## Case for support

### A. Scientific or technological basis

Metamaterials are artificial materials with characteristics beyond those found in nature that unlock routes to material and device functionalities not available using conventional approaches. Their electromagnetic, acoustic or mechanical behaviour is not simply dictated by averaging out the properties of their constituent elements, but emerge from the precise control of geometry, arrangement, alignment, material composition, shape, size and density of their constituent elements[1].

The field of metamaterials has seen a rapid increase of interest over the past two decades, with more than 16,000 scientific publications during 2019. In terms of applications, metamaterials have phenomenal potential in areas ranging from energy to ICT, defence & security, aerospace, and healthcare. Numerous market research studies predict significant growth over the next decade, for example, by 2030 the metamaterial device market is expected to reach a value of over $10bn[2].

The UK has been a global leader in the academic study of metamaterials, with its roots in the work of radar engineers in the 2nd World War[3], and being reinvigorated by the research of some of our most eminent academics, including Professor Sir John Pendry, who wrote seminal papers on topics ranging from artificial dielectrics to transformation optics, negative refraction and diffraction-beating imaging[4]. A host of other UK academics have offered world "firsts" in metamaterials, developing the science associated with sensing, photovoltaics, data storage, novel antennas, radar absorbers, reconfigurable photonics for communication, acoustic control, wireless power transfer, and many more[5], leading to university spinouts, such as Sonobex, Metasonics and Metaboards.

However, the UK risks falling behind the curve of metamaterials research and innovation. For example, the Chinese government has funded the development of the world's first large-scale metamaterial fabrication facility[6], which has capacity to produce 100,000 $m^2$ of metamaterial plates annually, with projects relating to aerospace, communication, satellite and military applications. The US has recognised a need for intervention, for example, the voice of the US national advanced manufacturing community, MForesight[7], highlighted actions necessary to ensure that metamaterials become more broadly adopted to address practical applications and deliver societal and economic value. Similar conclusions have come from UK bodies, including the UK's Advanced Materials Leadership Council (AMLC) who in a working group position paper[8] recognised the strengths of UK-based research, including topics such as nanophotonics, 2D nanostructures, and plasmonics that underpin photonic metamaterials, but highlighted that in metamaterials in general "the UK is lagging the USA and South East Asia".

**The intervention that this Network will provide will ensure that the UK is also part of this growth, and does not lag our international competitors. It will provide the stimulation of an enterprise cycle to meet desired outcomes for prosperity and consequentially, society, defence, and security.**

The importance of metamaterials to the UK's science and engineering base, and to its economy and sovereign capability, is already recognised by UKRI and Government. Current >£1M EPSRC investments include "Meta-Smart: Merging de novo designed biomolecules with plasmonic metamaterials for new technologies" (Glasgow, EP/S029168/1), "CDT in Metamaterials" (Exeter, EP/L015331/1), "Synthesizing 3D Metamaterials for RF, Microwave and THz applications" (Loughborough, EP/N010493/1), "The Physics and Technology of Photonic Metadevices and Metasystems" (Southampton, EP/M009122/1) and Software Defined Materials For Dynamic Control Of Electromagnetic Waves (Queen Mary, EP/R035393/1). While some of these projects demonstrate effective collaboration, an Innovate UK KTN Review of Metamaterials in the UK[5] identified the lack of coordination between R&D groups as a threat to the UK's progress.

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[1] Definition based on "Enabling a new degree of wave control with metamaterials: a personal perspective", J. Opt. 2017
[2] For example, Lux Research 2019 (http://ex.ac.uk/bSc); Market Research Engine 2019 (http://ex.ac.uk/bSd)
[3] For example, Cutler, "Genesis of the corrugated electromagnetic surface", Proc IEEE APS, 1994.
[4] List of publications on metamaterials by Prof Sir John Pendry since 2003: https://www.imperial.ac.uk/people/j.pendry
[5] "A state of the Art Review of Smart Materials", Innovate UK KTN http://ex.ac.uk/KTNreview.
[6] http://www.kuang-chi.com/en/
[7] http://mforesight.org/projects-events/metamaterials/
[8] "Materials for Communications and Electronics" http://ex.ac.uk/bSg

Furthermore, current metamaterials projects funded by Innovate UK are relatively scarce, e.g. "Advanced metamaterials for sodium-ion battery anodes" (Deregallera Ltd, ref: 133863) and "Sonobex Acoustic Barriers" (Sonobex Ltd, ref: 720393). This imbalance demonstrates a need for a concerted effort to drive metamaterials science and innovation and push this impactful research area towards real industrial application alongside enhanced national coordination of the low Technology Readiness Level (TRL) work.

There has been some effort to counter the above-mentioned imbalance, through the establishment of the UK Metamaterials Leadership Group, and recent KTN events including a Showcase of Emerging Technology and an academic and industrial metamaterial session at the MRE 2020[9]. From recent discussions with the Defence Science and Technology Laboratory (Dstl)[10], we understand that they recognise the need for a UK-wide programme in this area. They have already sought to develop a limited community around the recent "Metasurfaces for defence and security" competition (DASA[11]), and their financial support of our proposed Network (£150k cash) to foster cross-sector collaboration demonstrates their commitment to a dual-use (defence and civil) strategy.

Our Network will build a platform for metamaterial researchers to communicate and collaborate, while ensuring the impact of existing and future investment is fully exploited. As a national endeavour, it will be best placed to ensure the UK is competing globally by coordinating our capabilities to address national[12] and international challenges.

In November 2019, we held community consultation meetings across the UK during which more than 70 academic and industrial representatives highlighted metamaterial research and end-user requirements, and in particular the following scientific and engineering challenges: **Metamaterials manufacturing** (scale up, and 3D fabrication); **multifunctional behaviour** (e.g. combining strength and wave-response); the potential of **AI-design of new metamaterials**; **broad bandwidth metamaterials** (e.g. for solar absorbers, RF signature control); **non-planar, conformal and flexible surfaces** (e.g. for thin antenna systems, and optical wavefront shaping); **active metamaterials** for dynamic tunability and reconfigurability (e.g. for beam steering, lidar, holography and adaptive systems ); and the exploitation of **metamaterials for healthcare, medical imaging and biosensing**. The initial priorities of the Network will be based around these topics, and are anchored in EPSRC growth areas (e.g. RF and microwave devices; materials for energy applications; Artificial intelligence technologies).

The network will inherently support EPSRC's Delivery Plan 2019[13] objective for 'Delivering economic impact and social prosperity' across each of the 4 nations (*productive, healthy, resilient* and *connected*). Furthermore, it will target current and future industrial strategy challenges[12], such as 'Manufacturing and future materials' (e.g. light-weight and thin materials for antennas); 'Prospering from the energy revolution' (structured materials for energy storage or photo-voltaics); and 'From data to early diagnosis and precision medicine' (metasurfaces for improved imaging). In addition, we will facilitate the EPSRC objective 'Realising the potential of engineering and physical sciences research' via forming new connections across the research landscape, enhancing business engagement with small, medium, and large enterprises, and realising excellence in research and people through the network activities. We will be best placed to also support EPSRC in its objective 'Enabling the UK engineering and physical sciences landscape to deliver' through our focus on inclusive and diverse talent growth, promotion of opportunities to share facilities and equipment, and engagement with EPSRC showcase evets, case studies, and similar activities to inspire and inform the public.

## B. Objectives

The design, fabrication, characterisation and impact development of metamaterials is multi-disciplinary by nature (e.g. physics, engineering, maths, biology, chemistry, computer science), but we believe that the isolation of research groups and lack of platforms to exchange and develop

[9] Materials Research Exchange 2020 http://ex.ac.uk/bSf
[10] Dstl are a UK Government executive agency sponsored by the UK Ministry of Defence
[11] Defence and Security Accelerator, https://www.gov.uk/government/organisations/defence-and-security-accelerator
[12] E.g., Industrial Strategy Challenge Fund https://www.ukri.org/innovation/industrial-strategy-challenge-fund
[13] https://epsrc.ukri.org/newsevents/pubs/deliveryplan2019/

ideas currently inhibits the UK's access to the interdisciplinary potential existing within our universities, industries, and governmental agencies. It is of the utmost importance to develop interactions and mobility between these communities, to enable knowledge transfer, innovation, and a greater understanding of the barriers and opportunities. Therefore, our objectives are to

1. *Build a vibrant and creative, multidisciplinary community across academia, industry and governmental agencies, to accelerate novel and innovative metamaterials research via sharing expertise, knowledge and facilities.*
   - This will build and secure the UK's sovereign capability and global position in this crucial scientific area, leading to enhanced prosperity for the UK.
2. *Publish 'Review' and 'Roadmap' documents for UK Metamaterials;*
   - An up-to-date UK Review of Metamaterials (year 1) will summarise the state-of-the-art in terms of research expertise and facilities, and the economic and societal impact to the UK.
   - A Roadmap (year 3) will outline future challenges and opportunities for metamaterials to drive the UK economy.
3. *Bring the wealth of UK metamaterials expertise and end-users under one 'shop-window' and act as the hub for a community to address academic and industrial challenges;*
   - An openly accessible and easily searchable online database of UK expertise, end-users and facilities.
   - A team of leading experts to prioritise and coordinate research strategies.
4. *Build and support a talent pool of scientists and engineers to develop as future leaders;*
   - A platform to develop the potential of young researchers. With resources to facilitate the formation of new collaborations, with summer schools, and career-enhancing activities.
5. *Enhance awareness of the impact and importance of metamaterials, and interact in advisory roles with UKRI and Parliament;*
   - The Network will have critical mass to ensuring that the community plays its role in supporting UKRI and its objectives, as well as providing academic subject knowledge as appropriate.
6. *Act as an advocate of metamaterial science and engineering to school pupils, the general public, and college and university students;*
   - Key elements are the development of metamaterial demonstrators and participation at public science events, engagement with media and activities to foster awareness of and involvement in metamaterials research among undergraduates.
7. *Develop a legacy plan for the Network.*
   - Planning towards self-supported sustainability beyond the Network funding period.

## C. Initial Membership

During November 2019, consultation meetings to discuss the formation of the network were held in Manchester, Bristol and London with over 70 delegates from 41 different institutions (academia, industry, and governmental agencies) in attendance. This exercise sought to disseminate the investigators' vision for a Network, to identify the level of support from the community, and make initial recommendations for the Network structure, focus areas, and strategies. This engagement is confirmed through the >40 Letters of Support from 22 UK universities, 4 other supporters (e.g. NPL, UK Acoustics Network), and 20 project partners, which includes e.g. Dstl and a wide range of small (e.g. Waveoptics, Metasonixx) to large enterprises (e.g. Oxford Instruments, Cobham, Metamaterials Technologies Inc,, Airbus, Rolls Royce Thales). The letters detail of **£620k of in-kind support** from non-academic institutions, **and £177k of cash** to directly support Network activities (e.g. summer student bursaries, symposium, SIG funds). The academic membership involves multiple disciplines and groups across the already committed institutions. The spread of subject areas enables knowledge exchange and collaboration from theory to device design, with leading expertise in topics such as additive layer manufacturing, acoustics, antennas, auxetics, biomaterials, condensed matter, 2D materials, microwaves, modelling, nanomaterials, nonlinear optics and nanophotonics, opto-electronics, phase-change materials, photovoltaics, plasmonics, quantum technologies, sensing, soft matter, and terahertz devices.

## D. Network Structure: Community groups, Management, and Governance

The key Network activities will be undertaken by the **Leadership Team, Special Interest Groups** and **Forums**. An independent **Advisory Board** will offer advice on national and international developments and network internal activities. A part-time (0.2 FTE) **Administrative Assistant** will provide support for meetings etc.

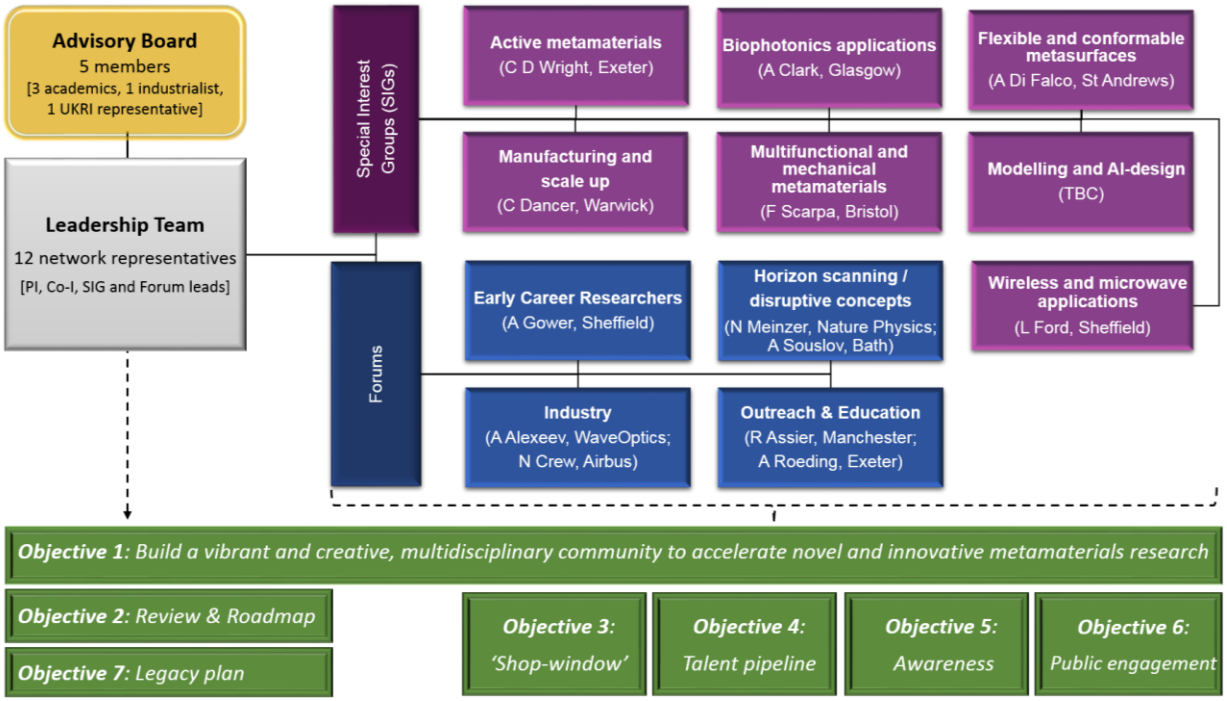


*Figure 1. The Governance and Objectives structures of the EPSRC UK Metamaterials Network.*

### *Leadership Team (LT) and Advisory Board (AB)*

**The LT** will comprise of the PI, leads from the SIGs and Forums, and the Co-I. The Co-I will be the Network Manager (0.7 FTE). The LT will meet quarterly to ensure that the Network deliverables are met. Its key activities will be strategic, and will include the compilation of a list of Grand Challenges that can benefit from metamaterial concepts. It will also coordinate the community's response to large capital funding or challenge-driven calls, consider up-skilling opportunities and tackling skill-gaps relevant to employers, and will lead the development of the "Review" and "Roadmap" documents. The Forums' themes and SIG topics will be regularly reviewed, and we expect to add SIGs, or evolve existing SIGs during the Network lifetime. The LT will offer an opportunity to disseminate best practice across the groups, while also addressing barriers to Equality, Diversity and Inclusivity within the network.

**The AB** will consist of 3 leading academics, a prominent industrialist, and UKRI membership. Prof. Maria Kafesaki, a governing Board Member of Metamorphose VI, has already agreed to join the AB as provisional chair, and will attend the Network launch meetings to steer its development. The AB will meet once per year with the LT to evaluate Network outputs, to monitor sensible spend, and to ensure a balance of focus across the metamaterials research landscape.

### *Special Interest Groups (SIGs)*

SIGs act as a platform for researchers and industry representatives with an interest in specific areas. The initial 7 SIGs (see Fig.1) reflect the priorities identified during the consultation process (see section A). Each will have at least 10 members from academia and industry. In addition to its strategic lead, each SIG will be co-led by an early career researcher (executive lead) to foster a more inclusive approach and offer opportunities for leadership development.

SIGs will meet twice a year for knowledge exchange, planning and review of SIG activities, e.g. preparation of special edition journals, delivery of topical sessions at conferences, brainstorming research ideas and coordinating responses to research challenges, collating lists of available capital facilities and equipment, White Paper development, feedback from engagement activities with UKRI/parliament, interaction with Forums (see topics below). The SIGs will each work closely

with a consultant to contribute to the 'Review' and 'Roadmap' documents (Objective 2).

***Forums***

These will be jointly led by 2 members and focus on subjects that are of relevance to all SIGs.

- The **Industry Forum** will identify pathways to exploitation, and consider opportunities to upskill industrial staff. It will support market analysis to develop strategic documents (e.g. White papers), and will position itself as a body capable of advising funders and policy makers.
- The **Horizon Scanning Forum** will work to identify emerging concepts and disruptive opportunities in metamaterial science and engineering. It will identify challenges and suitable Network activities (e.g. workshops, new SIG development) to address these.
- The **Early Career Researchers Forum** (including PhD students) will lead on People Development initiatives and activities (section E). Through the wider community, it will promote opportunities to engage with next-career-stage role models, and CV building experiences to develop future metamaterial leaders.
- The **Outreach & Education Forum** will coordinate outreach activities and production of demonstrators and videos across institutions. This group will develop a plan for talent pipeline support from school to undergraduate programmes.

We expect members of the Network will participate in multiple SIGs/Forums.

## E. Activities

The network activities are outlined in the Workplan, together with the lead / group responsible for their delivery, targets, and alignment to the Objectives. Key activities include:

*E.1 Integrative think tanks:* The Network will host one per year, chosen by the LT to yield maximum long-term benefit to the community. They will build on the concept pioneered and developed by the CDT for Statistical Applied Mathematics (SAMBa) at the University of Bath since 2015, involving senior academics, industrialists, and ECRs to tackle cutting-edge research problems by identifying preliminary routes to a solution and the mechanisms to take them forward (e.g. jointly funded studentships, joint research proposals, UG student projects, and consultancy work).

*E.2 Industry-Academic workshops:* Based on the concept introduced by Exeter's EPSRC CDT in Metamaterials anddesigned to develop the expertise and raise the profile of excellent PhD and ECRs, these will bring together academia, industry and Government to discuss the state-of-the-art in a focussed research area. They take the form of scientific/technical presentations with plenty of opportunity for networking and discussion.

*E.3 Research knowledge exchange:* We will fund short national and international research visits for all career stages, particularly for projects that cross discipline boundaries. The aims are to maximize the impact of UKRI's investments by facilitating sharing of expertise and facilities, and to encourage engagement across academia and with industry that could build into Fellowships and new collaborations. In addition, we will invite international academics to visit the institutions of Network members to give colloquium talks, which we will record and place on our website.

*E.4 Annual UK Symposium/International conference:* We will host an annual Metamaterials symposium with UK keynote research talks, strategy talks, industry case studies, presentations from funders (e.g., UKRI and UK Government), and a series of workshops focusing on collaboration; profile raising; project development for current/upcoming calls; roadmap writing; brainstorming new areas; and addressing industry needs. One these annual events will be a high-profile international conference, with keynote speakers invited from around the world.

*E.5 Advocacy to end-users and policy makers:* The wealth of metamaterials expertise will be made freely accessible via a strong online presence, with a searchable database of experts and facilities, and a single point-of-contact for enquiries. The Network will seek to actively inform decision-making processes through engagement with UKRI, e.g. through panel memberships, showcase events, and case study development. In addition, the network will promote the Parliament for Researchers initiative in order to enhance engagement e.g. with All-Party Parliamentary Groups (APPG), and Parliamentary Office of Science & Technology (POST) etc.

*E.6 People development:* A 2018 survey[14] of leading UK recruiters that would target graduating PhD students with materials or metamaterials expertise found that 75% of respondents expected great difficulty in doing so. The Network will enable the community to work together to better understand these skills gaps, and will help develop a talent pipeline, for example, by facilitating development of its members towards professional status. This will create industry-wide confidence which in turn will develop, attract and retain a higher skilled workforce. The Network will also benefit those working in industry without a scientific peer support group; it will offer opportunities for all members to collaborate and keep abreast of academic breakthroughs. We will complement many of the Network activities identified above with targeted researcher development sessions at summer schools, co-leadership of SIGs and Forums, summer studentship bursaries, and media and public engagement training. In addition, the Outreach & Education Forum will focus on activities at the undergraduate level, e.g. providing material for university taught courses.

E.7 Public Engagement and outreach: The Network will focus on national (e.g. New Scientist Live) and regional (e.g. PintofScience, Soapbox) outreach events, as well as supporting schools and colleges to help raise awareness of this cross-disciplinary research area and its impact on day-to-day life. This will include the development of a pool of metamaterial demonstrators (i.e. benchtop experiments and crib sheets for loan) and a series of videos for the layperson about key topics (e.g. active metamaterials) and the relevance to tomorrow's technology.

## F. Plans for dissemination

The Network will develop a Communication and Dissemination Strategy in order to coordinate and record activities, for its own members, and those beyond the Network. We will monitor the number of new connections made at network events (e.g. using Blendology), dissemination outputs, such as public engagement events, invited talks, white papers and joint publications. Furthermore, the Network website will include research and industry case studies, easy-to-understand introductions to metamaterial science and technology, links to technical training materials as well as the expert and facility database. An associated newsletter will celebrate successes from the community and highlight how the Network can facilitate engagement with upcoming opportunities. We will also engage with social media and develop press releases for national media. The industry-academia workshops will be open to widely promoted and open to all, and we will proactively engage with Parliament and UKRI to promote the successes of our community. We will engage with the international community through international centres and networks, e.g. Metamorphose-IV, seeking to host at least one international metamaterials conference in the UK. SIG leaders will be expected to organise special sessions at international conferences (e.g. Meta, CLEO, SPIE).

## G. Potential for collaboration

The Network will bring together researchers from all career stages, from academia, industry and Government, through the activities listed above, and the newsletter and website will promote Research Challenges, and upcoming opportunities and events. The Network will further increase membership with a target of 400 by 2023 and an emphasis on welcoming those who do not fully associate with the metamaterials community but have much to gain from doing so. We will use our links to existing academic collaborators and to KTN to reach out to new academic partners, SMEs, large enterprises, and spin-offs. Much of the Network's potential for success lies in the creativity unleashed when researchers engage with peers from outside of their own discipline: a common message voiced in our consultation meetings was that academics wanted to Network to help them make new connections beyond their own circle of expertise - some of the SIG topics have been chosen to do exactly this. We anticipate that Network activities (including promotion of Metamaterial science and technology to end-users, and the pro-active identification of emerging and under-represented areas) will attract funding to the community, as is already evidenced by many of our industry Letters of Support, and hence we envisage that the network will facilitate many new links to enable new innovative project collaborations and technology development. These may include, for example, augmented reality display technology, multi-domain signature control (e.g. IR and RF); mechanical metamaterials for energy harvesting; auxetics for acoustic control; origami antennas for space/satellite deployment, compact LIDAR for autonomous vehicles.

[14] http://ex.ac.uk/BMGreport