Institution: Imperial College London		
Unit of Assessment: 9 – Physics		
Title of case study: B9-9 Commercialisation of metamaterials delivering disruptive products in the optical, medical, aerospace, military and communications industries		
Period when the underpinning research was undertaken: 2000-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Prof Sir John Pendry	**Role(s) (e.g. job title):** Chair in Theoretical Solid-State Physics	**Period(s) employed by submitting HEI:** 1981 – Present
Period when the claimed impact occurred: 2013-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Metamaterials deliver electromagnetic properties not available in natural materials. These powerful concepts have engendered massive interest in the electromagnetic community encompassing RF through to optical applications. They were originally developed by John Pendry at Imperial College London, initially working as a consultant to Marconi. John Pendry is a co-inventor on more than 70 patents in this field. John Pendry's fundamental research has led to a new market, based around metamaterials. Multiple companies, existing and start-ups, such as Netgear and Kymeta, have commercially exploited these concepts, with products in the optical, medical, aerospace, military and communications industries (particularly in 5G products), providing revenues exceeding $500M globally and are contributing to a global market valued in the billions of dollars.

2. Underpinning research (indicative maximum 500 words)

Pendry showed that the electromagnetic properties of materials are as much influenced by their structure as by their chemical composition. As a result, these materials gain their properties from the underlaying structure and not the composition of the materials used to construct them. By using composite materials manufactured into repeating patterns at scales that are smaller than the wavelengths of the phenomena they are designed to influence, one can gain access to a range of hitherto unknown properties such as negative refraction, and magnetism at optical frequencies. These properties allow the control of electromagnetic fields beyond natural materials **[1,4]**, engendering a new field now described as "metamaterials".

Pendry's highly theoretical underpinning research on metamaterials and transformation optics has been translated into experiments and working devices by others who have taken up these concepts and applied them.

Although negative refraction was first postulated by Veselago in 1968, it has not been found to occur in nature and was only realised once metamaterials were available. It is a remarkable phenomenon which has introduced many new ideas into optics. For example, Pendry showed in 2000 **[1]** that using negative refraction it is possible to build a lens whose resolution is not limited by the wavelength of the light. By using a slab of metamaterial with a negative refractive index, it is possible to focus the light with a flat lens. Following the breaking of the Abbé diffraction limit **[1]** nanometre scale objects have been imaged. This paper has given birth to the present intense interest in the sub wavelength control of light by exploiting the properties of surface plasmons. Latest results show focussing of light to better than 1 nm.

Transformation optics replaces the ray picture of Snell's law with the field lines of Maxwell's equations and is an exact description of classical optics but retains the intuitive advantage of Snell. Following the discovery of the perfect lens in 2000 **[1]** and further work regarding metamaterials and negative refractive index **[2]**, the idea of transformation optics was most famously used to propose a cloak of invisibility in 2006 **[3]**, where the metamaterial directs and controls specific regions of the EM spectrum giving the illusion of invisibility to a detector. In operation, the object remains in position while the incident radiation is in effect guided around the object. With the advent of metamaterials this was rapidly translated into an experimental result **[4]**.

Valid on all length scales, transformation optics has variously been employed to construct novel RF devices and sub wavelength optical systems **[5,6]**. The concepts used in the cloak have been exploited in commercial applications as detailed below.

3. References to the research (indicative maximum of six references)

[1] Negative Refraction Makes a Perfect Lens J.B. Pendry *Phys. Rev. Lett.* **85,** 3966-9 (2000) https://doi.org/10.1103/PhysRevLett.85.3966 Cited 8394 (WoS)

[2] Metamaterials and negative refractive index. D.R. Smith, J.B. Pendry and M.C.K Wiltshire. Science 305, Issue 5685 pp 788-792 (2004) https://doi.org/10.1126/science.1096796 Cited 2467 (WoS)

[3] Controlling Electromagnetic Fields J.B. Pendry, D. Schurig, and D.R. Smith *Science* **312** 1780-2 (2006) https://doi.org/10.1126/science.1125907. Cited 5516 (WoS)

[4] Metamaterial electromagnetic cloak at microwave frequencies D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, D. R. Smith *Science,* **314,** 977-80 (2006) https://doi.org/10.1126/science.1133628. Cited 4625 (WoS)

[5] Transforming the optical landscape J. B. Pendry, Y. Luo, R. Zhao *Science,* **348,** 521-4 (2015) https://doi.org/10.1126/science.1261244. Cited 68 (WoS)

[6] Aubry, DY Lei, A.I. Fernandez-Dominguez, S. Maier and J.B. Pendry, 'Plasmonic Light-Harvesting Devices over the Whole Visible Spectrum', Nano Letters, 10, 2574-2579 (2010). https://doi.org/10.1021/nl101235d Cited 272 (WoS)

Citations from 27/02/2020 Web of Science (WoS)

4. Details of the impact (indicative maximum 750 words)

The pioneering work of John Pendry led to a new field of research and applications in metamaterials. He is widely credited as one of the inventors whose key concepts now allow their commercial use today **[A, B]** in highly disruptive technologies for a plethora of applications where control over electromagnetic radiation is key, including telecommunications, solar energy harvesting, biological imaging and sensing, medical diagnostics and many others. With David Smith, his collaborator who is developing an engineering platform based on the metamaterial concept, John Pendry's research has been the major driving force behind the impact of these new concepts. Today most major technology companies have some internal ongoing metamaterials research, one such example is Netgear. They have used metamaterials in all consumer wireless routers since 2008 **[C]**. In addition, several of the many start-up companies devoted to metamaterials are already shipping products as outlined below.

Intellectual Ventures, a private equity company that centres on the development and licensing of intellectual property has set up 7 companies based on the fundamental research of Pendry and collaborators at Duke University, with 3 more who have developed products based on metamaterials and are approaching the external funding phase **[D]**. The first and largest of these companies Kymeta Corporation (Redmond, WA, USA), which specializes in satellite communications was formed in August 2012 and launched its first commercially available product in March 2017 **[D, E, F]**. Since August 2013, the following 6 companies have been also been formed by Intellectual Ventures; Evolv Technology (Waltham, MA, USA), with a focus on security

screening applications; Echodyne (Redmond, WA, USA), a company commercializing metamaterial-based radar systems; Pivotal Commware (Kirkland, WA, USA), which develops metamaterial-based products for terrestrial communications; Carillon Technologies (Arlington, VA, USA), a start-up dedicated to military applications; Lumotive (Bellevue, WA, USA), a start-up dedicated to metamaterial-based LiDAR systems; and Metacept, a start-up designing and building complete electromagnetic systems. These seven start-ups target major industries where metamaterials have a highly likelihood of disruption **[D]** and have already attracted ~$534M of investment by the end of 2020 **[D, E]**. In doing so, they have helped create an entirely new market, the global metamaterial market, which is valued in the billions of dollars **[D]**.

Kymeta – Using metamaterials for always-on satellite connectivity

The most prominent of these companies is, Kymeta, a mature start up founded by Nathan Kundz, a metamaterial co-author with Pendry and Smith. Kymeta's technology directly derive from fundamental research undertaken by Pendry and his close collaborations with Smith and Kundz at Duke University. Following Intellectual Ventures incubation of the research, Kymeta was spun out in August 2012 and by the end 2020 had attracted over $330M of investment and is valued at between $500M-$1B **[E]**. Kymeta state that the research performed by Sir John Pendry was key to the technology and products they are currently selling and developing. A Kymeta series of blogs published in June 2017 states **[F]**: "*The cloak decisively demonstrated the power of transformation optics that Dr. Pendry had conceptualized, expanding the set of tools available for optical and electromagnetic design. Transformation optics and related techniques would later become part of the underlying tool set for Kymeta's technology*."

In January 2016 Toyota announced a partnership with Kymeta with an investment of $10M **[G]**, with the plan to integrate Kymeta's flat antenna technology into their future vehicles to allow for stable high bandwidth satellite communications on-board their vehicles, enabling autonomous vehicles. In March 2017, Kymeta launched the first commercially available, flat, electronic steering, metamaterials-based satellite antenna, the Kymeta mTennau7 which at wholesale costs $25,000 per terminal **[A]**. Using the properties of metamaterials, this flat antenna removes the requirement of a moving dish to maintain always on satellite communications - opening new possibilities for high-speed satellite data communications.

In October – December 2017 following the destruction of the Hurricane Maria, Puerto Rico was left without communications. Kymeta provided antennas to partners on the ground who visited 33 communities enabling 22,266 internet sessions that generated 813.44 GB of data usage and allowed residents to use temporary ATMs, file 2,504 Federal Emergency Management Agency applications and contact family and friends **[H]**. This rapid response was made possible by metamaterial-based technology. Furthermore, the technology enables emergency services to maintain communications during disaster response, especially in remote locations, continuous connectivity to marine and land vehicles **[H]**. At present Kymeta lists over 100 partners in 40 counties **[I]** with companies covering government, defence, media, maritime, mining, oil, and vehicle-based solutions.

Metamaterials in autonomous cars, 5G, and wireless charging

A key application area for metamaterials is in the autonomous driving marketplace, where significant investment has taken place from many of the major car manufacturers. Toyota and Hyundai have invested $10M in Metawave **[J]**, founded in 2017 (https://www.metawave.co/). The Metawave automotive radar system steers a highly-directive RF beam that can accurately determine the location and speed of all road objects - in all-weather conditions and cluttered environments.

Metawave also exploit metamaterial technology in 5G networks (which will be up to 1000 times the speed of 4G) utilizing a smart beam-forming approach that directs energy toward a specific user's device to provide the bandwidth needed to support the desired online experience and minimize source power requirements.

In the UK, Metaboards (https://www.metaboards.com/), founded in 2016 has recently secured $5M in funding to support the development of their metamaterials-based technology **[K]** to transmit and control magneto inductive waves. This is vital technology in the ability to remotely power electronic devices across large surfaces without the need for alignment and should have enormous implications in charging of consumer electronics.

Manipulating visible radiation using metamaterials

Metamaterial Technologies Inc. (http://www.metamaterial.com/), one of the earliest metamaterials companies founded in 2013, has developed eyewear protection for pilots (metaAIR Aviation Eyewear, commercially available since 2019) to eliminate the ever increasing problem of laser light strikes on aircraft. Variations of this product will also have relevance to the defence marketplace. By using metamaterial technology to trap sunlight from coming from all angles, Metamaterial Technologies Inc have also manufactured thin solar films that have the ability to increase the efficiency of solar cells.

Influence on policy and investment surrounding metamaterials

Through the research led by Pendry, the emergence of metamaterials and their properties regarding electromagnetic radiation has led the field to attract interest from national governments and defence programmes. An example of this is with the direction and policy decisions taken by Dstl and the MoD. A Dstl Senior Fellow, states that due to the interest in metamaterials he was asked to form the Emerging Technology Programme, now the Futures Programme **[L]**. Furthermore, they write "*This programme now deploys more than £15M per annum to horizon scan and explore unfamiliar, uncertain game-changing science and technology to mitigate the risk of technological surprise; and this is now influencing right to the top of UK government to inform policy, strategy and legislation relating to the importance of emerging technology, including metamaterials. More specifically in relation to metamaterials, the MODs core research portfolio is comprised of 25 programmes, today some 8 of these programmes are funding research in metamaterials and relying on talent skilled in metamaterials both internally and in the supply chain; this highlights the diversity of technological and application relevance*."

More widely John Pendry's research has led metamaterials being a focus for UK industry. The head of Materials for the Knowledge Transfer Network writes "*The area* [metamaterials] *was featured strongly in this year's Materials Research Exchange Showcase (MRE 2020) to get potential investors engaged and has led to the recent launch of the Metamaterials Innovation Network to work with the investment community and industry to exploit the opportunities offered by the extensive academic research.*" **[M]**

Such engagement with industry and policy makers has ensured that Metamaterials are recognised by the UK government as one of the key branches of advanced materials that would help to grow UK's wealth and well-being **[M]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] News article on metamaterial in products https://www.ft.com/content/c6864c76-de7d-11e7-a0d4-0944c5f49e46 (Archived here)
[B] News on John Pendry's research being using in metamaterial based products https://www.imeche.org/news/news-article/feature-'magic'-metamaterials-offer-amazing-new-properties (Archived here)
[C] Netgear using metamaterials https://www.techradar.com/news/routers-storage/networking/wi-fi/internet/broadband/netgear-is-living-in-a-metamaterial-world-181197 (Archived here)
[D] Letter from Intellectual Ventures
[E] Combined financial data for Kymeta, Evolv Technology, Echodyne, Pivotal Commware, Carillon Technologies and Lumotive from Crunchbase and Pitchbooks (Archived here)
[F] Statement from Kymeta on the importance of John Pendry's research in their products (Archived here)

[G] Partnership between Toyota and Kymeta https://global.toyota/en/newsroom/corporate/25249394.html (Archived here)
[H] Kymeta's work in deploying their metamaterials based technology (Archived here)
[I] Kymeta partners https://twitter.com/KymetaCorp/status/1343568559620894721 (Archived here)
[J] Investment to Metawave https://www.businesswire.com/news/home/20180515005064/en/Metawave-Raises-Additional-10-Million-Deliver-Smart (Archived here)
[K] Investment to Metaboards https://www.siliconrepublic.com/start-ups/metaboards-metamaterials-wireless-charging-funding (Archived here)
[L] Letter from Dstl Senior Fellow Principal Advisor to MOD for electromagnetic materials, and emerging technologies
[M] Letter from Head of Materials, Knowledge Transfer Network