Institution: University of Southampton

Unit of Assessment: 13 Electrical and Electronic Engineering, Metallurgy and Materials

Title of case study: 13-12 Advancing Clean Energy Research and Biosecurity through Novel Bragg Grating Technologies

1. Summary of the impact

Ultra-precise Bragg grating writing-technology, invented in the Optoelectronics Research Centre (ORC), has led to impacts in the areas of **security, safety, detection of bio-hazards** and the underpinning laser technology currently being pursued for **clean energy** generation for future energy security. This case study highlights two aspects of the technology namely: ***planar-based*** for optical microchip sensors in areas such as portable detection of biohazards, which has resulted in the spin-out Stratophase, and ***fibre-based*,** inside the US National Ignition Facility (NIF), the world's largest laser system, based in California, built for fusion-energy research, which has ORC fabricated fibre Bragg gratings within its laser amplifier chains. These ultra-high precision laser-written engineered gratings have enabled important advances in biosecurity, management of environmental hazards and clean energy research.

2. Underpinning research

The underpinning research uses a process of UV (244nm) stroboscopic laser direct-writing which has been applied in both geometries. For fibre-based gratings (***FBG***), the underpinning research has been focussed on ORC specialty fibres with combined functionality of high rare-earth concentrations and high levels of photosensitivity, and inscription/fabrication-techniques capable of producing gratings of very long length (>1metre) with unprecedented phase- and amplitude-complexity. For planar-based gratings (***PBG***) the challenge is to obtain highly uniform waveguides and gratings. A technique was developed to write the gratings and waveguide simultaneously. This approach allows the creation of sensors in a fluidic compatible format that allows for sensing of multiple chemical or biochemical targets.

Fibre Bragg Grating underpinning research has focussed on

- Development of high-concentration rare-earth doped (e.g. Yb^{3+}, Er^{3+}, or a combination of both) photosensitive fibres suitable for direct writing of short-cavity, high-efficiency, single-frequency fibre-lasers with output powers in the 10's of mW range, including research on glass spectroscopy and design of application-specific grating spatial and phase profiles.
- Demonstration and characterisation of high-performance rare-earth doped distributed feedback fibre-lasers yielding ultra-low phase- and intensity-noise. This work led to the first demonstration of all-fibre lasers operating in the important 1.5µm telecommunications wavelength band [3.1 and *US Patent 5,771,251*], and soon after to the demonstration of fibre-lasers in Yb^{3+} co-doped fibres operating in the 1µm wavelength region, as required for the front end of the NIF laser-system [3.2]. These distributed feedback fibre-lasers, all of which are based on our original technology, are now sold by several companies (NKT Photonics, Redfern Optical Components, IDIL Fibres Optiques, etc)
- Design of FBG fabrication methods to achieve full control of the phase- and amplitude-profile of grating-devices to allow for very complex apodisation and phase-shifted all-fibre structures [3.3 and *US Patent Nos. 6,072,926 & 6,334,013 & 6,384,977*].

Planar Bragg Grating underpinning research has focussed on

- New ways of creating optical waveguides with integrated gratings, by developing a single-step writing-process that optimises both of these steps [3.4].
- A technology that has been used to develop sensors by exposing the gratings to a fluid through an etched window. If the refractive index of the medium (for example water or antibodies) at the waveguide surface changes, this can then be sensed with extremely high precision by monitoring the wavelength that is back-reflected [3.5].

- Several gratings can be integrated along one waveguide so that multiplexed measurements at each grating site may be made, and if each grating is made sensitive to a different biochemical analyte, then multiple analytes may be detected simultaneously with extreme sensitivity [3.6].
- All the research on Bragg grating technology was carried out under several large-scale EPSRC research-grants [G1, G2, G4, G5, G6] while the underpinning research on the grating inscription was funded via industrial-funding from Pirelli Cavi SpA [G3].

This research was carried out between 1994-2008 (FBG), and 1998-2013 (PBG) respectively, involving the following *Sir David N. Payne*, (Director ORC). *Jon T. Kringlebotn*, (Visiting researcher from Optoplan A/S 1994-1996). *Wei H. Loh*, (Senior Research Fellow, joined Bragg Photonics Inc., Canada in 1997, returning to the ORC in 2004). *Richard I. Laming*, (Deputy Director ORC. Left the ORC to form spin-out Kymata Ltd. in 1998). *Michalis N. Zervas*, (Senior Research fellow, now Chief Scientist of ORC spin-out SPI lasers). *Martin J. Cole* (Ph.D.-student, joined QTERA, USA, in 1999). *Morten Ibsen* (Ph.D.-student, now Reader in the ORC). *Michael K. Durkin* (Ph.D.-student, joined SPI lasers in 2000). *Peter G.R. Smith* (Professor, ORC and co-founder of Stratophase in 2003). *Richard B. Williams* (Senior Research Fellow in the ORC, became CEO of Stratophase in 2003). *Sam P. Watts* (Ph.D.-student in the ORC, became Business Development Officer of Stratophase in 2003). *Greg. D. Emmerson* (Ph.D.-student in the ORC, became CTO of Stratophase in 2003). *Corin B.E. Gawith* (Principal Research Fellow, seconded to Covesion/Stratophase in 2009).

3. References to the research (best 3 are starred)

*****[3.1] J.T. Kringlebotn, J.-L. Archambault, L. Reekie, D.N. Payne, ‘Er^{3+}:Yb^{3+} -codoped fiberdistributed-feedback laser’, *Optics Letters*, **19**, p.2101, 1994.

[3.2] D.F. Browning, G.V. Erbert, ‘DFB Fiber Laser: The Heart of the National Ignition Facility’ Lawrence Livermore National Laboratories, NIF report, UCRL-ID-155446, 2003.

*****[3.3] M. Ibsen, M.K. Durkin, M.J Cole, R.I. Laming, ‘Sinc-sampled fiber Bragg gratings for identical multiple wavelength operation’ *Photon. Technol. Lett.*, **10**, p. 842, 1998.

*****[3.4] G.D. Emmerson, S.P. Watts, C.B.E. Gawith, V. Albanis, M. Ibsen, R.B. Williams, and P.G.R. Smith, "Fabrication of directly UV-written channel waveguides with simultaneously defined integral Bragg gratings," *Electronics Letters,* **38**, p. 1531, 2002.

[3.5] G.D. Emmerson, C.B.E. Gawith, I.J.G. Sparrow, R.B. Williams, and P.G.R. Smith, "Physical observation of single step UV-written integrated planar Bragg structures and their application as a refractive-index sensor," *Applied Optics,* **44**, p. 5042, 2004.

[3.6] R. M. Parker, J.C. Gates, M.C. Grossel, and P.G.R. Smith, "In vacuo measurement of the sensitivity limit of planar Bragg grating sensors for monolayer detection," *Applied Physics Letters*, **95**, p. 173306-1, 2009.

Underpinning Grants:

[G1] IRC in optical and laser related science & technology, EPSRC grant GR/J62036/01, W.A. Gambling, 1/4/1994 to 1/10/1996, £6,952,536

[G2] IRC rolling grant: The Optoelectronics Research Centre, EPSRC grant GR/L26971/01, D.N. Payne & D.C. Hanna, 1/10/1996 TO 30/09/2000, £6,397,585.

[G3] Rolling Pirelli Cavi SpA contracts, D.N. Payne, 1997 – 2000, £1,000,000 p.a.

[G4] Advanced optical fibre and waveguide devices and microstructured optical materials, EPSRC grant GR/M81854/01, P.I = D.N. Payne, 1/10/1999 -30/9/2003, £2,056,683.

[G5] Fabrication of Microstructured Glass & Crystal Photonic Materials & Devices , EPSRC grant GR/T11746/01, P.I. = D.N. Payne 1/4/2004. Subsumed into Portfolio Partnership in Photonics, 30/9/2004, £2,741,404.

[G6] Portfolio Partnership in Photonics, EPSRC grant EP/C515668/1, P.I was. D.N. Payne, 1/10/2004 – 31/3/2011, £7,179,095.

4. Details of the impact

The impact for our Bragg grating technology spans several related areas, which reflect the intrinsic characteristics of fibre (FBG) and planar (PBG) geometries. Impact here relate to ***Economic*** (*spin-out, creation of new business and adoption of new processes)* as well as ***Environmental*** (*achievement of environmental (green) objectives).*

FBG research has been directed at a wide range of technologies, but the focus here is for NIF, the National Ignition Facility, in Livermore, California, U.S.A. This is a massive enterprise aimed at fusion research, (which is hoped will replace current fission-based power stations) and which has at its heart, ORC-developed passive and active fibre Bragg grating technology.

The FBG process that led from research to impact was via the ORC involvement from an early stage of the developments of NIF, and concerned the contributed key technology and knowhow that was developed through FBG and optical amplifier designs. The 192 laser beams in NIF originate from a single 5cm long DFB fibre-grating-laser master-oscillator conceived as a concept and *first demonstrated* at the *ORC.* The critical requirement is that this laser operates at the precise wavelength required for all downstream laser and amplifier components [5.1, 5.2], and was chosen because of its exceptional wavelength and power-stability. Precise pulse control in the preamplifiers and the signal delivery fibres within NIF is done with 30cm long ORC-fabricated passive chirped FBGs. The critical operational requirements (long length, exact matching of passive dispersion-orders and low phase-noise) can only be achieved with ORC-fabricated gratings as there are no commercial suppliers or any other research organisations that are capable of delivering these requirements. It was this ***unique capability*** that led to NIF scientists collaborating directly with the ORC [5.3].

The nature of the impact is the possibility that fusion-based energy generation can provide that unlimited source of clean energy that would solve one of our most fundamental problems. Fusion has been termed the 'holy grail' and ‘game-changer’ of future energy technology, and it has vast potential to help meet the world’s future energy challenges. The success and promising concepts demonstrated at NIF are already spilling over into beneficiaries in Europe, China and Russia where several facilities are under construction creating new jobs in the industry, and promoting high-tech laser-development [5.4]. While it is recognised that there are many challenges remaining to be solved, it is undeniable that cheap and renewable energy is perhaps number one on the wish-list of every government. The world is closely following the fusion energy programme, which, should it prove successful, would solve one of the most fundamental problems of ***energy security***. It is a testament to its significance that grating-technology researched and developed at the ORC lies at the very heart of the quest for controlled fusion, and that a significant step towards this goal was reached on 5-July 2012 by NIF reaching its 1.8MJ, 500TW milestone [5.5], and on 13-August 2013 when, for the first time ever from any fusion facility in the world, the amount of energy released through the fusion reaction exceeded the amount of energy being absorbed by the fusion fuel [5.6].

The PBG process started from 1999, when Bragg gratings in planar geometries were developed, together with the first proof of concept for sensors. Prompted by feedback from industry, the University of Southampton patented the inventions (e.g. US Patent No. 7,440,653, filed May-2003, issued October-2008) and attracted VC-funding to establish the spin-out Stratophase, which initially had two core technologies, UV-written Bragg gratings and periodically poled lithium niobate (PPLN). The second of these was itself spun out in 2009 in another company, Covesion, which is the subject of a different case study. Soon after the first VC-funding, two patents were filed on evanescent field sensors utilising the original grating patent (US Patent No. 7,715,005, filed July-2005, issued May-2010, US Patent No. 7,541,573, filed July-2005, issued June-2009).

The nature of the impact and beneficiaries: Stratophase has led to ***high-tech employment*** (presently 12 staff), investment by US Investors of £6.8m, and cumulative sales and development contracts worth £3.2m [5.7]. Users of this technology include:

- CPI, Glaxo-Smith-Kline, Greenbiologics, for feedback control during bio-pharma production.
- DSTL and the MoD who successfully demonstrated detection of live agent bio-hazards at

Porton Down including ricin and anthrax, providing the UK with a national capability for detection of these ***bio-hazards*** [5.8].

- A number of life sciences companies [5.9] via the launch of a new set of products (Stratophase Ranger™) offering off-the-shelf solutions for batch monitoring and ***process-control***.
- The University of Cambridge's Institute of Biotechnology, Bristol Industrial and Research Associates and the Chelsea Technologies Group. In June 2011 Stratophase reported the successful completion of a feasibility study into a portable sensor unit for detecting ***foot-and-mouth disease***, which could allow veterinarians, inspectors and even farmers to diagnose the disease much more quickly than is currently possible using laboratory analysis [5.9].
- A contract with Biral, for the development and demonstration of live agent *air-sampled* detection capability at the Porton Down BSL 4 lab for the most toxic materials (e.g. Anthrax). The contract, awarded by the MOD/DSTL, was for £1.2m and is an excellent example of University research having impact on the work of Government scientists for greater protection of the UK population. [5.10]

5. Sources to corroborate the impact

Corroboration of DFB fibre lasers and chirped Bragg grating use in NIF, impact of NIF technology and milestones:

[5.1] 'Special Issue: Laser Technology for the National Ignition Facility', ICF Quarterly Report: October-December 1998, vol.9 no.1: UCRL-LR-105821-99-1, https://e-reports-ext.llnl.gov/pdf/236453.pdf

[5.2] D.F. Browning, G.V. Erbert, 'DFB Fiber Laser: The Heart of the National Ignition Facility', Lawrence Livermore National Laboratories, NIF report, UCRL-ID-155446, 2003.

[5.3] Barty, C.P.J. et al., 'An overview of LLNL high-energy short-pulse technology for advanced radiography of laser fusion experiments', Nucl. Fusion, vol. 44, no. 12, S266, 2004. Contact: Chief Technology Officer for NIF and Photon Science.

[5.4] http://www.hiper-laser.org/, and and Savage, L.: 'HiPER to expand Europe's role in laser-driven nuclear fusion technology', Photonics.com, June 2012. http://www.photonics.com/Article.aspx?AID=51006%20 and http://www-lmj.cea.fr/index-en.htm, and http://aries.ucsd.edu/fpa/fpn12-13.shtml: Contact: Director for Laser Fusion Energy at LLNL.

[5.5] Editorial: 'Laser fusion on the horizon', Nature Photonics, vol. 6, p. 267, 2012. and Hatcher, M.: 'NIF 'tantalizingly close' to ignition breakthrough', http://optics.org/news/3/7/21, and https://lasers.llnl.gov/

[5.6] http://www.bbc.co.uk/news/science-environment-24429621 and https://lasers.llnl.gov/.

Corroboration of the formation and operation of Stratophase, and impact of PBG sensors:

[5.7] www.stratophase.com, and Watts S., Bragg gratings: Optical microchip sensors, Industry Perspective: 'Bragg gratings: Optical microchip sensors, Industry Perspective', Nature Photonics, vol. 4, p. 433, 2010. doi:10.1038/nphoton .2010.150.

[5.8] http://pressreleasepoint.com/stratophase-successfully-completes-biodetection-project
and http://www.biospace.com/news_story.aspx?StoryID=230447&full=1
and http://optics.org/news/2/6/25, and http://optics.org/indepth/1/3/3
and http://www.chelsea.co.uk/PressReleases/FootAndMouth.htm
and https://connect.innovateuk.org/c/document_library/get_file?uuid=f2cf55f0-e6c4-4256-a000-fd8ae853beb7&groupId=46899.

[5.9] Contact: CEO of Stratophase

[5.10] http://www.biral.com/content/pibbdt_press_release