Institution: University of Exeter

Unit of Assessment: 9, Physics

Title of case study:

Harnessing the power of 'metamaterials' to drive innovation at QinetiQ

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

The manipulation of electromagnetic radiation using novel materials by physicists at the University of Exeter has given rise to new technologies for military stealth applications, anti-counterfeiting measures and Radio Frequency Identification (RFID) of pharmaceuticals, machinery and perishable goods. The research findings increased the global competitiveness of FTSE 250 defence and security company QinetiQ, driving innovation in its work with the MoD and leading to the creation of a successful spin-out, Omni-ID, that is meeting demand in the high-growth RFID market. Exeter's research underpinned the EPSRC decision to award the University and QinetiQ £3.2m to exploit applications of their patented technology.

2. Underpinning research (indicative maximum 500 words)

The development of novel electromagnetic materials is key to the next generation of 'stealth' technology for military use. These 'metamaterials' are also creating new solutions in the high-growth markets of Radio Frequency Identification (RFID) and anti-counterfeiting measures. About 5% of world trade is now in counterfeit goods, and unfortunately this booming industry is now moving from innocuous items like shoes and handbags to fake medicine and pesticides. By controlling electromagnetic radiation, it is possible to make performance improvements to RFID tags that make items easier to track and locate, and to help prevent theft and forgery.

Since 1997, the Electromagnetic and Acoustic Materials group at Exeter's School of Physics and Astronomy has forged a strong research partnership with the Smart Materials & Technologies (SMT) team at leading defence multinational QinetiQ. The main thrust of the collaborative research has been the investigation of structures that can tailor electromagnetic radiation to specific requirements. Led by Roy Sambles, Professor of Experimental Physics (1991-), and Professor Peter Vukusic (1998-) this research began with a MoD Research Fellowship in 1998 that funded a collaborative study of the structural colouration of butterflies [3.1, 3.2]. By understanding how butterfly wings create a myriad of visual effects (e.g. vivid colours) through subtle changes in the size, shape or structure of fine scales on their surface, the team could apply these principles to control infrared, microwave or radio wave radiation.

Further research provided a comprehensive understanding of the underlying optical effects caused by multi-layered structures within butterfly wings. This inspired a patented technology that could be used to create much clearer optical signatures within credit cards and banknotes to counter forgery [3.3]. In addition, it prompted our researchers to investigate whether structures based on butterfly wings could be metallised and scaled up to operate at longer wavelengths in the RF domain. This further prompted other thinking, for example, in the context of stealth technologies, could the principles be applied to render a military vehicle undetectable to radar?

The Exeter team embarked on new research at microwave frequencies, following the finding by Thomas Ebbesen that it is possible, to transmit light efficiently through opaque metal films perforated by arrays of subwavelength holes via surface plasmons. Sambles and Alastair Hibbins

(Associate Professor) created 'designer' surface plasmons at microwave frequencies [3.4]. The key discovery came in 2004 [3.5] when the Exeter team modelled the electromagnetic response of ultra-thin metal-clad wave-guiding structures, formed by simply removing metal from the cladding, giving a periodic array of sub-wavelength slits. The devices were found to absorb or transmit radiation of wavelengths some 100 times greater than their thickness, and compress millimetre waves into microns. This breakthrough drove fresh work at QinetiQ to prevent RF leakage through small gaps such as joints in airframes and gave QinetiQ researchers the opportunity to explore new ways to capture and safely redirect RF signals, rather than simply absorbing them in lossy materials [3.6].

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

References in bold best indicate the quality of the underpinning research.

3.1. **"Quantified interference and diffraction in single Morpho butterfly scales", P. Vukusic, J. R. Sambles, C. R. Lawrence and R. J. Wootton Proc. Roy. Soc. B, 266, 1403 (1999).**

3.2. **"Structural colour - Colour mixing in wing scales of a butterfly", P. Vukusic, J. R. Sambles and C. R. Lawrence, Nature 404, 457 (2000).**

3.3. WO Patent (2000) GB00/01837 (Lawrence C R, Sambles J R and Vukusic P), 'Multilayer surface (specialised surface).': http://www.google.ca/patents/US6753952

3.4. "Grating-coupled surface plasmons at microwave frequencies", A. P. Hibbins, J. R. Sambles and C. R. Lawrence J. Appl. Phys. **86**, 1791 (1999).

3.5. **"Squeezing millimeter waves into microns", A. P. Hibbins, J. R. Sambles, C. R. Lawrence and J. R. Brown, Phys. Rev. Lett. 92, 143904 (2004) (note Lawrence and Brown both at QinetiQ) - *This paper is in the top physics journal and concerns the core of the very thin radar absorbing material VTRAM idea which was also patented (see [5.2] below). It has been cited over 63 times.***

3.6. "Angle-independent microwave absorption by ultrathin microcavity arrays", J. R. Brown, A. P. Hibbins, M. J. Lockyear, C. R. Lawrence and J. R. Sambles J. Appl. Phys. **104**, 43105 (2008) - *This paper broadens the essential idea of the VTRAM into an azimuthally invariant version.*

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

Research into electromagnetic and acoustic materials at the University of Exeter has driven major scientific innovations within QinetiQ. Much of the work has been in the military arena of several MoD agencies, including the Counter-Terrorism Centre. The importance of Exeter's input is captured by QinetiQ's investment of £3.7m in Sambles' research group over 15 years to support stealth-related R&D.

Exeter's input has, according to QinetiQ [5.1], "helped to maintain an innovative culture" within its Smart Materials Technology (SMT) team, which has one of the highest patent generation rates in the company. Fourteen patent applications [5.2-5,5.9] have been filed with Exeter and the SMT team won the Divisional Prize for Technology Innovation in 2012. Nine ex-Exeter Physics postgraduates and graduates are currently employed at QinetiQ Farnborough.

Sambles et al's 2004 paper [3.5] led directly to the creation of the Very Thin Radar Absorbing Material (VTRAM). VTRAM, patented in 2004, is believed to be the world's thinnest practical RF absorber. Recognising the commercial opportunities, QinetiQ turned its attention to using VTRAM in RFID tag technology. RFID tags are used for automatic identification and tracking, for example to locate pharmaceuticals in warehouses. However, the signal from standard RFID tags cannot be read if the tags are in close proximity to metals and liquids. QinetiQ found that a modified version of VTRAM could be used to design new tags that were shielded from the metal or liquid, thus RFID tags could be used on any metallic or water-filled container. This offered a solution to companies like WalMart who wished to RFID tag all their goods. QinetiQ developed a portfolio of patents and created the spin-out company Omni-ID in March 2007 [5.6]. The company was founded on the technology originally developed at Exeter with James Brown, who completed his PhD under Sambles in 2010 and was technical director from 2007 to 2012.

Omni-ID grew rapidly, from an initial offering of 3 products to a portfolio in excess of 20 products. In 2009 it received $15m in funding from investors on the back of strong initial market demand for its RFID tags. It secured another $8m in September 2011 to finance expansion. In 2012, it won 'Best in Show' [5.7] at the RFID Journal Awards for its Visual Tag System, which provides workers with real-time information and instructions regarding moving assets. Its high-frequency RFID tag technology is being used by the US Government, IBM and Bank of America for cheaper and more efficient IT asset management; by BP, Shell Oil and Petrobas to increase the traceability of assets through the oil production process; by BHP Billiton and Holt Cat for tool inventory; and by GE Healthcare and Johnson & Johnson for safe monitoring of pharmaceuticals [5.8]. Specialist tag sales since 2007 total more than $5 million, and it has created 15 jobs in the UK and another 115 around the world.

The development of several joint patents between Exeter and QinetiQ contributed to the award in 2009 of a three-year £3.2m EPSRC Knowledge Transfer Account, one of 12 KTAs in the UK, for the two partners to explore the commercial potential of the intellectual property generated over a decade of research. The KTA focused on developing anti-counterfeiting technologies; the International Chamber of Commerce predicts the value of counterfeit goods globally will exceed $1.7 trillion in 2015. By 2012 the project generated four patent applications [5.9] and inspired the creation of Arkiris Ltd [5.10], a company jointly run by Exeter and QinetiQ to work in the security and tagging markets. The Arkiris project has taken IP that was not being used by QinetiQ and developed it into technology that is being licensed in the fields of security and anti-counterfeiting. A QinetiQ funded project at Exeter is currently with a security customer to integrate a technology described in two patents into their product.

A further outcome of the research is a collaboration between Exeter, QinetiQ and Sweden's Institute for Surface Chemistry that has succeeded in identifying new technologies that can be used to prevent the counterfeiting of documents. A three-year £180k project with QinetiQ began in September 2012, using Exeter's expertise in electromagnetic metamaterials to explore new stealth technologies based on vibroacoustics. In the same month, QinetiQ also placed an Industrial CASE award within the School of Physics and Astronomy to develop a deeper understanding of the Terahertz regime and explore new markets in what is still relatively virgin territory for commercial and governmental applications.

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

5.1. Quote from Head of Research, Research Services, QinetiQ who held a MoD CRP Research Fellowship (1998-2001): 'Zero-order diffraction from biomimetic materials' – *A Fellowship held by Lawrence that was built around a collaborative study of 'optics in* *nature', which led to the creation of a range of novel radar absorbing materials (RAMs) and visible/infrared control mechanisms*.

5.2. 'Electromagnetic radiation absorber' – *A key patent, developed and further explored in the Arkiris project* – AS Treen, CR Lawrence, ***JR Sambles***, ***AP Hibbins*** (2004) US 10/565047 Also 'Electromagnetic radiation absorber' ***AP Hibbins***, CR Lawrence, ***JR Sambles***, AS Treen (2008) EP 1647172 B1

5.3. Other Patents for 'stealth':
'Textured Surface' – *RF absorption induced at a metal surface bearing two superimposed sinusoidal profiles. –* ***JR Sambles*** (2003) EP 1238295 B1
'Low frequency electromagnetic absorption surfaces' – *A dielectric appliqué that converts a metallic surface into an absorber. –* ***AP Hibbins***, CR Lawrence, ***JR Sambles*** (2004) EP 1206814B1
'Radiation Absorption' – *Multi-resonance version of original thin absorber (US 10/565047)*, CR Lawrence, ***MJ Lockyear***, PA Hobson, ***AP Hibbins***, ***JR Sambles*** (2013) WO2013014406-A2

5.4. Patents for anticounterfeiting:
'Specialised surface' – *A security feature that provides overt, covert and forensic functions.* CR Lawrence, ***JR Sambles***, ***PS Vukusic*** (2003) EP 1181673 B1
'Iridescent materials and devices' – A multilayer surface comprising at least two layers, that can be used as an anti-counterfeit device.
CR Lawrence, ***JR Sambles***, ***P Vukusic*** (2006) EP 1330666 B1
'Signature mark recognition systems' – *Grating-based device for guidance systems and security features. –* CR Lawrence, ***JR Sambles*** (2008) WO 1998037514 A1
'Optical Multilayer' – *An optical multilayer comprising textured surfaces suitable for use in anti-counterfeiting and/or security applications –* ***IR Hooper***, CR Lawrence, ***JR Sambles***, AS Treen (2013) WO2013/124607 A1 Filing date: Feb 7, 2013

5.5. Other Patent:
'Novel grating' – *A slat-based device that can act as a filter, beam-steerer and absorber.* CR Lawrence, ***JR Sambles*** – (2003) EP 1264364 B1

5.6. http://en.wikipedia.org/wiki/Omni-ID : The history of the Omni-ID RFID technology that was inspired by the work on metamaterials [3.1, 5.1].

5.7. http://www.rfidjournal.com/articles/view?9408

5.8. http://www.omni-id.com/resources/#casestudies

5.9. Patents from KTA:
(01/05/2012) GB 1207602.2: ***M Biginton***, ***MJ Lockyear***, ***IR Hooper***, AS Treen: 'Low profile near-field antenna for RFID systems' – *A new antenna for efficiently detecting multiple, randomly-aligned RFID tags: a major problem for many markets*
Patent filed (02/12/2010) CR Lawrence, AS Treen, ***IR Hooper***, ***JR Sambles***: 'Hidden images in sculpted multilayers' ref P7817
Patent filed (28/08/2011) CR Lawrence, AS Treen, ***IR Hooper***, ***JR Sambles***: 'Thin white surfaces via embossing techniques' ref P7855
Patent filed (07/11/2011) ***MJ Lockyear***, ***IR Hooper***: 'Low profile near-field antenna for RFID systems' ref P7841

5.10. http://www.arkiris.co.uk/kta/ : The official website for Arkiris Ltd the registered company that resulted from the collaborative EPSRC KTA project.