Institution: University of Southampton

Unit of Assessment: 09 Physics

Title of case study: 09-03 Ytterbium-doped fibre amplifier

1. Summary of the impact

Researchers at the University of Southampton were the first in the world to introduce ytterbium-doped silica fibre as an optical gain medium. The work led to the creation of a new business sector around efficient industrial fibre lasers, which enable new manufacturing processes in the automotive, aviation, defence and medical device industries, with a reduction in carbon footprint relative to earlier technologies. The economic impact of this work includes the UK foothold in the $2 billion global industrial laser market through the success of two spin out companies - Fianium and SPI Lasers - with a combined turnover of £50 million, employing close to 300 people

2. Underpinning research

While much of the early work on fibre lasers used erbium doping to target telecommunications applications in the 1.5-µm wavelength window, the pioneering research led by Professors Anne Tropper (joined 1983, Head of Physics 2002 - 2005) and David Hanna (joined 1983, Deputy Director of the Optoelectronics Research Centre from 1989 until his retirement in 2007) in Southampton University's Physics Department highlighted the exceptional spectroscopic properties of ytterbium-doped silica fibre. Their publications document the early realization that ytterbium- doped silica fibre had almost ideal properties for a bright and efficient 1-µm wavelength optical amplifier, with the potential for high power operation, and even the broad spectral bandwidth needed to generate and amplify ultrashort optical pulses. Their work triggered world-wide interest in the further development and commercialization of ytterbium-doped fibre amplifiers and lasers, which are currently offered for sale by numerous suppliers.

Hanna and Tropper were the first to report the use of ytterbium-doped silica fibre as an optical gain medium in 1988. Professor R M Byer (Co-Director of the Stanford Photonics Research Center) writes "*I remember very well visiting you and David at Southampton and both of you showing me the Yb:Fiber laser with its soft green glow. I reached out to touch the fiber but was quickly warned not to do so because it was the only fiber of its type in the world.*" Of the key publications from 1994-1997, **[3.1]** identifies the spectroscopic properties of the ytterbium-doped silica gain medium that underpin its technological importance: a uniquely simple energy level structure that gives freedom from excited state absorption, concentration quenching and multiphonon nonradiative decay. **[3.2]** reports the large gain bandwidth exhibited by this system, enabling it to address a wide range of applications including the generation and amplification of ultrashort optical pulses. **[3.3]** is an early report of an ytterbium-doped fibre amplifier (YDFA), possibly the second in the literature, following a publication from Gerard Mourou at Rochester in 1996 that cites **[3.2]** in its motivation. **[3.4]** is the first publication to analyse the performance of the YDFA systematically, and show quantitatively how variation in fibre length, dopant concentration and pump characteristics control the gain and bandwidth of these devices. **[3.5]** describes the properties of a superfluorescent broadband source based on ytterbium-doped fibre, and **[3.6]** is the first publication to discuss the lifetime quenching effects that proved to be a major technological challenge as YDF sources scaled into the kilowatt average power regime. The research was funded by EPSRC **[3.7, 3.8]**.

Two of these papers **[3.2, 3.4]** have together been cited more than 600 times on Web of Science to date, laying the foundation for the continuing development around the world of high power, continuous-wave and ultrafast short-pulse lasers and amplifiers.

In summary, Hanna and Tropper were the first researchers to demonstrate ytterbium-doped silica fibre as an optical gain medium, to investigate the physics of the YDFA, and to identify the capability of this technology.

3. References to the research (the best 3 illustrating quality of work are starred)

***3.1** H. M. Pask, J. L. Archambault, D. C. Hanna, L. Reekie, P. S. Russell, J. E. Townsend, and A. C. Tropper, "Operation of cladding-pumped Yb3+-doped silica fiber lasers in 1-micron region," Electronics Letters **30**, 863-865 (1994).

***3.2** H. M. Pask, R. J. Carman, D. C. Hanna, A. C. Tropper, C. J. Mackechnie, P. R. Barber, and J. M. Dawes, "Ytterbium-doped silica fibre lasers - versatile sources for the 1-1.2-micron region," IEEE Journal of Selected Topics in Quantum Electronics **1**, 2-13 (1995). *(Cited 268 times on Web of Science, at Oct 2013*)

3.3 R. Paschotta, D. C. Hanna, P. DeNatale, G. Modugno, M. Inguscio, and P. Laporta, "Power amplifier for 1083 nm using ytterbium doped fibre," Optics Communications **136**, 243-246 (1997).

***3.4** R. Paschotta, J. Nilsson, A. C. Tropper, and D. C. Hanna, "Ytterbium-doped fiber amplifiers," IEEE Journal of Quantum Electronics **33**, 1049-1056 (1997). *(Cited 352 times on Web of Science, at Oct 2013*)

3.5 R. Paschotta, J. Nilsson, A. C. Tropper, and D. C. Hanna, "Efficient superfluorescent lightsources with broad bandwidth," IEEE Journal of Selected Topics in Quantum Electronics **3**, 1097-1099 (1997).

3.6 R. Paschotta, J. Nilsson, P. R. Barber, J. E. Caplen, A. C. Tropper, and D. C. Hanna, "Lifetime quenching in Yb-doped fibres," Optics Communications **136**, 375-378 (1997).

Grant support

3.7 IRC IN OPTICAL AND LASER RELATED SCIENCE & TECHNOLOGY, EPSRC grant GR/J62036/01, W.A. Gambling, 1-4-1994 to 1-10-96, £6,952,536.

3.8 IRC ROLLING GRANT: THE OPTOELECTRONICS RESEARCH CENTRE, EPSRC GR/L26971/01, DN Payne & DC Hanna, 1 Oct 1996- 30 Sept 2000 £6,397,585

4. Details of the impact

The substantial international effort that has led to the ‘birth’ of commercially available ytterbium-doped silica fibre light sources for materials processing and nonlinear optics was triggered by Tropper and Hanna's research. The CEO of Fianium Ltd, an ultrafast fibre laser company, states that “*published papers and many international conference presentations delivered by Professor Tropper and members of her group have not only helped stimulate significant world-wide interest in further scientific study of capabilities and limitations of fiber amplifiers, but have also given impetus to commercialization of ytterbium-doped fiber lasers and amplifiers, especially in the area of ultrafast optics*” **[5.1]**. Anatoly Grudinin, formerly a Professor at Southampton, founded this local Hamble-based company that has won two Queen’s Awards for Enterprise within the past 4 years **[5.2]**. Anatoly records that “*Fianium Ltd was formed in 2003 with a sole objective to commercialize ultrafast fiber lasers based primarily on ytterbium-doped fibers and the study carried out by Professor Tropper’s group has played a significant role in successful development of Fianium’s products, ranging from picosecond and femtosecond high power fiber lasers for material processing to novel and spectacular supercontinuum fiber lasers, which find applications in bio- medicine and metrology*.

We estimate that since 2008 the installed base of Fianium’s fiber laser is approximately 1,000 units worldwide and this follows directly from pioneering research conducted by Professor Tropper and colleagues. With our current devices being priced at between £12,000 and £80,000, this number of sales represents a significant impact on the commercial development of the ultrafast fiber laser market.” **[5.1]**

Products from Fianium include mode-locked ytterbium silica fibre lasers delivering trains of picosecond and femtosecond optical pulses, ytterbium fibre power amplifers, and supercontinuum sources of intense white light in a spatially coherent beam that can be fibre-delivered. The supercontinuum is generated by launching the intense infrared pulse beam from a fibre source into highly nonlinear 'holey fibre', where its spectrum becomes massively broadened **[5.2]**. The company's success in penetrating the markets for material processing and marking led to Fianium winning the Queen's Award for Enterprise (International Trade) in 2009 **[5.3]**, following sustained growth of 70% year on year. Fianium has since opened new facilities in the USA (2009) and China (2010) with new distribution networks established since 2009 in India, Korea, Russia, Israel and Sweden. In 2012 Fianium was awarded a second Queen's Award for Enterprise (Innovation) in recognition of its development of "WhiteLase" Supercontinuum Fibre lasers, which provide a source of white light several million times the brightness of the sun **[5.4]**. It is specifically the beam quality and power-handling capability of ytterbium fibre that make it possible to realize such a source in a rugged turn-key form, usable by non-specialists. End-users purchase these systems for applications that include illumination for keyhole surgery, and biomedical imaging techniques such as optical coherence tomography **[5.5].**

The other commercially important class of ytterbium fibre laser is the continuous-wave (i.e. not pulsed) kilowatt-power device integrated into materials processing systems destined for a manufacturing environment. Industrial lasers account for 25% of a laser market estimated to generate global revenue of $8.62 billion in 2013 **[5.6, p 41]**. Within this sector the high-power fibre laser represents a "disruptive technology", especially for sheet metal cutting, capturing in 2012 more than 20% of a market that in 2007 had been entirely dominated by carbon dioxide lasers **[5.6, p 42]**. The leading supplier of high-power fibre systems, IPG Photonics of Oxford Massachusetts USA, was ranked 9th in Fortune Magazine's list of fastest-growing companies in 2012, with a three- year-average annual revenue growth of 37% **[5.6 p 40]**. (Note that in the business literature, 'fiber laser' now implicitly means 'ytterbium fibre laser'.) Beneficiaries of the technology include car manufacturers making safer vehicles from new materials that cannot be conventionally machined; aerospace companies enabled to reduce the weight and aerodynamic drag of aircraft, and medical component manufacturers who exploit the spatial precision and contact-free nature of laser machining in the production of stents, pacemakers and other life-saving devices.

Closer to home, another Southampton spin-off company has benefitted from the local heritage of Tropper and Hanna's research to stake out a position in the high-power fibre market. SPI Lasers (SPIL) was originally established to exploit Southampton-developed erbium-doped fibre technology in the heady era of the telecoms bubble. When the bubble burst, the business was forced to refocus, and in 2002 switched strategies to concentrate on the design and production of ytterbium fibre lasers for manufacturing. In 2008 the German machine tool and disc laser specialist Trumpf acquired SPIL for £27.8 million, desiring a foothold in the industrial fibre laser market **[5.7]**. In 2008 SPI Lasers employed 170 people with a global turnover of approximately £15m per annum **[5.8]**. It now employs over 250 people with an annual turnover of $50m **[5.9]**.

5. Sources to corroborate the impact

5.1 Statement by CEO of Fianium Ltd

5.2 http://www.fianium.com/products.htm

5.3 http://optics.org/article/38824

5.4 http://www.fianium.com/company-news.htm

5.5 http://www.fianium.com/company-news.htm

5.6 ***Laser Focus World*** *annual review and forecast of the laser marketplace, January 2013*
http://www.laserfocusworld.com/articles/print/volume-49/issue-01/features/laser-marketplace-

2013- laser-markets-rise-above-global-headwinds.html

5.7 http://www.epic-assoc.com/news/?br=57

5.8 http://www.photonics.com/Article.aspx?AID=35133

5.9 Statement by CTO, SPI Lasers Ltd