Institution: University of Southampton		
Unit of Assessment: 12 Engineering		
Title of case study: 12-06 Delivering commercial, economic and environmental impact through the development and optimisation of smart High-Power Fibre Lasers for advanced manufacturing.		
Period when the underpinning research was undertaken: 2000 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Michalis N Zervas	Professor	January 1991 – present
David N Payne	Professor	October 1967 – present
Jayanta K Sahu	Professor	May 2000 – present
W Andrew Clarkson	Professor	October 1989 – present
Johan Nilsson	Professor	October 1995 – present
David J Richardson	Professor	March 1989 – present
Marilena Vivona	Research Fellow	April 2016 – June 2019
Christophe A Codemard	Research Fellow	April 2007 – December 2009
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Period when the claimed impact occurred: August 2013 – December 2020		
Is this case study continued from a case study submitted in 2014? Y		

1. Summary of the impact

University of Southampton (UoS) research into the development and optimisation of a new generation of highly efficient, smart High-Power Fibre Lasers (HPFLs) is directly responsible for the significant growth and commercial success over the impact period of SPI Lasers Ltd, a UK company originally spun out of UoS and now among the world's leading HPFL manufacturers. Over the seven-year period, SPI has generated cumulative revenues of GBP436m and cumulative gross profits of GBP109.8m; annual revenues increased from GBP35.3m at the beginning of the census period to a peak of GBP78.7m and annual gross profits rose from GBP7.6m to a peak of GBP23.0m. The company has supported up to 303 jobs and created 47 new roles. SPI's laser product ranges have benefitted companies across multiple industries, including the aerospace, automotive, energy and medical sectors, in 130 countries. Impact 'downstream' can be seen in substantial energy savings and emission reductions arising from the lasers' efficiency gains, and improving the capabilities of SPI customers in addressing key societal challenges, including the manufacture of lightweight aircraft parts, batteries and fuel cells, and life-enhancing medical devices such as pacemakers and synthetic bones.

2. Underpinning research

Fibre lasers, in which the active medium being used is an optical fibre doped in rare-earth elements, are one of the most recent entrants into the highly competitive laser market. Their strengths lie in their inherent stability, beam quality, compact size and their ability to achieve very high levels of power much more efficiently than conventional lasers. Use of fibre lasers across multiple industries including the automotive, medical, consumer electronics, materials processing and manufacturing sectors has increased rapidly in recent years, with Cambridge-based technology market research specialists IDTechEx forecasting global sales of GBP8.9bn by 2028.

Extensive research spanning two decades within the Optoelectronics Research Centre (ORC) has pioneered the development and optimisation of commercially viable HPFL technologies. In the early 2000s, the Group developed optical fibres and laser concepts that allowed scaling in average output powers and extended the range of operating modes to include both short-pulse and high-power, single-frequency operations. Practical all-fibre techniques were developed to couple the required pumping light derived from laser diodes into the fibre laser structure in a scalable, robust and compact fashion. This patented technology was critical for the development of UoS spinout company SPI Lasers Ltd (SPI). In 2004, ORC researchers conducted the world's first demonstration of a fibre laser (FL) system that could emit powers of greater than 1 kW, convincingly showing for the first time that fibre lasers could compete favourably with existing laser technologies [**3.1**]. A year later SPI was successfully floated on the Alternative Investment Market. Further work led to the development of a high-performance, single-frequency system that greatly extended the functionality and ultimate power scaling of fibre lasers [**3.2**].

SPI Lasers, now TRUMPF Lasers UK Ltd, funded the establishment of the ORC/SPI Advanced Laser Lab (ALL) at UoS in 2011 [**G1**] to fully optimise the fibre laser technologies. Subsequent collaborative research, led by Professor Michalis Zervas, who in 2016 was awarded a SPI Lasers/Royal Academy of Engineering Research Chair, has enabled the development of a new generation of smart HPFLs for advanced manufacturing that significantly outperform competing technologies. HPFLs now offer record wall-plug efficiencies (>35%), power scalability (10s of kW with near-perfect beam quality & 100s of kW of process-tailored beams), extended wavelength coverage (UV-to-green-to-mid-IR), beam delivery with unprecedented temporal and spatial control, as well as advanced process monitoring capabilities. Key research advances and technological 'firsts' that derived from ALL are summarised below; this research was transferred to SPI's IP portfolio and adopted into the company's production processes. It resulted in 8 patent filings, with the research publication following at a later date.

2.1 HPFL efficiency, stability and power scalability: Critical to the development of robust HPFLs for industrial use is the mechanically strong and low-loss fusion splicing of dissimilar fibres [**P1**]. The Group developed advanced fibre splicing techniques, resulting in an increase in optical-to-optical conversion efficiency from ~65% to >85%. It identified the power-scaling limitations in HPFLs and defined the fibre and pumping technologies required to maximise the power of individual single-mode FLs, which exceed current state-of-the-art performance by a factor of four to five [**3.3**, **3.4**].

2.2 Variable beam-shape output: The Group developed novel all-fibre techniques for dynamic output beam shape control, which involve mechanically adjustable in-fibre devices in standard power delivery fibres, enabling high-quality cutting of thin and thick mild-steel sheets at higher speeds [**3.5, P2**]. This has resulted in >20% faster 10-15mm mild steel cutting than multimode (MM) beams with same power and beam quality (M^2). It also succeeds in 20mm mild steel high quality cutting, which is not possible with same power MM beams.

2.3 Non-destructive preform characterisation: The Group developed a novel non-destructive optical technique for the rare-earth-doped optical fibre preform inspection. The technique can map the spatial distribution of ytterbium ions within the core, along the entire length of the preform [**3.6**], thus enabling the most appropriate and in-spec parts to be drawn into fibres. This increases the drawn fibre yield by 50-60% and shortens the fibre and laser production cycles by 20-30%, significantly reducing final product cost and increasing reliability.

2.4 CO_2 laser milling: A novel CO_2 laser milling technique for precise preform outer-surface preparation for optimum pump mode mixing was developed, which resulted in ~40% shorter, more compact, stable and energy efficient fibre lasers [**3.7**].

3. References to the research

3.1 Y. Jeong, J.K. Sahu, D.N. Payne, J. Nilsson, Ytterbium-Doped Large-Core Fiber Laser with 1.36 kW Continuous Wave Output Power, Optics Express, 12, pp 6088-6092, (2004). https://doi.org/10.1364/OPEX.12.006088

3.2 Y. Jeong, J. Nilsson, J.K. Sahu, D.N. Payne, R. Horley, L.M.B. Hickey, P.W. Turner, Power Scaling of Single Frequency Ytterbium-Doped Fiber Master Oscillator Power Amplifier Sources up to 500W, IEEE Journal of Selected Topics in Quantum Electronics, 13, pp 546-551, (2007). https://doi.org/10.1109/JSTQE.2007.896639

3.3 M.N. Zervas, C.A. Codemard, High Power Fibre Lasers: A Review, IEEE Journal of Selected Topics in Quantum Electronics, Vol 20 (5), 0904123, (2014). https://doi.org/10.1109/JSTQE.2014.2321279

3.4 M.N. Zervas, Power scalability in high power fiber amplifiers, European Conference on Lasers and Electro-Optics, paper CJ_6_1 (2017). https://doi.org/10.1109/CLEOE-EQEC.2017.8087024

3.5 N. Vukovic, J. Chan, C.A. Codemard, M.N. Zervas, S. Keen, V. Ruseva, R. Jessett, I. Botheroyd, M. Greenwood, Single-mode kilowatt fibre laser with adjustable beam profile and M2, European Conference on Lasers and Electro-Optics, paper CJ_9.2, Munich (2019). Available on request.

3.6 M. Vivona, J. Kim and M.N. Zervas, Non-destructive characterization of rare-earth-doped optical fiber preforms, Optics Letters 43, pp. 4907-4910 (2018). https://doi.org/10.1364/OL.43.004907

3.7 K Boyd, N Simakov, A Hemming, J Daniel, R Swain, E Mies, S Rees, WA Clarkson, and J Haub, CO_2 laser-fabricated cladding light strippers for high-power fibre lasers and amplifiers, Applied Optics, 55 (11), pp. 2915-2920 (2016) https://doi.org/10.1364/AO.55.002915

Key underpinning grants

G1 Establishment of Advanced Laser Lab (ALL), SPI Lasers; M.N. Zervas (PI); 11/6/2011; GBP1.78m.

G2 Preform Rare-Earth Profiler (PREP) EPSRC EP/M020770/1; M.N. Zervas (PI); 1 December 2015 – 31 March 2019; GBP311,702.

G3 Laser Technologies for Future Manufacturing, EPSRC Platform Grant EP/P027644/1; M.N. Zervas (PI); 1 July 2017 - 30 June 2022; GBP1.77m.

G4 Spatio-Temporal Beam Tailored Fibre Lasers for Energy Resilient Manufacturing, EPSRC EP/M014029/1; DJ Richardson (PI); 1 March 2015 – 31 August 2016; GBP649,938.

Selected patents

Three key patents representative of the 8 filed patents derived from the underpinning research:

P1 F. Ghiringhelli, M.N. Zervas, J.H. Shaw, A. Marshall, Optical fibre and optical fibre device, US10641961B2, PCT filed 24//5/2017

P2 A. Malinowski, C.A. Codemard, M.N. Zervas, P. Harrison, M. Greenwood, Apparatus and method for laser processing a material, WO2018025005A1, PCT filed 3/8/2017, priority data 4/8/2016.

P3 C.A. Codemard, M.N. Zervas, Apparatus and method for controlling the spatial beam profile of laser radiation, WO2019150064 A1, PCT filed 28/1/2019, priority data 30/1/2018.

4. Details of the impact

ORC research into the development of a new generation of highly efficient, smart HPFLs is directly responsible for the significant growth and commercial success over the impact period of SPI Lasers Ltd. The processing applications offered by SPI's HPFL technology platform have directly benefitted the company's customers across a broad range of industry sectors in 130 countries; welding, cutting, marking and micro-machining operations can be carried out faster and more accurately for better reliability, less waste and higher productivity.

Commercial benefits to SPI Lasers Ltd – and the wider economic impact

Early ORC research [**3.1**, **3.2**] formed the foundation of the fibre laser technology platform that SPI exclusively licenses from UoS. This platform underpins all of SPI's lasers, comprising two product ranges that are unique to the market: redENERGY® Pulsed Fibre Lasers and redPOWER® CW Fibre Lasers [**5.1**]. The former constitutes 20W-250W nanosecond pulsed fibre lasers, which offer flexibility and speed for laser marking and pulsed micro-machining; the latter is a range of continuous wave (CW) lasers that provide high levels of power and control while cutting, welding and drilling. Fundamental research within ALL to optimise the performance of HPFLs has developed in parallel with new market opportunities identified by SPI, facilitating rapid adoption of the underpinning science and technology by SPI's R&D team [**5.1**].

This research output has resulted in a number of key technological breakthroughs that have further enhanced the SPI product portfolio throughout the impact period and added unique selling points to existing products. These include [**5.1**]:

- GTWave™ pumping technology: unique cladding pumping technology, separating and "isolating" pump and signal paths and resulting in increased pump and fibre laser lifetime.

- Photo-darkening free active fibres without laser output power decay: increases pump and fibre laser lifetime.
- Pulse-shaping using semi-conductor seed laser-based nanosecond pulsed MOPA lasers, enabling a very broad operating range of pulse widths and pulse shapes, providing customers with class-leading results.
- Pulsed laser seed Stimulated Brillouin Scattering mitigating technique: extends operation parameter space of pulsed lasers and ensuring very high reliability for large-scale deployments.
- In-fibre beam shaping technology: variMODE^{TM} beam shaper, enabling high-quality cutting of thin and thick mild-steel sheets with lower power at higher speeds.

8 patents have been filed by the ORC during this period and licensed to SPI. This includes the research breakthroughs described in **2.1-2.3** [**3.3**-**3.6**], which were transferred to SPI under exclusive licenses in the period 2014 to 2018 [**5.1**]. The optical-to-optical conversion efficiency increases, secured through **2.1, 2.3** and **2.4** [**3.3**, **3.4**, **3.6** and **3.7**], has allowed use of lower-cost, lower-brightness pump laser sources and resulted in a cumulative ~28% reduction in required pump power in the period 2014 to 2018. Introduced to the HPFL manufacturing process, this resulted in a ~75% cost saving of pumping for SPI, which in monetary terms equates to GBP7500/kW and will equate to GBP5-10m saving in 2020 [**5.1**]. The increased levels of efficiency have resulted in substantially lower heating of the fibre and other critical components, facilitating power scaling of single laser units in excess of 2kW in 2018 from 0.5kW in 2013, and beam combined multi-kW laser sources to 20kW in 2018 from 3kW in 2013 [**5.1**].

The new fully automated splicing techniques introduced in SPI's production line, enabled by research described in **2.1** and **P1**, along with high-yield special fibres enabled through **2.3** (**3.6)**, resulted in a new range of 50W-300W high-power pulsed lasers of which SPI has shipped more than 10,000 units. These have enabled new micro-processing applications in consumer electronics manufacturing, battery cell manufacturing and solar cell manufacturing [**5.1**]. These new applications allowed SPI to transition from best-in-class laser marking to best-in-class pulsed welding and cutting from 2014 onwards [**5.1**]. The innovations in **2.1-2.4** (**3.3-3.7**) also led to a new production line of low cost, multi-kW fibre lasers for materials processing, targeting the extremely price-sensitive East Asia market, with a dedicated applications and sales centre established in Shenzhen, China in 2016. SPI expanded its main UK manufacturing facility in the Southampton area by nearly double in 2018 [**5.2**]. The technological breakthrough in **2.2** (**3.5, P2**) was transferred exclusively to SPI and formed a new range of HPFLs under the variMODE^{TM} trademark, launched at the Laser World of Photonics show in Munich in 2019 [**5.3**].

Confirming the direct relationship between UoS research and the growth and commercial success of SPI as a whole over the impact period, SPI CEO's said: "*University of Southampton research, both in the early to mid-2000s and since the establishment of our collaborative Advanced Laser Lab at the University in 2011, has been fundamental to the significant revenue and profit growth that the company has achieved between 2013 and 2020; without these technological breakthroughs this level of growth and commercial performance simply would not have been possible"* [**5.1**]. As a result, there is a direct link between ORC research and the following indicators of commercial and wider economic impact. SPI's cumulative revenues over the impact period were GBP436,000,000; annual revenues increased from GBP35,300,000 in 2013 (as of June 30 - the closest available records to the beginning of the impact period) to a peak of GBP78,700,000 in 2018. Its gross profits totalled GBP109,800,000; annual profits increased from GBP7,600,000 in 2013 to a peak of GBP23,500,000 in 2018 [**5.4**]. As of 2019, the company supports 303 jobs across its facilities in Southampton and Rugby, 36% of which are 'high-skilled'. In June 2013, 256 people were employed by the company, meaning 47 new jobs were created over the impact period [**5.4**]. SPI has directly invested GBP1,787,000 in UoS research within ALL over the impact period [**5.1**].

'Downstream' commercial benefits to SPI Ltd.'s customers, and the wider societal impact

SPI's customers span 130 countries and multiple industries including the aerospace, automotive, electronics health, sensor, energy and jewellery sectors. SPI's CEO summarises the overarching benefit to the company's customers as '*having a volume-deployable laser technology that is* *cost-effective and operates repeatably and reliably, replacing traditional cutting and joining methods*' [**5.1**]. In addition to substantially improving the quality, reliability and productivity of established processes, SPI's new generation of smart lasers require less total energy through allowing laser power to be correctly and efficiently deployed. This has resulted in a ~28% reduction in electricity running costs for the company's customers, which equates to a monetary annual saving of GBP1,400 for a 4kW laser UK user (based on average UK industrial electricity tariffs) [**5.1**]. SPI can achieve similar cut speed and quality with a smart 2kW fibre laser as can be achieved with a conventional 4kW fibre laser. In this case the electricity bill savings increase to GBP3,000. Similar gains are achieved in additive manufacturing, welding, ablation and micro-hole drilling, which when combined they result in a total reduction in running costs of 50% for the company's customers, equating to an annular saving of GBP2,000 over other laser technologies [**5.1**].

A series of case studies on SPI's website provides an overview of how their smart HPFLs are deployed by their customers [**5.5**]. For example, in the aerospace sector SPI's lasers are used in laser metal deposition to repair aeroplane engine blades, in additive manufacturing to produce lighter aircraft parts and in laser engraving of aerospace parts. In the automotive sector they are deployed to enhance the precision and efficiency of battery production for electric vehicles. In the health sector they are used to coat dental implants, to 3D-print teeth and spinal implants, and in the welding of medical devices. They are used in the manufacture of photovoltaic cells and in bespoke jewellery design. SPI pulsed and continuous wave smart fibre lasers offer technological advantages, including wavelength agility as well as extended stability and reliability, in applications such as print roll engraving [**5.6**]. Pulsed nanosecond fibre lasers have been used for marking and micromachining an extensive range of materials, uniquely offering pulse duration selection to enable a broad range of processes to be performed with a single laser, wide pulse frequency range allowing the selection of the optimum combination of average power, peak power and pulse energy, a variety of spatial profiles to further optimise the process and advanced control to allow sophisticated integration into processes and systems [**5.7**].

Environmental benefits

The increase in laser efficiency through the optimisation of the HPFL technology has minimised electrical power consumption and increased manufacturing speed and quality. The overall SPI laser wall-plug efficiency has increased from ~25% to ~35% over the impact period. This equates to a 28% reduction in electricity requirements [**5.1**], which in the case of SPI's heavy-duty industrial lasers translates into a reduction of 10,500-17,000 tonnes per year of CO_2 emissions. The lower limit is based on UK government greenhouse gas reporting conversion factors (0.37kgCO_2e/kWh [**5.8**]), averaged over the case study period. The upper limit reflects fibre laser world-wide usage in countries with higher conversion factors (0.6kgCO_2e/kWh).

5. Sources to corroborate the impact

5.1 Corroborating statement from the Chief Executive Officer of SPI Lasers Ltd.
5.2 LaserFocusWorld article on the expansion of SPI's manufacturing capabilities, April 2018: https://www.laserfocusworld.com/lasers-sources/article/16571710/fiberlaser-maker-spi-lasers-expands-its-manufacturing-capability
5.3 SPI press release: Launch of VariMODE product range at Laser World of Photonics, 2019: https://www.spilasers.com/news/laser-world-of-photonics-24th-to-27th-june-2019-munich-germany/
5.4 Filing history of SPI Lasers Ltd via Companies House: https://beta.companieshouse.gov.uk/company/03290610/filing-history
5.5 Case studies of SPI Laser 'real-world' use: https://www.spilasers.com/case-studies/aerospace/; https://www.spilasers.com/case-studies/automotive/; https://www.spilasers.com/case-studies/dental/; https://www.spilasers.com/case-studies/medical/; https://www.spilasers.com/case-studies/solar/.
5.6 Corroborating statement from SPI customer Applied Laser Engineering Ltd (ALE).
5.7 Corroborating statement from SPI customer Needham Laser Tech.
5.8 Government conversion factors for company reporting of greenhouse gas emissions: https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting