Institution: Imperial College London

Unit of Assessment: 9 Physics

Title of case study: P2 - Commercial success of high power, all-fibre supercontinuum sources

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

The development of a high average power, all-fibre integrated, supercontinuum (or "white light") source, has led to a completely new product that has had significant commercial impact on the fibre laser and applications market place. The basic science, the technologically important power scaling and all-fibre integration were undertaken and first demonstrated by Imperial College staff. This device is currently sold as a compact free standing device by companies such as Fianium, NKT Photonics and IPG Photonics. Sales of supercontinuum lasers at Fianium alone have greatly exceeded £10M. The device has also been successfully incorporated into spectroscopic and medical imaging instrumentation generating new business activity through this disruptive technological change.

2. Underpinning research (indicative maximum 500 words)

The concept of the "supercontinuum" is not new. Spectral broadening in lasers or external to the laser cavity as a result of nonlinearity has been identified and utilized since the late 1960s. However, no commercial devices were developed simply because of the unwieldy experimental configurations and the instability and irreproducibility as a result of lens focussing into the nonlinear medium. With the appearance of low loss optical fibre in the 1970s control of nonlinearity became simpler and more reliable yet lens coupling from bulk lasers prohibited commercial development of supercontinuum sources.

A major step in the miniaturization, power scaling and reliability of fundamental pump sources came with the development of the all fibre master oscillator power fibre amplifier scheme or MOPFA [1]. This was an experimental technique that was pioneered and developed by the Imperial College group in collaboration with IPG Photonics, the world's largest manufacturer of fibre laser and amplifier based instrumentation, in the mid-1990s. By 1997, the group in collaboration with IPG Photonics developed an extremely compact moderate average power (1W) supercontinuum source [2] that was commercialized by IPF Technology in the UK, a spin-off company from IPG Photonics and led by ex-Imperial College Physics Department personnel. This device was not a "white light" source, instead utilizing soliton-Raman cascading, a technique developed by the Imperial College group, to cover the near infra-red range from 1000nm to 2300 nm.

With the introduction of photonic crystal fibre at the end of the 1990s and the demonstration of supercontinuum generation in that medium utilizing a femtosecond Ti:Sapphire laser, interest was renewed in supercontinuum generation and the potential of "white light" generation. These latter systems were identical to the earlier schemes of the 70s and 80s in their experimental configurations, exhibiting instability and low average power levels of only a few milliwatts with little chance of spectral power increase.

The quantum jump in supercontinuum sources was undertaken by the Imperial group in 2002 [3]. The post deadline report in 2004 at the prestigious international Conference on Lasers and Electro-Optics (paper CPDC7, Conference on Lasers and Electro Optics, CLEO 2004) described the fully integrated all fibre supercontinuum source incorporating a picosecond Yb MOPFA with photonic crystal fibre as the non-linear platform [e.g. 2] drew academic and commercial interest alike. The spectral power density was three orders of magnitude greater than could be achieved with Ti:Sapphire lasers and the construction was compact, reliable, reproducible and completely hands free. In 2003 details of the construction were passed to Fianium in the UK, a manufacturer of pulsed fibre lasers.

During the period of the current REF consideration, we have further developed the source power-scaling by more than another order of magnitude [3, 4] and solved the problem of extension of the supercontinuum to blue/UV spectral region [5, 6]. We identified that limitations to short wavelength extension were caused by long wavelength loss and confirmed that control of soliton-dispersive wave interactions were vital for short wavelength extension [4]. This is implemented either through tapering of the nonlinear PCF fibre or by controlling and lowering the loss in the manufacture process or it can also be solved by simple power-length scaling.

The Imperial personnel contributing to this research programme were Academic Staff Members Prof JR Taylor and Dr SV Popov, RA Dr S.V. Chernikov and PG Research Students Mr. J.C. Travers, Mr. A.B. Rulkov, Mr. B. Cumberland, Mr E.J. Kelleher and Mr. B. Chapman. Dr Rulkov (PhD 2008) is now employed by IPG Lasers GmbH. Dr Cumberland (PhD 2009) is employed by Coherent UK.

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

[1] S.V. Chernikov, J.R. Taylor, et al., "*1083 nm ytterbium doped fibre amplifier for optical pumping of helium*", Electronics Letters 33, 787 (1997), DOI, **35 citations (30/11/12)**

[2] * S.V. Chernikov, Y Zhu, V.P. Gapontsev and J.R. Taylor , "*Supercontinuum self-Q-switched ytterbium fiber laser*", Optics Letters 22, 298 (1997), DOI, **117 citations (30/11/12)**

[3] * B.A. Cumberland, J.C. Travers, S.V. Popov and J.R. Taylor, "*29W High power CW supercontinuum source*", Optics Express, 16, 5954 (2008), DOI, **59 citations (30/11/12)**

[4] J.C. Travers and J.R. Taylor, "*Soliton trapping of dispersive waves in tapered optical fibres*", Optics Letters 34, 115 (2009). DOI, **24 citations (30/11/12)**

[5] * J.C. Travers, A.B. Rulkov, B.A. Cumberland, S.V. Popov and J.R. Taylor, "*Visible supercontinuum generation in photonic crystal fibers with a 400W continuous wave fiber laser*", Optics Express 16, 14435 (2008), DOI, **66 citations (30/11/12)**

[6] B.A. Cumberland, J.C. Travers, S.V. Popov and J.R. Taylor, "*Toward visible cw-pumped supercontinua*", Optics Letters 33, 2122 (2008), DOI, **27 citations (30/11/12)**

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

There have been several important development stages undertaken by the Imperial College group, all with strong industrial interaction and product feed through, that has led to the commercial and academic success of the all-fibre integrated supercontinuum source. Before our seminal publication in 2004 there were no commercial supercontinuum sources with visible radiation capability, although our infra-red system of 1997, which was commercialized by IPF Technology, did have the capability but required external frequency doubling and this was not available as a commercial add-on.

The high power supercontinuum source has had significant impact on various fields from time resolved spectroscopy, imaging and remote sensing and most certainly has been a commercial success. The major beneficiaries have been manufacturers of the fibre based product: high power, supercontinuum fiber lasers are now sold by commercial laser companies such as Fianium (UK), NKT Photonics (Denmark) and Toptica (Germany and USA). Devices have been available from 2006, but visible spectral coverage was limited. Our research publications showing how short wavelength spectral extent of the supercontinuum was linked to long wavelength loss, e.g. [6], and our demonstrations illustrating mitigation of this effect and allowing short wavelength extension to the blue have led to commercial devices operating throughout the complete visible spectrum with high spectral power density. Impact has been made on the commercial devices which are now truly "white light", in fact covering practically the complete window of transmission of optical fibre. Minimizing the IR loss allowed manufacturers to introduce simpler fibre structures and improve the performance and specification of commercial products.

The best example of a commercial Yb fibre MOPFA-powered, fully integrated supercontinuum source incorporating photonic crystal fibre is exemplified by the Fianium product line [A]. The Whitelase supercontinuum sources provide "*a spectrum from below 390nm to beyond 2400nm,*

enabling applications such as fluorescence imaging, broadband spectroscopy, optical coherence tomography (OCT), and time-correlated single-photon counting" [B]. In a letter Fianium states the important contribution of J.R. Taylor's group, and in particular publication [4], to the "*development of commercial supercontinuum fiber lasers*". It confirms that "*the current installed base of supercontinuum fiber lasers is approximately 1000 units worldwide and this follows directly from pioneering research conducted by Professor J.R. Taylor's group. 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 market*" [C]. In 2012 Fianium, which has headquarters in Southampton and offices in the US, Europe and Asia, won the Queen's Award for Enterprise in the Innovation Award category for the development of the Whitelase Supercontinuum Fibre laser [D].

The Danish company NKT Photonics offers a range of commercial supercontinuum lasers under the SuperK brand. Their SuperK Extreme supercontinuum lasers "*represent the next generation of supercontinuum lasers that are truly turn key with industry leading brightness covering the entire 400-2400nm wavelength range*" [E] and "*with more than 8W of total power and 2W of visible power, the SuperK EXTREME lasers are the brightest supercontinuum lasers on the market*" [F]. The SuperK Extreme laser "*covers a broad range of applications such as Fluorescence Lifetime Imaging (FLIM), Optical Coherence Tomography (OCT), Time Correlated Single Photon Counting (TCSPC), Förster Resonance Energy Transfer (FRET), Flow cytometry, DNA sequencing, White Light Inteferometry (WLI), Test and Measurement and many others*" [E]. In a letter NKT Photonics confirms the key role the Imperial group played in the research and development of fiber based supercontinuum sources, in particular paper [4]. It also confirms the effect of this on the products it offers: "*this basic configuration of the all-fibre integrated scheme, pumped by a MOPA...provided as inspiration for commercial high power supercontinuum sources, several types and models which [the] company produces*" [G]. Users of the SuperK product include Leica Microsystems, Germany, the RECENDT Research Centre for Non Destructive Testing GmbH, Austria, and the Karlsruhe Institute of Technology, Germany [H].

Important to the further simplification and power scaling was the realization by us that continuous wave fibre lasers could be employed for supercontinuum generation as opposed to the general consensus that efficient nonlinear optics required high peak powers. This was achieved through a complete understanding of the non-linear processes controlling supercontinuum generation, in particular modulational instability that initiates it and the process of soliton–dispersive wave interaction that mediates long and short wavelength extension. The potential for commercialization was acknowledged through the award of a Royal Society Brian Mercer Feasibility Award in 2008 [I]. Through this we have looked at the complete simplification of the supercontinuum source, minimizing the number of components in order to produce a very commercially competitive device. IPG Photonics have "*indicated [their] willingness to support the commercialization of this in collaboration with Prof Taylor's group*" [J]. The Feasibility Award has now ended and the potential commercialization of the technology is on-going.

Following the commercial success of high power supercontinuum sources, J.R. Taylor from the Imperial College group, in collaboration with Professor J.M. Dudley at the University of Franche-Comte, was commissioned to prepare a commercially successful research text "Supercontinuum Generation in Optical Fibers", Cambridge University Press, ISBN 978-0-521-51480-4 (2010). In the first year since publication this text book has sold 460 copies.

Additionally, during the period of this impact assessment, our pioneering work in developing the systems and clarifying the underlying science and technological challenges has been recognized in the field through 21 invited talks (solely on high power supercontinuum generation) at the major international conferences incorporating Industrial Trade Shows where commercial supercontinuum sources were exhibited. For example at Biophotonics '11 (Sweden), International Conference on Laser Optics 2010 (Russia), The Latin American Optics & Photonics Conference (Brazil), International Conference on Materials & Advanced Technologies (Singapore), Asia Optical Fiber Communications & Optoelectronics Exposition and Conference (China). Fianium confirm that the "*many international conference presentations delivered by Professor J.R. Taylor and members of his group have helped stimulate significant world-wide interest and demand for commercial*

supercontiuum products" [C].

The beneficiaries of our research span all fields as a direct result of the diverse applications of the high power supercontinuum source. These devices have been directly cascaded into research and imaging diagnostics, with primary application in health care as well as in the biomedical research base. According to Antonoly Grudinin, CEO of Fianium Ltd, "*Ultrafast fiber lasers in general and super-continuum sources in particular have good prospects to become a key technology in biomedical applications*" [K].

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

[A] The Fianium Powerful WhiteLase Supercontinuum sources product line http://www.fianium.com/supercontinuum.htm (Archived at https://www.imperial.ac.uk/ref/webarchive/5pf on 8/8/13)

[B] Fianium press release about the supercontinuum fiber laser in Laser Focus World, Feb 2012 http://www.laserfocusworld.com/articles/2012/10/supercontinuum-fiber-laser-from-fianium.html (Archived at https://www.imperial.ac.uk/ref/webarchive/6pf on 8/8/13)

[C] Letter from Dr Anatoly Grudinin, CEO, Fianium Ltd, 29th Nov 2012. Letter confirms the significant impact that Imperial's pioneering research by JR Taylor's Femtosecond Optics Group had on the development of commercial supercontinuum fiber lasers (available from Imperial on request).

[D] Fianium win Queen's Award for Enterprise for Whitelase laser, Fianium news from 1/10/12, http://www.fianium.com/company-news.htm (archived at https://www.imperial.ac.uk/ref/webarchive/ssf on 20/9/13)

[E] NKT Photonics SuperK Extreme product page http://www.nktphotonics.com/superkextreme?cid=7858 (Archived at https://www.imperial.ac.uk/ref/webarchive/qsf on 17/9/13).

[F] Optics.org, Jun 2011, "NKT Photonics releases SuperK EXTREME - the world's brightest, most reliable supercontinuum laser series", http://optics.org/products/P000018993 (Archived at https://www.imperial.ac.uk/ref/webarchive/8pf on 8/8/13)

[G] Letter from Dr Thomas Tanggaard Alkeskjold, Group Manager, Fiber Technology, NKT Photonics, 3rd Dec 2012. Letter confirms the significant impact the research by JR Taylor's group had on the development of fiber-based supercontinuum sources (available from Imperial on request).

[H] Users of SuperK Extreme, http://www.nktphotonics.com/side7855.html (archived at https://www.imperial.ac.uk/ref/webarchive/rsf on 17/9/13)

[I] Royal Society Brian Mercer Feasibility Award 2008 http://royalsociety.org/news/tomorrows-world/ (Archived at https://www.imperial.ac.uk/ref/webarchive/9pf on 8/8/13)

[J] Letter from Valentin Gaponstev, CEO and Chairman, IPG Photonics, 4th Dec 2012 (available from Imperial on request).

[K] Optics.org, June 2012, "Fiber lasers challenge traditional sources" http://optics.org/indepth/3/5/4 (Archived at https://www.imperial.ac.uk/ref/webarchive/0pf on 8/8/13)