Institution: Imperial College London

Unit of Assessment: 9 Physics

Title of case study: P3 - The commercialisation of fibre laser sources with medical applications

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

The development of a family of compact and efficient, high-power, fibre-based lasers that are designed to operate over broad wavelength ranges has led to new product lines that have had recognizable economic impact on the commercial laser market place. The basic research on these unique lasers was initially undertaken by Imperial College London and their development, power scaling and application were carried out in collaboration with IPG Photonics Corporation, the world's leading manufacturer of high power fibre lasers and amplifiers. Devices operating in several wavelength ranges have been particularly commercially successful in the scientific laser market and have also been applied in various clinical trials and treatments, demonstrating impact in the heath sector. Sales of the high-power, fibre-based lasers with IPG Photonics have exceeded $3M in the past few years.

2. Underpinning research (indicative maximum 500 words)

Over the past decade probably the most spectrally versatile laser based source has been the so called "white light laser" or supercontinuum source. The ability to cover the complete window of transmission of silica based fibre from about 330nm to 2300nm has enabled applications as diverse as remote sensing and medical imaging. High average power supercontinuum operation is possible with up to 100mW/nm spectral power density achievable [e.g. 1], albeit using an industrial scaled pump laser. Most typical commercial supercontinuum units deliver maximum spectral power densities in the region of 10mW/nm and at Imperial College we have developed such modestly powered continuously pumped systems for medical imaging applications, such as optical coherence tomography (e.g. Bizheva et al, Proc. Natl. Acad. Sci. USA, 10, 1073, 2006). For many real world applications spectral diversity coupled with high average power operation in specific spectral windows is an essential requirement and spectral selection or filtering from a supercontinuum provides inadequate average power levels. The realization of more applicable fibre based sources is the subject of this impact case study.

A key contributing component to the spectrally diverse, high power fibre laser sources described here was the introduction of the concept of the master oscillator power fibre amplifier (MOPFA) that was developed by the Imperial College group in collaboration with IPG Photonics [2]. The advantage of the MOPFA technique is that it utilizes an integrated low power seed and this seed can be in any format continuous wave (cw), nanosecond or picosecond. It can be a laser diode or fibre laser that is sequentially amplified in fibre to average saturation powers well in excess of 1kW. Single frequency operation is possible through manipulation of the amplifier geometry, while nonlinear effects such as spectral broadening can be negated through use of large mode area amplifying fibre.

Our initial MOPFA based studies primarily related to Yb and Yb:Er rare earth doped schemes, operating with tuneable bandwidths of about 40nm in the spectral region around 1060nm and 1550nm respectively. We originally investigated spectral diversity through the use of single pass second harmonic generation (SHG) in periodically poled lithium niobate (PPLN) in 1998 [3], however, with average powers of several watts in the green, photo-darkening in the PPLN was a severe limiting problem. Photo-darkening with high power operation at 530nm was overcome in 2004 by the Imperial College group through the use of MgO doped stoichiometric periodically poled lithium tantalite [4]. Since then, and under the auspices of a Royal Society Industrial Fellowship carried out in association with IPG Photonics, Dr S. Popov of the Imperial College group has collaborated with the industrial partner in further developing high average power green sources based upon doubling in novel cavities incorporating poled crystals pumped by cw Yb MOPFA schemes.

In the visible, wavelength versatility was also demonstrated by the Imperial group in the first reported frequency doubling of a bismuth silica fibre laser giving up to 6.5W average power in the yellow at 589nm (a wavelength of interest for artificial guide star generation and also of relevance for acne and vein treatments) single pass in PPLN [5]. Wavelength diversity was also achieved at the watt level by a second cascaded second harmonic generation of both the Yb and Yb:Er laser systems, allowing operation in the blue and ultra violet. Sum frequency wavelength mixing of the Yb and Er systems also permitted somewhat limited wavelength tunability around 635nm, again at watts average power levels.

The greatest wavelength diversity was achieved through development of the fibre Raman MOPFA undertaken at Imperial College in collaboration with personnel from IPG Photonics. The use of novel short length, high power cascaded fibre Raman laser structures allowed complete wavelength coverage from 1000nm to 2000nm. Our research programme, undertaken to minimize the effects of in-fibre nonlinearity, allowed high power operation with narrow linewidths and polarization preserving geometries. This allowed highly efficient second harmonic generation of the tunable Raman lasers from 500nm to 1000nm and with operational powers in the harmonic signals in excess of 3W [6], consequently permitting spectral coverage matching the supercontinuum source but with average power levels nearly three orders of magnitude higher.

The personnel contributing to this research programme at Imperial College London were Dr S V Popov, Prof J R Taylor, and PG Research Students Mr. A.B. Rulkov, Mr. B. Cumberland and Mr S.A. Guskov. Dr Rulkov (PhD 2008) is employed by IPG Lasers GmbH. Mr Cumberland (PhD 2009) took up employment with Coherent UK. Mr Guskov joined IPG Lasers GmbH as lead scientist in the high power fibre laser programme.

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

[1] * J.C Travers, A.B. Rulkov, B.A. Cumberland, S.V. Popov and J.R. Taylor, “Visible supercontinuum generation in photonic crystal fibre with a 400W continuous wave fiber laser”, Optics Express 16, 14435 (2008), DOI, **Times cited: 65 (as at 5/11/12)**

[2] S.V. Chernikov, J.R. Taylor et al., "1083 nm Ytterbium doped fibre MOPFA for optical pumping of helium", Electronics Letters 33, 787 (1997). DOI**, Times cited: 35 (as at 5/11/12)**

[3] S.A. Guskov, S.V. Popov, S.V. Chernikov, J.R. Taylor, “Second harmonic generation around 0.53 µm of seeded Yb fibre system in periodically poled lithium niobate”, Electronics Letters 34, 1419 (1998). DOI, **Times cited: 16 (as at 5/11/12)**

[4] A.G. Getman, S.V. Popov and J.R. Taylor, “7W average power, high-beam quality green generation in MgO doped stoichiometric periodically poled lithium tantalite”, Applied Physics Letters, 85, 3026 (2004). DOI, **Times cited: 13 (as at 5/11/12)**

[5] * A.B. Rulkov, A.A. Ferin, S.V. Popov, J.R. Taylor et al., “Narrow-line, 1178nm CW bismuth-doped fiber laser with 6.4W output for direct frequency doubling”, Optics Express 15, 5473 (2007). DOI**, Times cited: 56 (as at 5/11/12)**

[6] * D. Georgiev, V. P. Gapontsev, A. G. Dronov, M. Y. Vyatkin, A. B. Rulkov, S. V. Popov, and J. R. Taylor , “Watts-level frequency doubling of a narrow line linearly polarized Raman fiber laser to 589n”, Optics Express, Vol. 13, 6772 (2005). DOI, **Times cited: 75 (as at 5/11/12)**

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

Following the underpinning research at Imperial College that led to the demonstration of a family of high average power, fibre-based lasers operating throughout the visible and the near infra-red, impact has been identified and acknowledged by the commercialization of the developed systems and in the application of the lasers in diverse medical treatments.

From 2006 to 2010 Dr Popov College held a Royal Society Industrial Research Fellowship, which was undertaken in association with IPG Photonics. During this time and in collaboration with Dr Popov, the IPG group of companies undertook the commercial development of several of the high power fibre laser systems that had been researched at Imperial College, in particular, the (i) frequency doubled Yb and Yb:Er fibre lasers, (ii) MOPFA type fundamental and frequency doubled Raman fibre lasers and (iii) the Thulium based system operating around 2µm. In a letter, IPG Photonics confirms that in *"we established a mutually beneficial programme to investigate the frequency doubling of Yb based MOPFAs (master oscillator power fibre amplifiers) in periodically poled materials. The thrust of that programme was to use controlled seed signals from laser diodes or fibre lasers and to amplify these to moderately high average powers, in the many tens of watts regime, before efficient frequency doubling in various poled crystals. The programme was very successful and deploying Yb, Er and Raman based amplifiers in various formats, tuneable red, green, yellow and blue sources were demonstrated at tens of watts average power"* [A]. It confirms *that in "the past few years, with further development, IPG have commercialized the high power green system based upon SHG [second-harmonic generation] in crystals pumped by seeded Yb fibre lasers and these highly reliable and efficient systems should rapidly replace large frame inefficient Argon ion lasers and other traditional solid state solutions*" [A].

Regarding sales of the visible fibre laser systems developed from the original research programme of the Imperial group, IPG confirms that "*In the past few years sales of green systems has exceeded 100 units of various specification, with the power in this family of devices now exceeding 100W at 530nm and associated revenue was in excess of 3 million US$. Sales of Raman based units exceed those of the 530nm system*." [A]

The marriage of MOPFA technology with frequency doubling techniques in simple configurations has led to the commercialization of a family of compact and efficient high power lasers with exceptional wavelength coverage. With the lasers fundamentally based upon developments in telecommunications and through the use of telecommunications specified components, this has led to greater reliability and simplification, such that the basic commercial laser product requires no maintenance and is characterised by a simple user interface that requires no laser optimization procedures. As a consequence, the systems are in demand in the applications market place and this is best exemplified by the medical laser market, where the reliability, compactness, no need for servicing and cost reduction of fibre based laser medical systems has had instant impact.

Over the period 2006-2010, high power Thulium fibre lasers operating at 1940nm were developed in collaboration with IPG Photonics for applications in surgery. The water peak absorption of tissue at 1940nm allows for faster ablation and tissue removal compared to procedures developed for the Holmium laser at 2100nm. A 120W laser system was developed utilizing single transverse mode pumping from a Yb:Er laser system - the Thulium Fiber Laser System [B]. Collaborative clinical trials were instigated at the Chelyabinsk Medical Centre, Russia and at StarMedTech in Germany. StarMedTech, an international medical technology company specialising in surgical laser system technology, also includes a 120W 1.9µm Thulium laser in its product line – the vela® XL laser [C]. This laser is advertised for use in "*urology, gynecology, ENT, pneumology, neurology and surgery*" [C]. As with the IPG Photonics 1940nm lasers, due "*to its high absorption in water, the optimized wavelength of 1.9µm is ideal for haemostatic cutting of soft and hard tissue*" [C].

Dr Popov and the Femtosecond Optics Group at Imperial College have collaborated closely with the Medical Laser Division of IPG in the development, trials and commercialization of several fibre laser platforms for various medical procedures, some of which are now routinely applied. This is confirmed in a letter by NTO-IRE Polus (part of the IPG Photonics Corporation): "*The research and development in fiber lasers at Imperial College, followed by commercialization by IPG Photonics allowed us to develop integrated medical devices, conduct trials and qualify medical technologies for surgery, ENT, gynaecological, prostate treatments and vein therapy in Russia, Germany and USA"* [D]. In Russia alone "*over one thousand ENT operations were successfully performed on 330 patients, 3.5 to 66 year old, in the Second Central Medical Clinic using Raman and Er fiber laser* *based surgical instruments. In Chelyabinsk at the Medical and Physics Center of the Chelyabinsk State Medical Academy 104 patients, age 34 to 68, with gynaecological problems were successfully treated using Tm fiber laser based devices"* [D].

Further confirmation of the medical impact of the fiber lasers comes from the University of Illinois at Chicago. The director of the Dental Emergency Medicine Responder Training (DEMRT) Office confirms "*Dr. Popov and I have collaborated in the research and development (R&D) of fiber based lasers for medical and dental spectroscopy, diagnostics, non-surgical, and surgical applications since 2008. His applied and clinical laser device and applications research, for laser based diagnostics, dentistry, medicine, and surgery, have been critical for our clinical needs…We have collaborated with a number of medical centers and companies across the world, all of whom express continued interest in developing new medical and dental devices and procedures for global and international health needs...The lasers developed at Imperial College have been commercialized by IPG Photonics and applied in medical applications such as dentistry, oral surgery, ENT, gynecology, prostate treatment; aesthetics and have already passed medical trials and certification in Russia, Europe, USA and Asia."* [E]

The important role of Dr Popov and the Femtosecond Group in the commercialization of the fiber laser sources is nicely summarized in the following additional quotes: "*Dr Popov's input has been an important and vital ingredient in the route to commercialization [*of medical laser systems]" [A], and "*The results of the research conducted by Dr Popov at Femtosecond Group at Imperial College in collaboration with IPG Photonics have clearly resulted in practical apparatus which was successfully applied to novel low-invasive medical treatments"* [D].

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

[A] Letter CEO and Chairman, IPG Photonics, 20/12/12 (available on request)
[B] IPG Photonics 'TLR Series - Thulium Fiber Lasers' product details webpage http://www.ipgphotonics.com/app_medical_tlr.htm (Archived at https://www.imperial.ac.uk/ref/webarchive/cqf on 8/8/13)
[C] StarMedTec 'vela® XL, 1.9µm thulium laser' product details webpage, http://www.starmedtec.de/en/products/produkte-detail/vela-xl-en/ (archived at https://www.imperial.ac.uk/ref/webarchive/bqf on 8/8/13)
[D] Letter from Head of Medical Lasers Division, NTO-IRE Polus (part of IPG Photonics), 8/1/13 (available on request)
[E] Letter from Director, DEMRT Office, University of Illinois at Chicago, 7/1/13 (available on request)