Institution: University of Southampton

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

Title of case study: 13-02 Microstructured Optical Fibres for Laser and Biomedical Applications

1. Summary of the impact

This research has led to the *creation of new business sectors* in laser development for medical and healthcare applications, which has enabled the creation of a world-wide market worth US$96 million in 2011, and a local spin-out, Fianium Ltd, which now has more than 50 employees and an annual turnover of around £10 million. Exploiting a radically new optical component invented at the University of Southampton, the microstructured optical fibre (MOF), this research has led to economic benefit through the creation of hundreds of jobs worldwide, and enabled the development of new diagnostic and medical technologies.

2. Underpinning research

Optical fibres have a vast and ever-increasing range of practical applications that range from underpinning the internet infrastructure to the development of high-precision medical instrumentation. The technology enhances the lives of most of society and is critical to many manufacturing and leisure industries. The underpinning research, undertaken between 1993 and 2013 at the Optoelectronics Research Centre (ORC), comprises an extensive body of work on the development of microstructured optical fibres (MOFs), also known as photonic crystal fibres (PCFs), which transmit light via a fundamentally different mechanism to pre-existing fibres: instead of the conventional solid core, MOFs contain a sophisticated arrangement of microscopic air holes incorporated in the fibre cross section that extend along the entire fibre length. The underpinning research, funded by a continuous series of large EPSRC grants [3.7-3.10], includes the development of the original ground-breaking idea, early theoretical work predicting their unique properties, fabrication of the first PCF in 1995, and more recent work on improving the design and manufacture of MOFs and demonstrating practical approaches to realising novel MOF-based laser sources. The work has spawned a whole new field of research with > 8,200 journal papers written to date on the topic (source: Web of Science, September 2013), all of which have resulted from the first MOF work at Southampton [3.2].

Nature of the research insights or findings which relate to the impact or benefit claimed:

1. First numerical demonstration of the possibility to obtain bandgap guidance in hollow core MOFs representing a fundamentally new means to guide light in an optical fibre [3.1] (1995);
2. The first demonstration of a light guiding MOF [3.2] (1995-1996);
3. The development of the first numerical method capable of modelling MOFs, which highlighted their exceptional dispersive and nonlinear properties [3.3] (1999);
4. First measurement of the high nonlinearity of small core MOFs, which generated enormous interest in these fibres and ultimately paved the way to the realisation of modern all-fibre based supercontinuum sources [3.4] (1999);
5. First demonstration of supercontinuum generation using a short pulse Ytterbium doped fibre laser with a suitably designed PCF, the configuration currently exploited by commercial supercontinuum vendors, such as Fianium Ltd. [3.5] (2002).
6. Extensive contributions to the improvement of the manufacturing process of silica (US-PATENT-6968107, 2005) and non-silica based MOFs (US-PATENT-7155099, 2006);
7. Improved physical understanding of supercontinuum generation and technological improvements to increase the nonlinearity of MOFs responsible for its occurrence [3.6] (2006).

Key Researchers:

- Professor Sir David Payne (1962 to present, ORC Director)
- Professor Philip Russell (1986 to 1996, Reader progressing to Director of the Max Plank Institute for the Science of light, Erlangen, Germany).
- Professor Tim Birks (1987 to 1996. Now a full Professor at the University of Bath)
- Professor Jonathan Knight (1996. Now a full Professor and Head of the Physics Department at the University of Bath)
- Professor David Richardson (1989 to present, now ORC Deputy Director)
- Professor Tanya Monro (1998 to 2005, Now Director of the Institute for Photonics & Advanced Sensing at the University of Adelaide).
- Dr Francesco Poletti (2003 to present, now Royal Society Research Fellow at the ORC).

3. References to the research

3.1)** T. A. Birks, P. J. Roberts, P. S. J. Russell, D. M. Atkin, and T. J. Shepherd, "Full 2-D Photonic Bandgaps in Silica/Air Structures," Electronics Letters 31, 1941-1943 (1995). ***[225 citations]

3.2)** J. C. Knight, T. A. Birks, P. S. Russell, and D. M. Atkin, "All-Silica Single-Mode Fiber with Photonic Crystal Cladding," Optics Letters 21, 1547-1549 (1996). ***[1498 citations]

3.3)** T. M. Monro, D. J. Richardson, N. G. R. Broderick, and P. J. Bennett, "Holey Optical Fibers: An Efficient Modal Model," IEEE Journal of Lightwave Technology 17, 1093-1102 (1999). ***[323 citations]

3.4) N. G. R. Broderick, T. M. Monro, P. J. Bennett, and D. J. Richardson, "Nonlinearity in Holey Optical Fibers: Measurement and Future Opportunities," Optics Letters 24, 1395-1397 (1999). ***[235 citations]***

3.5) J. H. V. Price, W. Belardi, T. M. Monro, A. Malinowski, A. Piper, and D. J. Richardson, "Soliton Transmission And Supercontinuum Generation In Holey Fiber, Using A Diode Pumped Ytterbium Fiber Source," Optics Express 10, 382-387 (2002). ***[50 citations]***

3.6) J. Y. Y. Leong, P. Petropoulos, J. H. V. Price, H. Ebendorff-Heidepriem, S. Asimakis, R. C. Moore, K. E. Frampton, X. Feng, T. M. Monro, and D. J. Richardson, "High Nonlinearity Dispersion-Shirted Lead-Silicate Holey Fibers for Efficient 1µm Pumped Supercontinuum Generation," IEEE Journal of Lightwave Technology 24, 183-190 (2006). ***[67 citations]***

Underpinning Grants:

3.7) IRC In Optical And Laser Related Science And Technology, EPSRC, GR/J62036/01, W.A. Gambling, 1-04-94 to 1-10-1996, £6,952,536. (Professor W. A. Gambling was founding Director of the ORC in 1989-1995, which is why the grant is in his name.)

3.8) IRC Rolling Grant 7-Year Review: The Optoelectronics Research Centre, EPSRC, GR/L26971/01, D.N. Payne et al., 1-10-96 to 30-9-2000, £2,056,683

3.9) Advanced Optical Fibre and Waveguide Devices and Microstructured Optical Materials, EPSRC, GR/M81854/01, D.N. Payne et al., 1-10-99 to 30-9-2003, £2,056,683.

3.10) Fabrication of Microstructured Glass and Crystal Photonic Materials & Devices EPSRC grant GR/T11746/01, D.N. Payne et al., 1-4-2004 to 31-3-2008, £2,741,404.

4. Details of the impact

The Process: from research to impact

The invention of the MOF has led to a step-change in a range of applications of fibre-optic technology, and created new business sectors within the global optoelectronics industry which has adopted this new form of fibre not only to improve or extend the performance of existing product lines, but also to exploit its unique properties and develop revolutionary new products and services. Several of these are already having transformational impact across important application sectors. The biggest impact so far is the use of MOF technology to create a revolutionary new laser device, the ***Supercontinuum Fibre Laser (SFL),*** which generates white light that can be > 1 million times brighter than possible by pre-existing technologies, and exploits the unique nonlinear optical properties in MOFs [5.1].

1. Economic Impact (creation of new business sectors and adoption of new technology)

Creation of a local spin-out: The invention of MOFs and subsequent early research on nonlinear MOFs conducted at the ORC led to the creation and continuing success of the **spin-off** company Fianium, which was founded in 2003 by Professor Anatoly Grudinin, and is now one of the world's leading suppliers of compact, all-fiberised supercontinuum sources. During the period between 2008 and 2013 the company more than doubled in size. It currently has an **annual turnover of ~£10million** and **employs more than 50 people** in the Southampton area, many of which are post-doctoral researchers coming from the ORC. The growth has earned the company **two Queen's awards**: for International Trade (2009) and Innovation (2012) [5.1]. Fianium maintains strong links with the ORC, where it funds research at the level of £100k per annum, and exports more than 90% of its products, thereby generating revenue and profits for the UK [5.1].

Creation of a new business sector: Besides Fianium, several other companies worldwide have been created to commercialise supercontinuum sources: NKT Photonics (Denmark), Menlo Systems (Germany) and Toptica Lasers (Germany). Furthermore, MOFs are also sold as a product in their own right by companies such as OFS (Denmark, USA), Fujikura (Japan) and Yangtze Optical Fibre Company (China). Most other major fibre manufacturers (e.g. Corning, Furukawa) have established large MOF research programs and capabilities, even though they do not currently openly advertise MOF products. [5.2]. The estimated **global market for MOF and SFLs in 2011 was $96 million** and this is predicted to rise to $621 million in 2016 [5.3].

2. Health impacts

The use of MOFs to generate compact supercontinuum lasers has enabled the development of new biomedical instrumentation and diagnostics. With the very recent commercial availability of SFL-enabled products, MOF technology is now beginning to be used in laboratories and hospitals across the world to enchance our understanding of biological systems and to aid diagnosis and treatment of medical conditions for improving the health and well-being of the general public, as illustrated in the examples below:

In the area of **biological imaging**, these MOF-enabled broadband laser sources have a multitude of applications, including the areas of fluorescence lifetime imaging, flow cytometry, and in-vivo optical molecular imaging. In broadband **spectroscopy,** high-resolution optical coherence **tomography** and **endoscopic illumination**, these devices are being applied across a range of important medical applications. SFLs, using Fianium products, have been key to the development of a technique developed by Stefan Hell from the Max Planck Institute for Biophysical Chemistry in Göttingen to push the resolution of conventional microscopy beyond the conventional diffraction limit, thereby achieving significantly **sharper levels of detail** in biological imaging [5.5]. Scientific instrument manufacturers have started to integrate supercontinuum sources in their products. In 2012 Japan-based manufacturer of precision instruments HORIBA integrated the high intensity and broad wavelength range of a supercontinuum laser into a **commercial spectrofluorometer** for improved diagnostic capability [5.6]. In 2013, Leica Microsystems - a world leader in microscopy and imaging solutions - began marketing products that use supercontinuum lasers as "the ultimate source for **confocal microscopy**" [5.7]. Manufacturer Bioptigen develops **non-invasive ophthalmic imaging systems**, generating high-resolution images of the cornea and retina. Early in 2013 the company integrated a supercontinuum source into its products "to achieve a breakthrough in ophthalmic imaging for preclinical research" [5.8].

3. Impact on public and professional services

In the field of metrology, supercontinuum lasers based on the new MOF technology have enabled ultrastable frequency combs that provide a direct link between optical and microwave frequencies. This has made the measurements of frequency, time and length far more accurate than hitherto possible, with profound impact on both the fundamental science program and **commercial services**, such as the distribution of accurate time through an optical fibre network and time stamping services for financial transactions, now offered by the National Physics Laboratory (NPL) [5.4] and other such standards labs worldwide. This is an important contributor to global international trade and world stock-markets.

5. Sources to corroborate the impact

5.1. **Information about Fianium:** http://www.fianium.com/
Impact of SFLs on Fianium's business, company growth and funding to ORC research:
Contact: Vice President of Business Development, Fianium Ltd
Fianium's Queen's awards:

- 2009 for International Trade: http://optics.org/article/38824 (27/04/2009)
- 2012 for Innovation: http://www.fianium.com/company-news.htm (21/04/2012)

5.2 **For overview of current and potential market of MOF from a leading fibre manufacturer:**
OFS Fellow, OFS Denmark

5.3. **Global market value of supercontinuum fibre lasers based on nonlinear MOFs (Bcc research report, 2013)**
http://www.ceramicindustry.com/articles/global-market-for-photonic-crystals-to-reach-34-5-billion

5.4. **To support the impact of MOFs (nonlinear and hollow core) on metrology based work at the National Physical Laboratory (NPL), contact:** Senior NPL Fellow, Time & Frequency, National Physical Laboratory

5.5. **Development of stimulated emission depletion (STED) microscopy technique**
http://optics.org/news/3/4/27 (using a Fianium supercontinuum laser)

Leading scientific instrument companies integrating SFL sources in their products:

5.6 ***Horiba:*** http://www.horiba.com/us/en/scientific/news-events/latest-news/article/horiba-scientific-and-nkt-photonics-introduce-the-worlds-first-commercial-integrated-supercontinuum-powered-spectrofluorometers-18507/

5.7 ***Leica:*** http://www.leica-microsystems.com/science-lab/white-light-laser/;
http://www.leica-microsystems.com/products/confocal-microscopes/details/product/leica-tcs-sp5-x/;

5.8 ***Bioptigen:*** http://www.bioptigen.com/news/bioptigen-introduces-1%EF%81%ADm-resolution-sdoct-imaging-system-in-collaboration-with-nkt-photonics-supercontinuum-white-light-laser-source-at-arvo-conference-in-seattle/