Institution: University of Bath		
Unit of Assessment: B9 Physics		
Title of case study: Commercialisation of antiresonant hollow optical fibres with major investment in two SMEs		
Period when the underpinning research was undertaken: 2000 – 2014		
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:**
Abdelfatah Benabid	Reader, previously Lecturer	January 2001 – August 2011
Jonathan Knight	Professor and Pro-Vice Chancellor (Research)	September 1996 – present
Philip Russell	Professor	March 1996 – March 2009
William Wadsworth	Professor, previously Reader, Royal Society Fellow and Lecturer	March 1999 – present
Period when the claimed impact occurred: 01/08/2013 to 31/12/2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

A hollow optical fibre has long been a technical goal in order to overcome problems in manufacturing, communication and instrumentation. In an empty core there is no material to damage when using a high power laser, and no material to absorb the light when working at wavelengths far into the ultraviolet or infrared. It has required researchers to find an efficient physical process to trap light in a hollow core.

University of Bath research showed that this can be achieved with an antiresonant hollow optical fibre and that an inwardly curving core wall further reduces the optical losses. Antiresonant hollow optical fibres incorporating these designs are the founding technology of GLOphotonics, a University of Bath spin out, and Lumenisity, with a combined workforce of more than [text removed for publication] people, sales revenues of EUR[text removed for publication] and more than GBP[text removed for publication] investment in this REF period.

2. Underpinning research

Hollow optical fibres offer low latency, low nonlinearity and can transmit at wavelengths where the material that they are made from is highly absorbing. In 2000 the only fibres capable of guiding light in a hollow core relied on a photonic bandgap. These were difficult to fabricate and offered performance enhancements of only a factor of 100 or so over the loss and nonlinearity of the constituent material.

Research at the University of Bath turned to simpler structures relying on the antiresonant effect to guide light in hollow optical fibres. Unlike total internal reflection in solid optical fibres, or the photonic bandgap effect in earlier hollow optical fibres, the antiresonant effect does not provide total confinement of the light. This inherent leakage had led to antiresonance not being seriously considered for hollow optical fibres. However, structures for antiresonant guidance are simpler and are easier to make than photonic bandgap structures. Bath research has shown that the amount of light that leaks out can be made to be very small, so that these fibres have become a practical solution. In 2002 Benabid, Knight and Russell published the first effective antiresonant hollow optical fibre, using a kagome lattice [1]. This idea was developed further by Benabid [2]. With associated patent families WO2006077437A1(US8079763B2) and WO2009044100A1(US8306379B2) it was a key technology in the formation of a spin-out company GLOphotonics in 2008. Further research in Bath led to the development of an inwardly curving boundary of the hollow core as an important way of reducing the leakage of light from antiresonant hollow fibres, Fig. 1(a), first announced as a high-profile post-deadline contribution at the CLEO 2010 conference and published soon after [3].

The inward curvature and antiresonant boundary developed in Bath are the key elements of all of the current generation of successful hollow optical fibres.

These elements were immediately picked up by other researchers as they showed the potential for simplifying the structure to just the thin, inwardly-curving antiresonant core wall [A]. The numerical simulation in [A] showed that the projected optical transmission far exceeded that of the structure that had actually been made. Wadsworth and Knight realised this potential, Fig. 1(b) [4], demonstrating that these simple structures could reduce absorption to less than one thousandth of the absorption of the material of the fibre, and light could be trapped in the fibre core over distances of up to 100m.

The demonstration of the effectiveness of this simplified design spurred activity in a large number of research groups to replicate, improve and apply hollow optical fibres based on antiresonant guidance. Bath researchers contributed with a nested design for low attenuation, Fig. 1(c) [5], and a design for low bend loss, Fig. 1(d) [6]. The highest performance hollow optical fibre to date [B] stems from a patent citing [5]; it is a fibre using the nested tube idea of Fig. 1(c) with the tubes not touching as in Fig. 1(d).

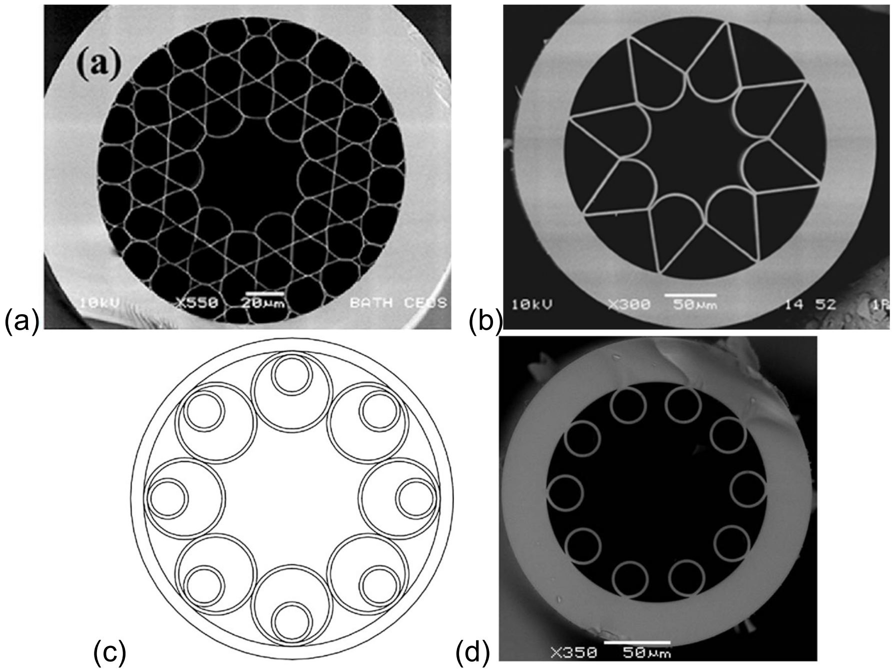


Figure 1. Antiresonant hollow optical fibres developed in Bath. (a) Kagome cladding fibre with inwardly curving core wall [3]. (b) Simplified antiresonant hollow core fibre [4]. (c) Further improved low-loss hollow-core fibre design [5]. (d) Fibre with low loss and low bending loss [6].

3. References to the research

[1] Benabid, F, Knight, JC, Antonopoulos, G & Russell, PSJ 2002, 'Stimulated Raman scattering in hydrogen-filled hollow-core photonic crystal fiber', *Science*, vol. 298, no. 5592, pp. 399-402. https://doi.org/10.1126/science.1076408

[2] Couny, F, Benabid, F & Light, PS 2006, 'Large-pitch kagome-structured hollow-core photonic crystal fiber', Optics Letters, vol. 31, no. 24, pp. 3574-3576. https://doi.org/10.1364/OL.31.003574

[3] Wang, YY, Wheeler, NV, Couny, F, Roberts, PJ & Benabid, F 2011, 'Low loss broadband transmission in hypocycloid-core Kagome hollow-core photonic crystal fiber', *Optics Letters*, vol. 36, no. 5, pp. 669-671. https://doi.org/10.1364/OL.36.000669

[4] Yu, F, Wadsworth, WJ & Knight, JC 2012, 'Low loss silica hollow core fibers for 3-4 μm spectral region', *Optics Express*, vol. 20, no. 10, pp. 11153-11158. https://doi.org/10.1364/OE.20.011153

[5] Belardi, W & Knight, JC 2014, 'Hollow antiresonant fibers with reduced attenuation', *Optics Letters*, vol. 39, no. 7, pp. 1853-1856. https://doi.org/10.1364/OL.39.001853

[6] Belardi, W & Knight, JC 2014, 'Hollow antiresonant fibers with low bending loss', *Optics Express*, vol. 22, no. 8, pp. 10091-10096. https://doi.org/10.1364/OE.22.010091

4. Details of the impact

University of Bath research established a new paradigm with its first antiresonant hollow optical fibres, and has been pivotal in the continued development of improved guidance. As well as initiating the underlying technology of antiresonant guidance for single material hollow optical fibres [1,2], further significant Bath contributions include introducing the important elements of an inwardly curving core wall [3], used in all current fibres of this type, and nested antiresonant structures [5], which are used in the highest performance fibres to date. The route to impact has been through dissemination alongside protection of some of our results, which has enabled a worldwide community to explore ways to exploit this new paradigm.

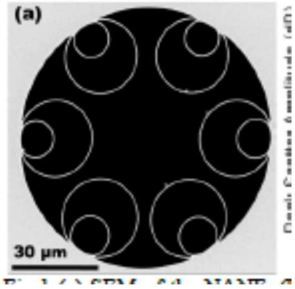
During the REF period a spin-out company GLOphotonics has expanded, and a new company Lumenisity has been formed to exploit the technology of antiresonant hollow-core optical fibres. Existing major laser manufacturers promote antiresonant hollow-core optical fibres as a unique solution for flexible delivery of their high performance pulsed lasers.

Growth of GLOphotonics. While he was at Bath, Benabid founded GLOphotonics in 2008 to spin out the technology that he had developed for kagome-style fibres. The company re-located to Limoges (France) and now focuses on OEM products, including both kagome fibres and fibres based on structures like Fig. 1(d). During this REF period the company has increased its sales revenue from EUR[text removed for publication] to EUR[text removed for publication], with aggregated sales revenues of EUR[text removed for publication] since the start of 2014 to the end of 2019 [C]. The company also increased the number of employees [text removed for publication]over this period [D]. It has received new backing, including from major laser manufacturers Amplitude and Trumpf, and machine tool manufacturer DMG Mori Seiki. An investment block of EUR[text removed for publication] primed the growth of the company which led to investment in late 2019 of EUR[text removed for publication] [D,E]. Trumpf and Amplitude promote hollow optical fibres to simplify integration of their lasers into machines (Fig. 2). The Managing Director Research and Development, Trumpf Laser technology division says: "*The hollow-core fibre opens up new technical avenues for machine makers and system integrators.*" "*This greatly simplifies processes on the shop floor*" [F].

[text removed for publication]

Figure 2. Beam delivery systems using hollow core fibre marketed as an add-on for high-value pulsed lasers by Amplitude Laser. The linked datasheet promotes "Ultrafast laser integration in your micromachining station is as simple as connecting a fiber" [G,H].

Foundation of and investment in Lumenisity. Building on Bath's research in antiresonant hollow-core optical fibres, researchers at Southampton filed a patent on a low-loss design using nested tubes [J,K]. The patent description explicitly states the importance of antiresonance and negative curvature, both of which are Bath developments [1,2,3], and the description cites the origin of the nested tube idea in the Bath research [5]. The claims in the patent combine the nested tube idea with non-touching tubes, Fig. 3(a). Lumenisity Ltd was founded in 2016 to exploit these fibres in communications applications. Lumenisity is in early stage venture capital funding, but has grown rapidly in the first 4 years. It has received investment of USD6,820,000 in 2017, USD19,000,000 in 2019 and a further GBP7,500,000 in 2020 [L], and employs more than 30 people in 2020 [L]. In 2020 Lumenisity launched antiresonant hollow optical fibres as its first product, CoreSmart™ cables [M].

(a) 

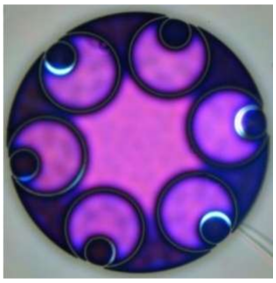
(b) 

Figure 3. a) Record low loss antiresonant hollow optical fibre being commercialised by Lumenisity Ltd [B]. The structure is based on the nested tube configuration developed in Bath, Fig.1(c) [5]. b) Antiresonant hollow optical fibre offered as a commercial product: Lumenisity CoreSmart™ [M].

Summary of impact

The development of antiresonant hollow-core optical fibres from Bath research has directly resulted in:

- GLOphotonics (spin-out founded in Bath in 2008) received new investment in the REF period including from Trumpf, Amplitude Laser and DMG Mori (EUR[text removed for publication] total) and grew from [text removed for publication] employees [C,D].
- GLOphotonics aggregated sales revenues of EUR[text removed for publication] over the REF period [C].
- Lumenisity Ltd founded in 2016 to exploit hollow optical fibre technology. Received more than GBP25,000,000 investment between 2016 and 2020, and employs more than 30 people [L].

5. Sources to corroborate the impact

[A] Pryamikov, AD, Biriukov, AS, Kosolapov, AF, Plotnichenko, VG, Semjonov, SL & Dianov, EM 2011, 'Demonstration of a waveguide regime for a silica hollow - core microstructured optical fiber with a negative curvature of the core boundary in the spectral region > 3.5 μm', *Optics Express*, vol. 19, no. 2, pp. 1441-1448. https://doi.org/10.1364/OE.19.001441

[B] Bradley, TD, Jasion, GT, Hayes, JR, Chen, Y, Hooper, L, Sakr, H, Alonso, M, Taranta, A, Saljoghei, A, Mulvad, HC, Fake, M, Davidson, IAK, Wheeler, NV, Fokoua, EN, Wang, W, Sandoghchi, SR, Richardson, DJ & Poletti, F 2019, ‘Antiresonant Hollow Core Fibre with 0.65 dB/km Attenuation across the C and L Telecommunication Bands’, in *45th European Conference on Optical Communication: ECOC 2019*. vol. 2019, IET, pp. 294. https://doi.org/10.1049/cp.2019.1028

[C] Financial information from GLOphotonics, 4 September 2019.

[D] Investment and employee statement from GLOphotonics, 4 December 2020.

[E] Press release, GLOphotonics, January 2020. https://www.glophotonics.fr/index.php/press.html

[F] News item: TRUMPF acquires stake in GLOphotonics, 10 January 2020. https://optics.org/news/11/1/15

[G] Amplitude web site, beam management products. https://amplitude-laser.com/add_ons_category/beam-management/ (accessed 13/01/2021).

[H] Amplitude product datasheet, FIBER-rev-c https://cdn.amplilaser.com/wp-content/uploads/2020/08/FIBER-rev-c.pdf (accessed 13/01/2021).

[J] Patent WO2015185761 (2015), Patent for the fibre design of [H].

[K] Poletti, F 2014, 'Nested antiresonant nodeless hollow core fiber', *Optics Express*, vol. 22, no. 20, pp. 23807-23828. https://doi.org/10.1364/OE.22.023807

[L] Lumenisity investment evidence 2017 - 2020

a) Lumenisity investment in 2017 and number of employees 2020, data from https://pitchbook.com/profiles/company/322504-03 (accessed 12/12/2019).

b) Lumenisity investment in 2019, data from https://pitchbook.com/profiles/company/322504-03 (accessed 10/11/2020).

c) Lumenisity investment in 2020 https://www.businesscloud.co.uk/news/fibre-optic-tech-firm-closes-7-5m/ (accessed 15/01/2021).

[M] J. Wallace, Laser Focus World, *Lumenisity unveils hollow-core fiber-optic cable for 10 Gbit DWDM transmission over 10 km links*, 1/10/2020. https://www.laserfocusworld.com/fiber-optics/article/14184480/lumenisity-unveils-hollowcore-fiberoptic-cable-for-10-gbit-dwdm-transmission-over-10-km-links