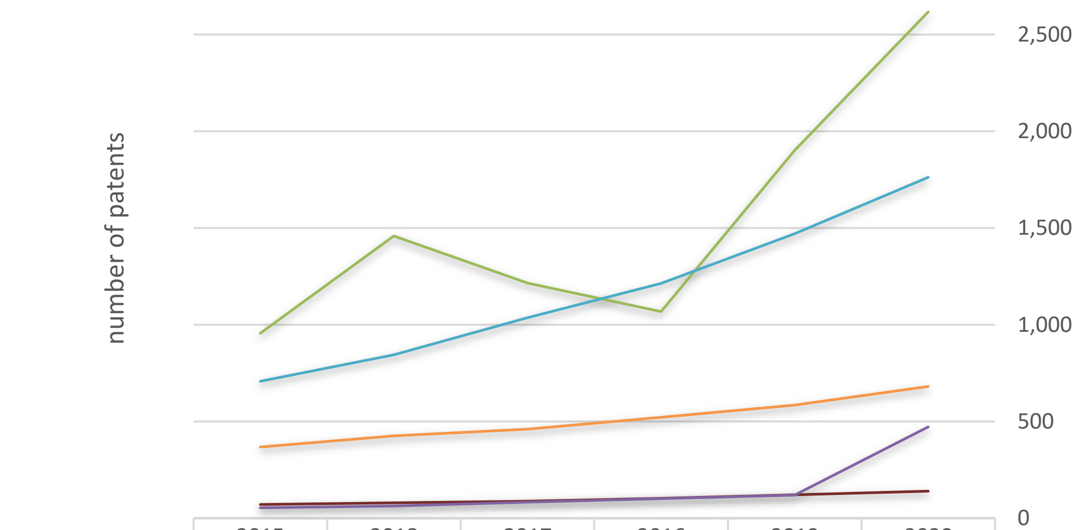
Table 3.1: *Top 10 countries for Metamaterials / metasurfaces publications volume (total since 2001, Web of Science, 20 July 2021)*

Country	**Publications**
China	11463
USA	8599
UK	3267
RUSSIA	2270
France	1995
Germany	1969
Italy	1713
South Korea	1405
AUSTRALIA	1377
SINGAPORE	1373



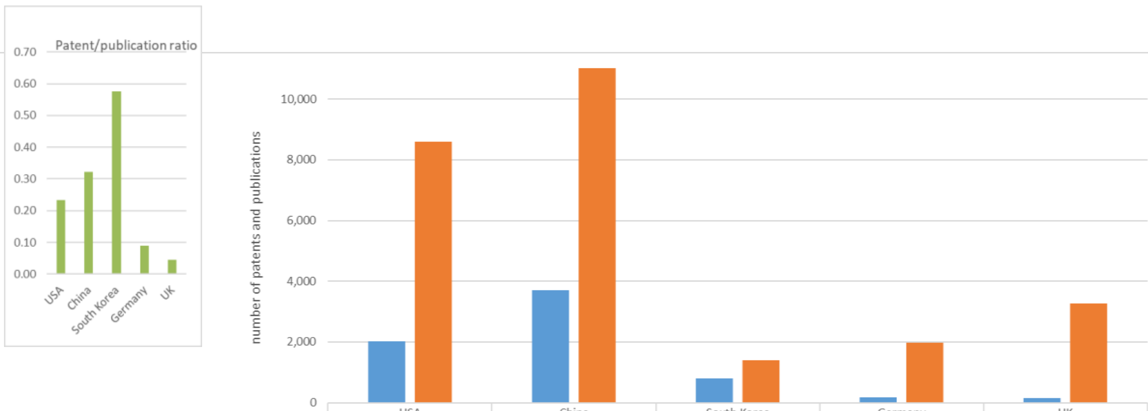
	2016	2017	2018	2019	2020
China	937	1142	1486	1677	1713
USA	901	1054	1233	1110	901
UK	253	282	304	290	287
Germany	129	168	180	192	166
South Korea	117	126	181	167	167

Figure 4: Development of Metamaterials/metasurfaces publications (Web of Science, 20 July 2021) as an indicator of international research activity.



year	2015	2018	2017	2016	2019	2020
China	956	1,459	1,215	1,068	1,900	2,617
USA	708	844	1,036	1,214	1,471	1,762
UK	71	79	88	103	121	140
Germany	54	63	83	101	120	472
South Korea	368	425	460	522	585	681

Figure 5: Global Metamaterials/metasurfaces patent registrations development (PatentSight, 02 Jul 2021).



	USA	China	South Korea	Germany	UK
Patents for metamaterials & metasurfaces (total by 2021)	2,013	3,704	809	176	150
Metamaterials & metasurfaces publications (total by 2021)	8599	11463	1405	1969	3267

Figure 6: Comparison of patents (blue) vs publications (orange) total for Metamaterials/Metasurfaces by country in 2021. The inlet shows the conversion ratio of patents/publication with the UK being last among the competitor countries. (Publications data source: Web of Science, 20 July 2021; Patent data source: PatentSight, 02 Jul 2021).

Commercialising Metamaterials Innovation Network

Report on Community Engagement

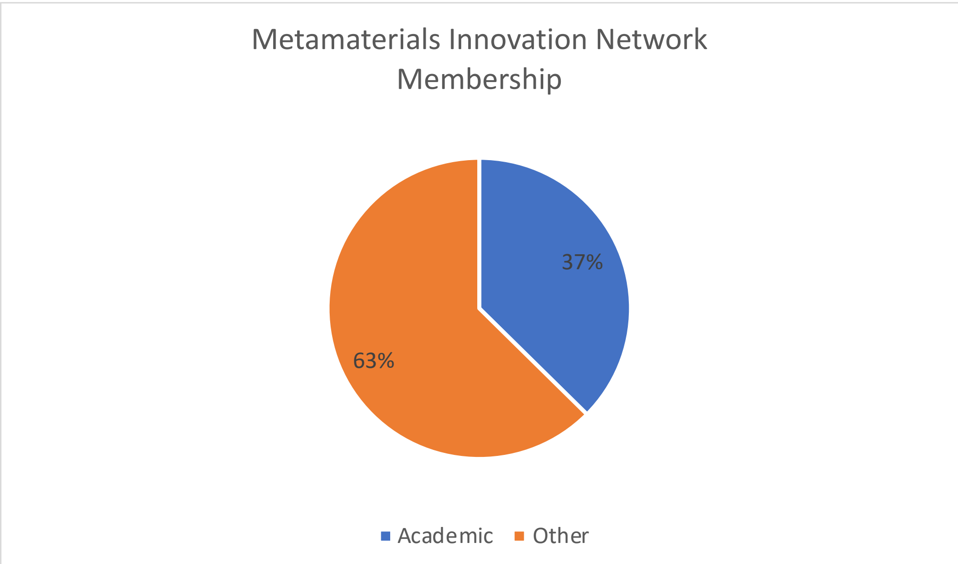
Version: 1
Date: 060721
Author: S Morris

Contents

Background

Commercialising Metamaterials presents a significant and timely challenge. These materials are not easy to understand, require sizeable resources to deliver useful products, require skills and expertise that are difficult to find and require the creation of novel supply chains. There is much fundamental R&D to be undertaken and this is leading to a chronic failure to translate extant research into timely products and services. UK has excellent academic research in this field but lacks industrial uptake from end-users. Prior to the launch of the network in September 2020, KTN has supported the UK Metamaterials Community a little in the last few years with some 386 organisations having attended recent dedicated events, workshops or conferences. The community is strongly academically-biased – though with large and small companies engaged and with start-up and spin-out participants.

The current community stands at 705, broken down into academic and industry, including RTO, as follows:

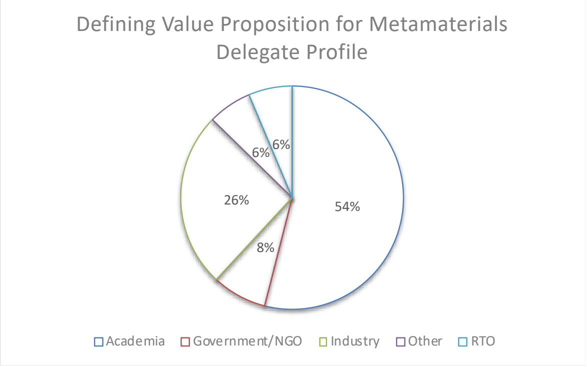


Defining the Value Propsition for Metamaterials

There were 62 delegates registered for the event who were introduced to the concept of a value proposition as understanding the needs and challenges of the target application, matching these with the features and benefits of their technology and defining the gaps that need to be addressed in order to bring their solution to market.

Defining the Value Proposition for Metamaterials

The outcomes were:



Needs and Issues

- Overall, it was felt the end users don't understand the functionality/performance that Metamaterials can bring. This is because it is challenging to communicate a multidisciplinary and technically challenging technology of the benefits to industry
- Specifically, there is a need for smaller and more efficient antenna that can operate over a wide bandwidth as well as coatings to control EM over diverse wavelengths Other opportunity lies in monitoring and sensing (self-powered) in infrastructure (with EM requirements).

Features and Benefits

- There was mention of high efficiency antenna systems with wider frequency and beam scanning for 5G, as well as Metamaterials to sense and communicate change.
- There also seems to be the ready ability to building consortia to test at scale

Gap Analysis

- Engagement to life sciences and medical
- Manufacturing is a key area in gap analysis. There is a need for additive manufacturing at scale as well as manufacturing for large area MM with complex shapes. Manufacturing readiness is low and there is a need for insights to integrating MM into established products/manufacture.
- Dual use, i.e., a civil application for large SA metasurfaces to match potential requirements in defence and security.
- Advanced modelling acceptable to industry is key as is the links between industry and academia helping academia to understand industry needs
- Supply chain is being seen as under development with a need for potential collaborators and partners (in industry sectors/applications) to help build it.

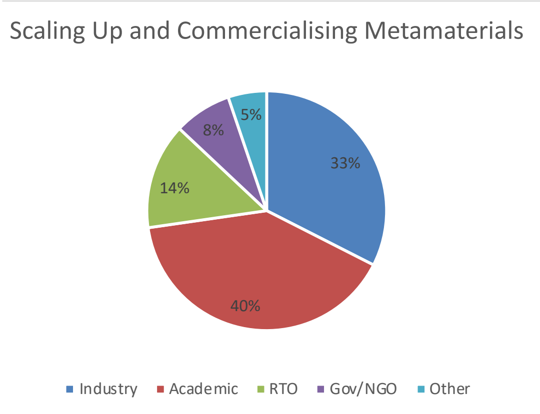
Planned Next Steps for Outputs

These will feed into an event in May/June looking to develop a pitch for investors as Straw Data. They will help researchers to understand the broader range of thoughts on the challenge of developing a value proposition for Metamaterials that forms the basis of a pitch to investors.

The data will also help develop the programme for the Metamaterials Applications and Manufacturing workshop on 30th March where we will ask breakout groups to look at data on Metamaterials length scale and functionality in relation to the use of Metamaterials in a particular application and relate it to the challenge of manufacture.

Scale Up and Commercialising Metamaterials

There were 78 delegates registered for this event which looked to offer SME's and Start-Up's the opportunity understand the support from various organisations including access to funding competitions through Innovate UK; helping businesses identify the most important challenges in developing an innovative product, service or process through KTN's Innovation Canvas; helping access to markets and pitch training to investors from Innovate EDGE; the role of Catapults in the upscaling of products from laboratory to prototype and on to commercial scale; academic support in modelling and new manufacturing technologies; interacting with designers and understanding the role of design in new product development and understanding the importance of how to access finance through investors.

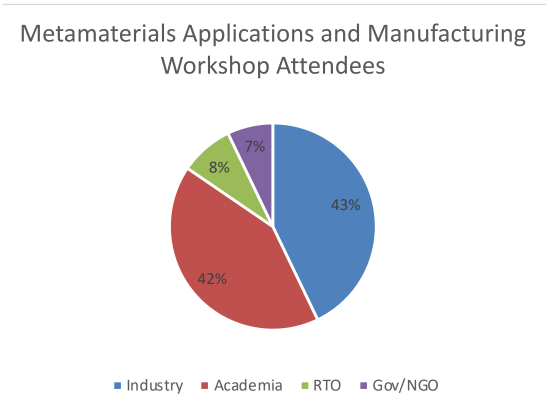


Metamaterials Applications and Manufacturing

A workshop was held on 30th March that brought together some 98 people from industry, academia, research organisations and Government and NGO's to undertake the challenge of validating information on technology, sectors and applications and manufacturing relating to MM and their potential to add value. The data was presented in chart form and delegates invited to comment within breakout groups.

Overview

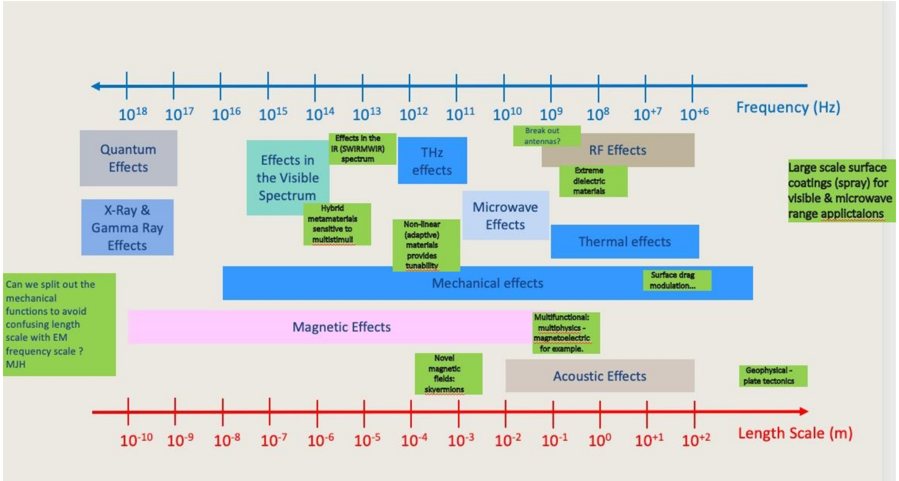
- There is a need to revisit current manufacturing to understand what it can deliver in terms of MM technology to potential sectors/applications. A question of tweaks to deliver MM added value.
- New and potentially disruptive manufacturing technologies are needed to deliver some MM technologies, so a review of relevant ones is required. The issue of cost vs. benefit important here. Examples of potential sources might be the likes of Johnson Matthey!
- Visibility of MM is an issue. Make the message a simple one that's not tied up with length scale and functionality, i.e., this is what it can do for you (in your sector/application).
- A panel of experts, in technology, manufacture and applications, to seek to find grand challenges to solve with MM. An A4I opportunity!



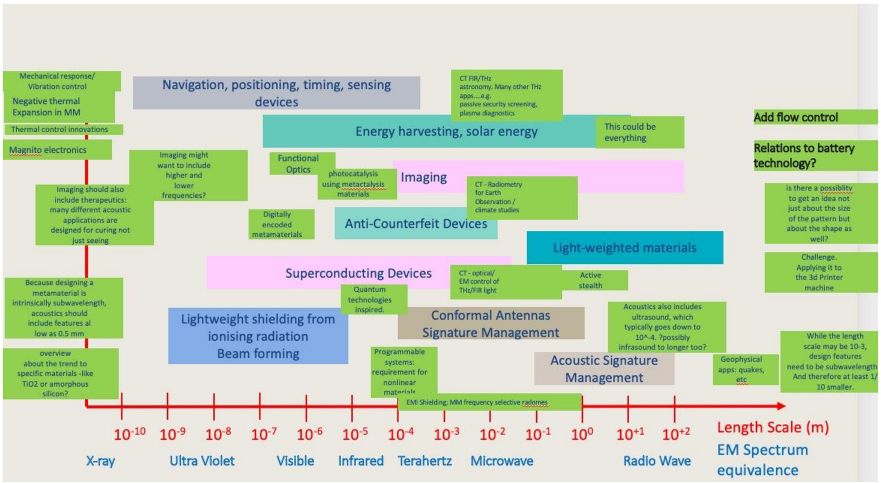
Planned Next Steps for Outputs

There will be a webinar at the end of April to disseminate the outcomes of the event and to present the modified charts. The initiations will go out to the delegates who attended the event and those who were unsuccessful in attending in order to broaden the comments before further dissemination through the UK Metamaterials Network website and mailing.

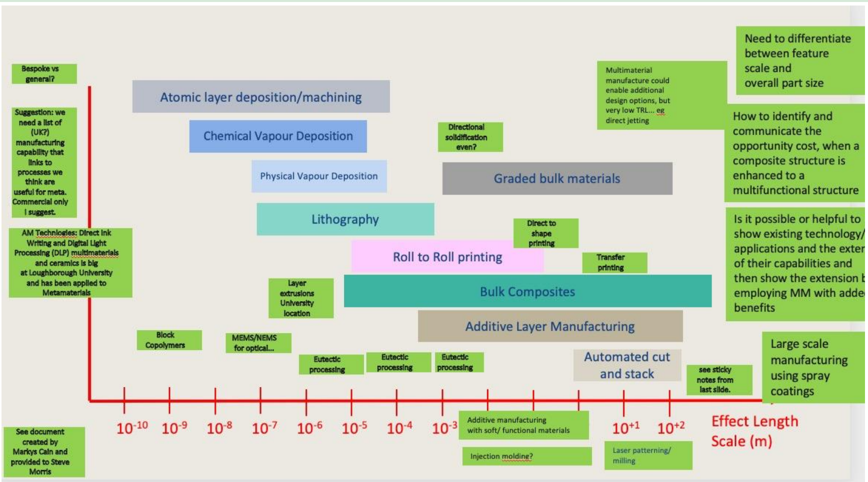
Technical Functionality vs Length Scale



End Use Application vs Length Scale

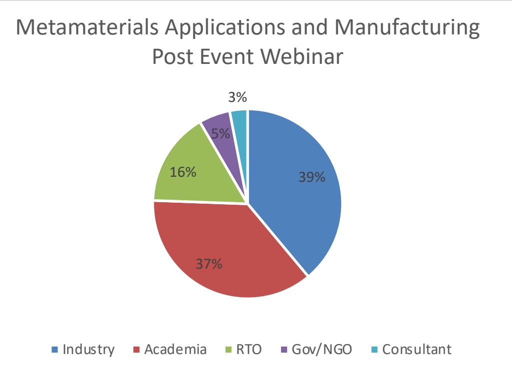


Manufacturing Process vs Length Scale (Effects)



Post Event Webinar: Applications and Manufacturing

There were 135 registered for the webinar which as designed to share the outcome of the workshop on 30th March, especially amongst those who registered but were unable to attend because of a limit on numbers. Some 80 people shared the findings and were invited to share their views.



Outcomes

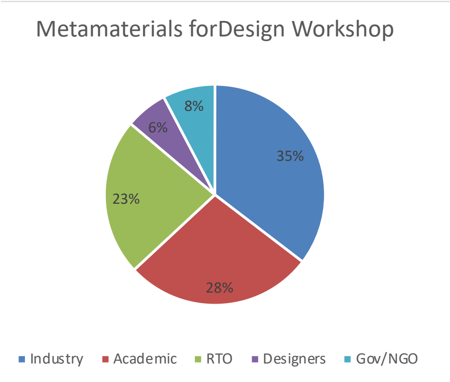
It was suggested that the Catapults perhaps need to do a better job in promoting their expertise and abilities. By matching industry needs and technology readiness they could build capability using core grant to do whatever is identified as key from studies to investing in open access facilities. The Catapults could work with KTN in facilitating collaborations between industry and academia or academia and industry and bid into competitions from Innovate UK, ATI, EPSRC, etc.

There was talk about the importance of accessibility and demystifying Metamaterials through demos as well as manufacturing and both civil and military examples using knowledge and need. There was also discussion about the prospect of perhaps small amounts of money (£15K) for feasibility studies that might lead to a series of demos.

There is the need for case studies and there is resource with EPSRC and KTN, who also have a marketing plan for interviews, thought pieces and the like to help spread the word about MM.

It was agreed to launch the MM Clinic, “Meta Mondays”, straight away confirming the format as a series of up to six short meetings of 10 minutes to cover challenges, roadmaps and technology sharing.

Metamaterials for Design



This workshop was by invitation only and some 48 people of the 68 invited participated to deliver some clear and simple definitions of Metamaterials and what they can do as well as some potential new applications and challenges to their use. This information is being collated to deliver some key three or four Metamaterials and applications that we can look at in more details as regards manufacture/scale up and provision of demonstrators.

The outputs from the event included 12 simple definitions of the most popular Metamaterials technologies and their associated applications outside the core applications and sectors already identified and their challenges other than the common challenges for the use of Metamaterials.

Examples are:

A metamaterial is an engineered structure that can provide a function which can't be achieved in a bulk material.

It is like a bulk material but a lot better because you can design, reconfigure and control its performance in real time.

Applications:

- Modulation of data
- Smart road signs
- Vibration control
- Smart surfaces
- Data transmission in textiles

A patterned surface is a Meta Material that can modify the reflection or transmission of microwave radiation.

It is like a regular antenna but a lot better, because we can introduce an active element to the design permitting beam steering or stealth/camouflage.

Applications:

- Data transmission in aircraft, cars and ships
- NDT/SHM

Challenges:

- Cost vs. Value Add
- Manufacturing
- Metrology and standards
- Regulations
- Multi material Processing
- Experimental evidence/successful use
- Technology TRL/MRL too low
- Modelling the materials
- Educating designers
- Scale of function vs. Scale of product
- End of Life
- Recyclability

KTN-facilitated Sector and Capability Meetings

Between September and October run a series of meetings with key supply chain organisations and End Users presenting the potential value added by Metamaterials matched against the innovation roadmap and challenges and needs of the sectors.

The meetings will feature a champion of Metamaterials related to the theme or sector and supported by existing technologies from industry or close to commercialisation technologies from academia.

We will use some of the definitions developed in the design workshop and the charts of technologies, applications and manufacturing developed in previous workshops to help convey the message.

The key is to help industry to better understand what Metamaterials are and what they can do that is relevant to their industry.

Meeting Format

Participants:

- Advisory Board Member
- KTN Facilitator
- KTN Sector Team
- Industry Supply Chain
    - Technical (Academic and Industrial)
    - Product design
    - OEM
    - End User
    - Tier 1/Manufacturers

Aims:

- Access and understand the needs and issues of the sector
- Determine potential value add for MM
- Discuss manufacturing implications
- Understand supply chain
- Engage with wider community

Outcomes:

Report findings, insights, and recommendations on the potential value of MM in the sector; the scale, strengths and gaps (SWOT, including in the context of any competing factors – internationally or in terms of alternate solutions) in achieving the value; and plausible interventions.

Sectors and Capabilities

Aerospace and Aviation (*with ADS, ATI, etc., possibly with different primes like Airbus, Boeing, BAE, etc*)
Automotive (*with APC, WMG & SMMT plus manufacturers like Nissan, Toyota, BMW, and JLR – what about bus and lorry companies?)*
Acoustic and thermal (*with Built Environment, Rail and Marine*)
Electronic and Photonic (*with Consumer Electronics, Healthcare, Creative Industries etc.*)
Sensing (*use of MM technologies amenable to developing an active functionality for delivering NDT, etc*.)
Comms and Antennas (*CSA Catapult, Swansea Uni, TCS, BAE, etc*.)
Energy (*Generation and storage including batteries, wind turbines, PV's, etc.*)

APPENDIX 6 – SUPPORTING STATEMENT FROM DST

SUPPORTING STATEMENT FOR THE METAMATERIALS REVOLUTION BIG IDEA PAPER

<redacted>