Institution: Imperial College London

Unit of Assessment: 9 Physics

Title of case study: P11 - Metamaterials and transformation optics: commercial, communication and defence impacts

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

Metamaterials deliver electromagnetic properties not available in natural materials. 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. These powerful concepts, originally developed by Prof John Pendry, have engendered massive interest in the electromagnetic community encompassing radio frequency (RF) through to optical applications. His advice is sought by numerous companies and these concepts are now filtering through into products. In the last 5 years there has been great involvement of industry and particularly of the defence establishment in the USA who run several multi mullion dollar programs on metamaterials based at DARPA, WPAFB and Sandia. A company, KYMETA, was formed in 2012 to market this technology with $12M of investment funding, and is developing a laptop-sized antenna that gives instant Internet hotspot access anywhere in the world, with an ultimate application allowing cheap and fast Internet connections for the everyday consumer. In the UK, BAE Systems is using metamaterials for several applications including compact, directional antennas.

2. Underpinning research (indicative maximum 500 words)

The concepts of metamaterials and transformation optics were originally developed by John Pendry, a professor at Imperial since 1981 but working as a consultant of the Marconi Company from 1996 to 2000. These concepts have been extensively patented both by The Marconi Company and by Intellectual Ventures, with Pendry's name appearing on more than 70 patents in the field [P1].

The project began with the consultancy at Marconi, during the course of which Pendry realised that electromagnetic properties of materials were as much influenced by their structure as by their chemical composition [1, 2]. The name metamaterials was later applied to the concept by others. Naturally occurring material properties available are somewhat limited and properties such as negative refraction can only be accessed via metamaterials. The same is true of magnetism at optical frequencies which Landau claimed did not exist but can now be created using metamaterials.

Negative refraction, first postulated by Veselago in 1968 and only realised once metamaterials were available, is a remarkable phenomenon introducing many new ideas into optics. For example Pendry showed in 2000 [3] that using negative refraction it is possible to build a lens whose resolution is not limited by the wavelength. Nanometre scale objects have subsequently been imaged by such a device and this paper, cited more than 4,000 times, has given birth to the present intense interest in the sub wavelength control of light.

Transformation optics had its origin in research Pendry conducted at Imperial in the mid 1990's and early 2000's and took a sabbatical during 2002-2003 to focus on metamaterials during this critical period. This research was most famously was used to design a cloak of invisibility in 2006 [4] which was rapidly translated, using metamaterials, into an experimental realisation [5]. 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. Valid on all length scales it provides an intuitive design paradigm that has variously been employed to construct novel RF devices and sub wavelength optical systems [6].

The underpinning research on metamaterials and transformation optics is highly theoretical but has been translated into experiment and into working devices by others who have taken up these

concepts and applied them. An extensive collaboration exists with Professor David Smith at Duke University in the USA. His group specialises in the experimental realisation of the metamaterial concept and has extensive involvement with companies such as Toyota, Boeing, and Intellectual Ventures, as well as with DARPA, the CIA and the US military.

The research was funded from numerous sources including EPSRC, the Leverhulme Trust, DSTL, the European Commission, AFOSR and Kodak.

List of **patents** arising involving John Pendry, many of which arise from the work described above: *http://www.patentmaps.com/inventor/John_Brian_Pendry_1.html*

3. References to the research (* References that best indicate quality of underpinning research)

[1] J.B. Pendry, A.J. Holden, W.J. Stewart, I. Youngs, "*Extremely Low Frequency Plasmons in Metallic Mesostructures"*, Phys. Rev. Lett*.,* 76**,** 4773-6 (1996). DOI, **1,650 citations (WoS as at 7th Nov 2012)**

[2] *J.B. Pendry, A.J. Holden, D.J. Robbins, and W.J. Stewart, '*Magnetism from Conductors and Enhanced Non-Linear Phenomena',* IEEE transactions on microwave theory and techniques, 47, 2075-84 (1999). DOI, **2,911 citations (WoS as at 7th Nov 2012)**

[3] *J.B. Pendry, '*Negative Refraction Makes a Perfect Lens'*, Phys. Rev. Lett*.,* 85**,** 3966-9 (2000). DOI, **4,352 citations (WoS as at 7th Nov 2012)**

[4] *J.B. Pendry, D. Schurig, and D.R. Smith*, 'Controlling Electromagnetic Fields'*, *Science,* 312, 1780-2 (2006). DOI, **1,847 citations (WoS as at 7th Nov 2012)**

[5] D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, D. R. Smith, '*Demonstration of a Metamaterial Electromagnetic Cloak at Microwave Frequencies'*, Science*,* 314**,** 977-80 (2006). DOI, **1,517 citations (WoS as at 7th Nov 2012)**

[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). DOI, **74 citations (WoS as at 7th Nov 2012)**

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

The research outlined above, continuously developed over a period of more than a decade, has introduced a new paradigm to electromagnetic studies in general, impacting the electromagnetic spectrum from static fields to optical frequencies. The work has since resulted in numerous interactions with commercial and government organisations. Pendry has personally consulted on metamaterials for BAE Systems (2008-9), The Marconi Company (1996-2000), Thales (2009), Defence Science and Technology Laboratory (DSTL, 2012-), Wright-Patterson Air Force Base (WPAFB, 2011), the US Air Force Office of Scientific Research (AFOSR), EADS (2008), Kodak (2007-11), Intellectual Ventures (2004-), and Corning (1999-2000). These radical new concepts are now filtering through into products.

KYMETA Corporation

Intellectual Ventures developed a satcom device in 2010-11 that is an order of magnitude cheaper than current products with a target marketing price of $500 and operates from the USB port of a laptop. The company had been interested in applications of metamaterials for some time [A] and in 2010 began to explore, in earnest, what "*markets could be penetrated or created through the integration of metamaterials-based designs*" [B]. Its main focus was on the development of flat-panel reconfigurable antennas. In this area it was able to "*leverage the work [Pendry had] done in metamaterials*" [B]. Specific areas of influence included resonant element design and numerical tools which help to predict system response; such as homogenization techniques. Pairing these toolsets with newly developed techniques in reconfigurable metamaterials, holographic metamaterials and high-efficiency system design and fabrication resulted in a "*new technology*" referred to as Metamaterial Surface Antenna Technology (MSA-T) [B, C, D]. This "*technology has many applications, but the first target for Intellectual Ventures (IV) was selected to be the satellite industry"* [B]. In *"an effort to exploit this opportunity, IV spun off a new company, Kymeta Corporation*" [B]. Kymeta is currently (Aug 2013) over a year into its existence as an independent

entity and "*has attracted significant interest in its industry; including large development contracts from leading satellite service providers*" [B]. Kymeta has 56 full time employees (as of July 2013) and is continuously hiring [K] and was formed with $12M in investment funding from Bill Gates, Lux Capital and cable company Liberty Global [E, F].

By using metamaterials, the antenna will be able to electronically tune the array *"to point and steer a radio signal toward a satellite",* creating *"an unbroken broadband link to whatever device is carrying the antenna—whether it's a boat, plane, or laptop"* [F]. The company's first product will be *"a portable, laptop-sized antenna that gives you an instant Internet hotspot anywhere in the world"* [F], with an ultimate application allowing *"cheap and fast Internet connections on airplanes, trains, buses, cruise ships, and military vehicles"* [F]. Intellectual Ventures says the company's first customers will likely be mining and defence [F]. In addition, a spokesperson at Kymeta said*: "the device has potential benefits for news reporters in the field, emergency responders in disaster areas, or even just average consumers looking to untether from public Wi-Fi and mobile broadband signals"* [G].

Kymeta, based in Washington state, expects to have its first products commercially available in 2015 [H]. It has already attracted significant interest in its industry including "*large development contracts from leading satellite service providers*" [B]. Intellectual Ventures continues to invest in new application areas for MSA-T and metamaterials technology more broadly in a variety of application areas [B].

BAE Systems

BAE Systems has shown a longstanding interest in metamaterials, originating with the work with Marconi (now part of BAE) in the 1990s, and is looking to apply the principles behind metamaterials and transformation optics in several areas. The techniques from the work between Pendry and Marconi "*have been used within missile seekers for RF filters and reflectors, and in "stealth" applications where frequency dependent absorption & filtering built into a structure is useful*" [I]. Acknowledging Pendry's role in the area of metamaterials, BAE Systems states that "*essentially, you have fathered a whole area of scientific and engineering endeavour*" [I]. A further application of metamaterials by BAE is that in antennas, particularly making antennas much more compact with increased directionality. Such developments are "*very significant in designing small, compact antennas for small platforms including Unmanned Aerial Vehicles, and small antennas to work at very low frequencies, for example for submarines*" [I].

A study for the European Defence Agency (EDA) on Active Camouflage and cloaking informed BAE of the difficulties in using transformation optic approaches to hide a complex object, which in turn gave very good indications of "*what might be practical for military applications*". As a result BAE's studies "*have looked at extending the potential uses of metamaterials and the transformation optics approach into [the] underwater acoustics domain*" [I]. A further area of application for BAE which is being considered is in counter IED blast protection, with metamaterials structures potentially being able to divert a blast wave around an object.

BAE comments on the significant level of activity worldwide relating to metamaterials. It monitors the literature and patents arising in this area (particularly those with relevance to a company like BAE Systems) and has noted that a very significant level of work is being undertaken in the USA as well as a significant level in China.

US Department of the Air Force and Office of Scientific Research (AFOSR)

In 2006 Pendry participated in an AFOSR-sponsored collaboration with David Smith at Duke University. Since then research in metamaterials has exploded and as a granting agency this is reflected in the AFOSR's records which "*presently include over thirty grants listing "metamaterials" as a keyword, totalling over $11 million in funding, on projects ranging from cloaking to plasmonics, particle-based nanoantennas, implementation of electrically-controlled metamaterials, and a great deal more*" [J]. The US Air Force's interest in the subject is a direct result of engagement with Prof Pendry and the results of his previous research [J].

Pendry actively engaged with AFOSR and related offices such as the Air Force Research Labs (AFRL), visiting the labs on a number of occasions and conferring with them on basic research tasks. His "*consultation was directly responsible for advances in an AFRL program to develop conformal antenna arrays, using RF-photonic elements to sample incident fields and embed them on an optical carrier*" [J]. This allowed flexible beam forming, imaging, and other applications, in addition to improved electromagnetic interference resistance. Pendry's "*recent work on broad band light harvesting structures was directly applied to that [AFRL] program to yield improved bandwidth and overall efficiency, resulting in a recent demonstration of a first-of-its-kind metamaterial conformal RF-photonic array*" [J]. The AFOSR testifies that the contributions of Pendry and his group have had "*considerable impact*" on the organisation.

Widespread impact

Almost every major organisation concerned with electromagnetism has a shown interest in this field. The impact of metamaterials is widespread with many thousands of references in the scientific and popular press and on television. For example, there was an article on the BBC discussing Pendry's research and its application in the development of an invisibility cloak [K].

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

[A] Intellectual Ventures Metamaterials page, http://www.intellectualventures.com/OurInventions/Metamaterials.aspx (archived at https://www.imperial.ac.uk/ref/webarchive/dqf on 9/8/13)

[B] Letter from Chief Technology Officer, Kymeta Corp (letter available from Imperial on request)

[C] Kymeta MSA-T Technology page, http://www.kymetacorp.com/technology/ (archived at https://www.imperial.ac.uk/ref/webarchive/lqf on 9/8/13)

[D] Intellectual Ventures MSA-T page, http://www.intellectualventures.com/index.php/inventions-patents/our-inventions/msa-t (archived at https://www.imperial.ac.uk/ref/webarchive/mqf n 9/8/13)

[E] Xconomy article, 'Kymeta Raises $50M To Upend Satellite Antenna Business', 9/7/13, http://www.xconomy.com/seattle/2013/07/09/kymeta-raises-50m-to-upend-satellite-antenna-business/ (archived here)

[F] IEEE Spectrum article, 22/8/12, http://spectrum.ieee.org/tech-talk/telecom/wireless/intellectual-ventures-spinoff-to-market-metamaterials-antennas (archived at https://www.imperial.ac.uk/ref/webarchive/qqf on 9/8/13)

[G] Forbes article, 'Bill Gates Invests In Intellectual Ventures' Spin-Out Kymeta', 21/8/12, http://www.forbes.com/sites/ericsavitz/2012/08/21/bill-gates-invests-in-intellectual-ventures-spin-out-kymeta/ (available here)

[H] Kymeta Portable Satellite Terminal page, http://www.kymetacorp.com/products/portable-satellite-terminal/ (archived at https://www.imperial.ac.uk/ref/webarchive/nqf on 9/8/13)

[I] Letter from Technology Executive, BAE Systems, 4/2/13 (letter available from Imperial on request)

[J] Letter from International Program Officer, US Department of the Airforce, Airforce Office of Scientific Research, 15/2/13 (letter available from Imperial on request)

[K] BBC News 'Invisibility Cloak' article, 12/11/12, http://www.bbc.co.uk/news/science-environment-19661503 (archived at https://www.imperial.ac.uk/ref/webarchive/fqf on 9/8/13)