Institution: University of Southampton		
Unit of Assessment: 12-12 Engineering		
Title of case study: Hollow Core Fibres: Delivering economic impact via the commercialisation of a disruptive optical fibre technology for next-generation communications systems.		
Period when the underpinning research was undertaken: 2003 – 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:**
David Richardson	Professor and ORC Deputy Director	January 2000 – present
Francesco Poletti	Professor and Royal Society University Research Fellow	October 2007 – present
Marco Petrovich	Professor; Seconded to Lumenisity Ltd from February 2017	October 2005 – present
John Hayes	Senior Experimental Officer	October 2005 – present
Yong Chen	Senior Research Fellow	October 2012 – present
Natalie Wheeler	Royal Society University Research Fellow	December 2011 – present
Gregory Jasion	RAEng University Research Fellow	April 2011 – present
Eric Numkam Fokoua	RAEng University Research Fellow	January 2016 – present
Thomas Bradley	Senior Research Fellow	December 2012 – present
Period when the claimed impact occurred: January 2016 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Pioneering studies at the University of Southampton's Optoelectronics Research Centre (ORC) have demonstrated a set of hollow core optical fibre structures with world-record properties, proving the commercial viability of a technology designed to disrupt how data communications systems operate and meet increasing global demand for higher bandwidth. Through the spin-out of fast-growing company Lumenisity Ltd in January 2016, the commercialisation of hollow core fibre (HCF) technology has delivered significant economic impact, including: [text removed for publication] raised in external investment, with ~50% coming from overseas into the UK economy; the creation of more than 50 highly skilled engineering and manufacturing jobs at a new [text removed for publication] facility in the Southampton area; and revenues approaching [text removed for publication] from the sale of first-generation products with very strong growth forecast in the coming years. The first commercial deployment of HCFs has delivered technical, and therefore financial, benefits to companies in the financial services sector with proof-of-concept trials planned in other data communication and telecommunication applications: notably in data centre interconnect and 5G backhaul – both critical if the UK is to meet its broadband connectivity goals. Lumenisity and the ORC are now receiving enquiries and are engaged with many world-leading companies both in the UK and internationally.

2. Underpinning research

Fibre optics has revolutionised telecommunications. However, current fibres are operating close to the physical limits of the glass that forms their core. This places fundamental restrictions on the power and wavelength range over which signals can be transmitted and the speed at which signals propagate. A transformative technological step is required to increase the information capacity and power delivery capability of optical fibres to accommodate a rapid rise in global data centre IP traffic, which Cisco predicts will reach 20.6 zettabytes in 2021, a three-fold increase in five years.

Existing fibre optic limitations can in principle be overcome by exploiting new light guidance mechanisms in fibres with a hollow core. Such fibres, where a conventional glass core is replaced by a gas or vacuum and light flows in the empty void surrounded by a matrix of microstructured glass membranes, are called Hollow Core Fibres (HCFs). Compared with currently used solid glass-based structures, they are capable of supporting 50% faster light speeds, thus resulting in less information delay (30% lower latency - equating to a latency saving of 1.54μs/km) and can provide higher data transmission capacity as well. However, the commercial viability of HCFs in optical communications has to date been restricted by their relatively high optical attenuation. The Hollow Core Fibre Group at the Optoelectronics Research Centre (ORC) has sought to overcome these research challenges in order to pioneer a disruptive optical fibre technology that will lead to a fundamental change in the way devices, machines, data centres and cities are connected – for faster, cheaper, more resilient and secure communications.

The concept of low-loss air-guidance in a HCF was first predicted by Professor Phillip Russell at the University of Southampton in 1994. Experimental work on HCF began in earnest within the ORC in 2003 and it is now a primary research focus having attracted total funding well in excess of GBP25m from EPSRC, the EU and industry since 2010 [**G1-G5**]. The ORC has successfully demonstrated: a variety of HCF structures with world-record properties [**3.1**, **3.3**, **3.6**, **3.7**]; the scaling of fabrication approaches to yield continuous fibres of multi-kilometre lengths [**3.2**, **3.3**]; radically different fibre concepts, patented designs and manufacturing methods compatible with low attenuation levels [**3.2**, **3.3**, **3.5, 3.6**, **3.7**]; and demonstrations of the key benefits of HCFs for high-bandwidth, low-latency communications over distance scales appropriate to important optical communication application spaces, including both within and between data centres [**3.1**, **3.3**, **3.4**, **3.6**, **3.7**].

Key research advances that have enhanced the commercial viability of HCF technology include:

- First demonstration of broadband (>200nm) low loss (~3dB/km) hollow core photonic bandgap fibres [**3.1**, **G1**].
- Demonstration of new modelling techniques to model the fluid dynamics of fibre drawing, enabling rapid trialling of new fibre designs and exquisite control of HCF fabrication processes [**3.2**, **G3**, **G4**].
- First demonstration of production of hollow core fibres in continuous >10km lengths [**3.3**, **G1**, **G3**] – another essential step to prove the commercial viability of the technology.
- Improved physical understanding of optical guidance in hollow core photonic bandgap and anti-resonant fibres that resulted in development of the concepts needed to achieve record low attenuation levels [**3.4**, **3.5**, **G1**, **G2**, **G4**].
- Invention of the Nested Antiresonant Nodeless Fibre (NANF), the key enabler for <1 dB/km ultra-broadband transmission window fibres [**3.5**, **G2**, **G4**].
- Demonstration of an HCF with a record-breaking loss of 0.65dB/km [**3.6**, **G4**, **G5**].
- A further record breaking HCF with a loss of only 0.28dB/km [**3.7**, **G4**, **G5**].

The earlier studies [**3.1**, **3.2**, **3.4**, **3.5**] also led to the publication of two master patents [**P1**, **P2**] and were a key component of the ORC's winning Queen's Anniversary Prize entry in 2017. These patents were exploited commercially and **P2** used to achieve the world records for HCF attenuation, reducing the minimum attenuation by a factor of >4 in just 18 months (September 2018 – March 2020), from 1.3dB/km to 0.28 dB/km.

3. References to the research

3.1 F. Poletti, N.V. Wheeler, M.N. Petrovich, N. Baddela, E. Numkam Fokoua, J.R. Hayes, D.R. Gray, Z Li, R. Slavík and D.J. Richardson, "Towards high-capacity fibre-optic communications at the speed of light in vacuum," NATURE PHOTONICS Volume: 7 Issue: 4 279-284. Published: 1 Apr 2013. https://doi.org/10.1038/nphoton.2013.45

3.2 G.T. Jasion, J.S. Shrimpton, Y. Chen, T. Bradley, D.J. Richardson, F. Poletti, "MicroStructure Element Method (MSEM): viscous flow model for the virtual draw of microstructured optical fibers," OPTICS EXPRESS, Volume: 23 Issue: 1, 312-329. Published: 1 Dec 2015. https://doi.org/10.1364/OE.23.000312

3.3 Y. Chen, Z .Liu, S.R. Sandoghchi, G.T. Jasion, T. Bradley, E. Numkam Fokoua, J.R. Hayes, N.V. Wheeler, D. Gray, B. Mangan, R. Slavík, F. Poletti, M.N. Petrovich, D.J. Richardson, "Multi-kilometer Long, Longitudinally Uniform Hollow Core Photonic Bandgap Fibers for Broadband

Low Latency Data Transmission," JOURNAL OF LIGHTWAVE TECHNOLOGY, Volume 34 Issue: 1, 104-113. Published: 1 Jan 2016. https://doi.org/10.1109/JLT.2015.2476461

3.4 F. Poletti, M.N. Petrovich, D.J. Richardson, "Hollow-core photonic bandgap fibers: technology and applications," NANOPHOTONICS, Volume: 2 Issue: 5-6 Special Issue: SI 315-340. Published: 2013. https://doi.org/10.1515/nanoph-2013-0042

3.5 F. Poletti, "Nested antiresonant nodeless hollow core fiber," OPTICS EXPRESS, Volume: 22 Issue: 20, 23807-23828. Published: 6 Oct 2014. https://doi.org/10.1364/OE.22.023807

3.6 T. Bradley, G.T. Jasion, J.R. Hayes, Y. Chen, L. Hooper, H. Sakr, M. Alonso, A. Taranta, A. Saljoghei, H.C. Mulvad, M, Fake, I.A. Davidson, N.V. Wheeler, E. Numkam Fokoua, W. Wang, S.R. Sandoghchi, D.J. Richardson, F. Poletti, "Antiresonant Hollow Core Fibre with 0.65 dB/km Attenuation in the C and L Telecommunication Bands," in Proc. *European Conference on Optical Communications* 2019, Postdeadline paper PD.3.1. https://doi.org/10.1049/cp.2019.1028

3.7 G. T. Jasion, T. D. Bradley, K. Harrington, H. Sakr, Y. Chen, E. N. Fokoua, I. A. Davidson, A. Taranta, J. R. Hayes, D. J. Richardson, and F. Poletti, "Hollow Core NANF with 0.28 dB/km Attenuation in the C and L Bands," in Proc. *Optical Fiber Communication Conference*, (Optical Society of America, 2020), Postdeadline paper Th4B.4. https://doi.org/10.1364/OFC.2020.Th4B.4

Key patents

P1 Hollow-core photonic bandgap fibers and methods of manufacturing the same, E. Numkam Fokoua, F. Poletti and D.J. Richardson, US9904008 (and associated family).

P2 Hollow-core optical fibers, M.S. Abokhamis and F. Poletti, US10139560 (and associated family).

Underpinning grants

G1 MODEGAP - Multi-mode capacity enhancement with PBG fibre, European Union FP7 - 258033, D.J. Richardson, M.N. Petrovich, F. Poletti, EUR3.5m, 1 October 2010 to 31 March 2015.

G2 Transforming the Internet Infrastructure: The Photonic HyperHighway, EPSRC EP/I01196X/1, D.N. Payne, D.J. Richardson, I. Henning, W.H. Loh, D. Simeonidou, W.J. Stewart, GBP7,288,218, 1 November 2010 to 30 April 2017.

G3 EPSRC Centre for Innovative Manufacturing in Photonics, EPSRC EP/H02607X/1, D.N. Payne, D.W. Hewak, W.H. Loh, W.A. Clarkson, L.J.A. Nilsson, G.T. Reed, J.K. Sahu, M.N. Zervas, D.J. Richardson, GBP5,124,642, 1 July 2010 to 30 Dec 2015.

G4 Lightpipe - Antiresonant Hollow Optical Fibres for a Quantum Leap in Data and Optical Power Transmission, Consolidator Grant, F. Poletti, European Union ERC-2015-CoG, EUR2.75m, 1 July 2016 – 30 June 2021.

G5 Airguide Photonics, EPSRC EP/P030181/1. D.J. Richardson, D.N. Payne, J.K. Sahu, R. Slavik, F. Poletti, P. Petropoulos, W.J. Stewart, GBP6,160,545, 1 June 2017 to 31 May 2023.

4. Details of the impact

Over the last two decades the ORC has spun out several successful companies based on its world-leading research into novel optical fibres. In keeping with this established track record, Lumenisity Ltd was founded by Professors Richardson, Poletti and Petrovich, and Dr David Parker, ex-CEO of SPI Lasers, a global leader in fibre lasers. Formally incorporated in January 2016, the company set out an ambitious vision: to revolutionise telecommunications nearly 50 years after the development of ultra-low-loss solid glass optical fibres [**5.1**]. By commercialising HCF technology, Lumenisity's aim is to develop advanced fibre optic cable solutions to address the 'bandwidth crunch' and increase network performance in high data capacity communication systems.

Economic and commercial impact through rapid growth of a university spinout company

Lumenisity was formed solely on the basis of a portfolio of IP and know-how in HCF that had been developed within the ORC between 2010 and 2016 [**G1**-**G3**; **P1**-**P2**; **3.1**-**3.5**]. The company licensed the original body of IP and, with Richardson assuming the role of the Chief Scientific Officer, funded the ORC to further develop this IP in close partnership, as well as actively collaborating with the Lightpipe [**G4**] and Airguide Photonics [**G5**] programmes [**5.1**]. This led to the creation of multiple classes of IP that were subsequently licensed by Lumenisity. By the end of the impact period, Lumenisity has licensed 8 distinct patent families covering HCFs in terms of their design, fabrication and application (comprising 55 individual granted national patents (including UK, US, Europe, Japan, China, Hong Kong and Singapore) with [text removed for publication] applications currently under examination) [**5.2**]. The development of Lumenisity's IP portfolio has been 'fundamental' to the company's fast growth [**5.1**].

Lumenisity has made significant advances both technologically and commercially and has established itself as the global leader in HCF cables for telecommunications. It is currently the only fibre supplier capable of producing and cabling HCFs of low enough loss for telecommunications over >10km distance scales [**5.1, 5.3**]. This has enabled Lumenisity to raise first and second round funding totalling [text removed for publication] over the impact period, 50% of which constituted foreign direct investment (FDI) into the UK [**5.1, 5.4**]. This level of external investment allowed the company to invest [text removed for publication] in [text removed for publication] R&D, manufacturing and office facilities in the Southampton area and to create >50 high-skilled manufacturing and research engineering jobs [**5.1, 5.5**].

Lumenisity has developed several cable product lines based on different forms of HCF and cable structure, which have been customised for particular applications and environments, and has developed key deployment technology, IP and know how. The initial target markets are in financial services where the advantages of reduced latency for algorithmic trading are well known [**5.8-5.9**]. The ultimate goal is to connect high-capacity datacentres together at greater separation by extending the latency envelope (for which low cable attenuation is critical). This will have significant economic and environmental impact. The company is approaching [text removed for publication] in sales since its founding and is expecting very strong growth in future years. The company has engaged with a number of carriers and Hyperscale data centre operators to undertake substantial proof-of-concept deployments over the next [text removed for publication]. The collaborative R&D between the company and the ORC has been essential in securing these deployments and will continue to be essential moving forward to realise the ultimate goals. [**5.1**].

Technical and commercial advantages for Lumenisity's customers within the telecommunications sector

From 2018, Lumenisity's key customers have deployed the HCF products within their global telecommunications networks, benefitting both technically and commercially through significantly reduced latency in specific sections of their network. As the technology develops, enabling longer transmission distances and greater strand count, these applications will grow. [**5.6**]

A key factor in all applications is the "latency envelope". This limits the maximum physical separation of network assets. The reduction in latency in HCF increases the usable geographic footprint of any data centre, or 5G backhaul network, by a factor of 2.25 over conventional fibres, offering significant reductions in cost and environmental impact. [**5.7**]

Influencing business priorities and strategic direction of wider industry by demonstrating the commercial viability of HCF technology

The breakthroughs in HCF technology described in papers [**3.6**, **3.7**] provided wider industry with confidence in the practicality and deployability of HCFs. In demonstrating losses below 1dB/km for the first time [**3.6**], the ORC team overcame a psychological limit that many had thought impossible to break [**5.10**]. The further attenuation record [**3.7**] significantly narrowed the performance gap between HCF and mainstream optical fibre technology (to within a factor of 2). As a result, and with Lumenisity's forecast that the global HCF cable market will be worth £100's of millions over the next five years, there is clear evidence that leaders in the telecommunications sector have directed business investment and strategic initiatives towards the commercial exploitation of HCF technology [**5.8**, **5.9**]. The economic impact is also very great within the operating and end user community, possibly 10x this value. In some key markets such as autonomous vehicles and real time augmented reality, the benefits could be transformational.

Trials and proof-of-concept deployments are underway or planned with the major players in the Hyperscale environment, leading operators [text removed for publication], major carriers and world-leading network equipment manufacturers [**5.1**].

The demonstration of the commercial viability of HCFs has led to their application in other sectors beyond telecommunications, particularly in high power, short pulse laser delivery and gyroscopic navigation systems [**5.10, 5.11**]. This has resulted in HCFs being used in manufacturing to produce consumer and specialist goods at lower costs and to demonstrate ultraprecise positional measurements for the benefit of wider society.

5. Sources to corroborate the impact

5.1 Corroborating statement from the Executive Chairman of Lumenisity Ltd.

5.2 Report detailing the body of Southampton IP licensed and supported by Lumenisity Ltd.

5.3 Lumenisity press release on state-of-the-art deployable cable product and deployment and use [text removed for publication]. https://lumenisity.com/wp-content/uploads/2020/09/Lumenisity%C2%AE-Limited-announces-worlds-first-deployable-hollowcore-fibre-optic-cables-for-10Gbit-DWDM-transmission-over-10km-links.pdf

5.4 Lumenisity press release on BFG/Parkwalk Investment in Lumenisity. https://Lumenisity.com/wp-content/uploads/2020/09/Lumenisity®-Limited-receives-a-major-investment-from-a-consortium-of-investors.pdf.pdf

5.5 Latest Lumenisity Financial Reporting at Companies House. https://beta.companieshouse.gov.uk/company/09971631/filing-history

5.6 Corroborating statement from [text removed for publication] (Fintech customer).

5.7 Corroborating statement from [text removed for publication] (Technology trials and potential future user).

5.8 Wall Street Journal article discussing use of Lumenisity cables for financial applications. https://www.wsj.com/articles/high-frequency-traders-push-closer-to-light-speed-with-cutting-edge-cables-11608028200

5.9 Enterprise Networking article on hollow core fibres for ultralow latency systems https://www.nojitter.com/enterprise-networking/hollow-fiber-new-option-low-latency

5.10 IEEE technical press article discussing recent ORC work on attenuation reduction in hollow core fibres and discussing the implications in different application sectors including laser power delivery. (Provides a direct link to the relevant technical paper also). https://spectrum.ieee.org/tech-talk/semiconductors/optoelectronics/new-hollow-core-optical-fiber-is-clearer-than-glass

5.11 Optical Society of America article discussing recent ORC results obtained with Honeywell on the benefits of using hollow core fibres in gyroscopes. (Provides a direct link to the relevant technical paper also). https://www.osa.org/en-us/about_osa/newsroom/news_releases/2020/new_optical_fiber_brings_significant_improvements/?utm_source=miragenews&utm_medium=miragenews&utm_campaign=news