Institution: University of Bath		
Unit of Assessment: B9 Physics		
Title of case study: Supercontinuum fibre lasers show the colour of their money		
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:**
Timothy Birks	Professor, previously Reader	June 1996 – present
Jonathan Knight	Professor, 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
Dimitry Skryabin	Professor, previously Reader and Lecturer	September 2001 – present
James Stone	UKRI Innovation Fellow & Proleptic Lecturer, previously KTP Associate, Research Associate, Research Assistant	May 2007 – present
Period when the claimed impact occurred: 1/8/2013 to 31/12/2020		
Is this case study continued from a case study submitted in 2014? Y		

1. Summary of the impact

Supercontinuum laser sources have a narrow directional beam like a normal laser, but a spread of wavelengths that is many orders of magnitude wider, spanning from the ultraviolet to the near infrared. They are used in a wide range of applications (for example confocal microscopy) to replace multiple, separate lasers, thereby saving cost and space, and improving reliability and robustness.

University of Bath researchers developed the supercontinuum laser source in a form that is compatible with fibre lasers. Fianium Ltd commercialised this source and worked with Bath researchers to improve its colour content, power and lifetime. [text removed for publication]. Between 2014 and 2016 Fianium Ltd grew from [text removed for publication] employees with an aggregate revenue of more than GBP[text removed for publication], at which point it was sold to NKT Photonics for GBP21,000,000. The Bath/Fianium technology continues to [text removed for publication]supercontinuum lasers sold by NKT Photonics, with an aggregate revenue of EUR[text removed for publication] since 2016, and supporting [text removed for publication] FTE employees. Supercontinuum lasers from NKT Photonics are incorporated by original equipment manufacturers (OEMs) into products with an annual market value of EUR[text removed for publication].

2. Underpinning research

Members of Bath's Centre for Photonics and Photonic Materials (CPPM) (Knight, Russell, Wadsworth) realised an optical fibre with a small core surrounded by large air holes in 2000 [1], including a demonstration of supercontinuum generation.

These early supercontinuum sources were very much laboratory experiments, requiring expensive and complex ultrashort pulse Ti:sapphire lasers. However, Wadsworth realised that many more applications and far greater impact would be possible if the same results could be achieved using the much simpler and cheaper technology of Nd^{3+}- or Yb^{3+}-based

lasers. This required the design of new fibres with dispersion suited to the different laser wavelengths, as well as an understanding of how the physics of the generation would change from the ultrashort pulses used originally, to longer (quasi-continuous) pulses [2].

In 2004, members of the CPPM (Wadsworth, Knight, Birks, Russell) published a paper demonstrating supercontinuum with compact, long pulse, Nd^{3+}-based lasers, which was also entirely compatible with the Yb^{3+}-based fibre lasers being developed by Fianium Ltd at the time [3]. Wadsworth patented an aspect of this as WO2005062113A1 (2005) (patent family: EP1697793B1, US7787503B2, JP4921977B2). Fianium contacted Bath researchers to commercialise this technology, and by 2005/06 Fianium were selling supercontinuum sources. With the potential for further commercialisation opportunities obvious to both parties, Fianium and CPPM researchers embarked on a very fruitful collaboration.

Further research on supercontinuum fibres followed in Bath, including extending the visible wavelength coverage out to the blue [4] and then the ultraviolet (320nm) [5]. Short wavelengths in the blue and UV are particularly important for many key applications, including for use in fluorescence microscopy. Complementary theoretical work in Bath by Skryabin [6] elucidated the physical processes controlling the commercially-important shortest wavelengths in the supercontinuum spectrum and Knight, Skryabin and Stone patented these developments as WO2009098519A1 (2009) (patent family: EP2597513B1, EP2250529B1, US8422519B2, US8467422B2, US9217824B2, US9634457B2).

To take the findings of this fundamental research forward, and to develop routes to new technologies, Fianium and Bath entered into collaborative research projects funded by the Technology Strategy Board (TP/4/NGL/6/I/22227, 2006-2008; TP11/LLD/6/I/AF052H, 2008-2011), Knowledge Transfer Partnerships (KTP 8624, 2011-2014 and sKTP 1000710, 2013) (winning KTP Best of the Best Award for engineering excellence 2015), an FP7 project and two CASE studentships (from 2012 to 2018). By working closely with researchers in Bath's CPPM, Fianium Ltd. was able to understand, influence and licence developments in supercontinuum laser technology in order to bring new products to market rapidly [A]. The supercontinuum product range [text removed for publication]of Fianium's business when a sale of the company to NKT Photonics was agreed in 2016 [B]. After this acquisition, [text removed for publication] an improved range of supercontinuum products from NKT Photonics. [text removed for publication] the Fianium brand has been retained in the product with the highest power in the important blue part of the spectrum [C].

3. References to the research

[1] Wadsworth, WJ, Knight, JC, Ortigosa-Blanch, A, Arriaga, J, Silvestre, E & Russell, PSJ 2000, 'Soliton effects in photonic crystal fibres at 850 nm', *Electronics Letters*, vol. 36, no. 1, pp. 53-55. https://doi.org/10.1049/el:20000134

[2] Coen, S, Chau, AHL, Leonhardt, R, Harvey, JD, Knight, JC, Wadsworth, WJ & Russell, PSJ 2002, 'Supercontinuum generation by stimulated Raman scattering and parametric four-wave mixing in photonic crystal fibers', *Journal of the Optical Society of America B-Optical Physics*, vol. 19, no. 4, pp. 753-764. https://doi.org/10.1364/JOSAB.19.000753

[3] Wadsworth, WJ, Joly, N, Knight, JC, Birks, TA, Biancalana, F & Russell, PSJ 2004, 'Supercontinuum and four-wave mixing with Q-switched pulses in endlessly single-mode photonic crystal fibres', *Optics Express*, vol. 12, no. 2, pp. 299-309. https://doi.org/10.1364/OPEX.12.000299

[4] Stone, JM & Knight, JC 2008, 'Visibly "white" light generation in uniform photonic crystal fiber using a microchip laser', *Optics Express*, vol. 16, no. 4, pp. 2670-2675. https://doi.org/10.1364/OE.16.002670

[5] Stone, JM & Knight, JC 2012, 'From zero dispersion to group index matching: How tapering fibers offers the best of both worlds for visible supercontinuum generation', *Optical Fiber Technology*, vol. 18, no. 5, pp. 315-321. https://doi.org/10.1016/j.yofte.2012.06.004

[6] Gorbach, AV & Skryabin, DV 2007, 'Light trapping in gravity-like potentials and expansion of supercontinuum spectra in photonic-crystal fibres', *Nature Photonics*, vol. 1, no. 11, pp. 653-657. https://doi.org/10.1038/nphoton.2007.202

4. Details of the impact

[text removed for publication]
As a result of its collaboration with University of Bath researchers, by 2014 Fianium Ltd was firmly established as a world leader in supercontinuum sources, with annual supercontinuum sales of GBP[text removed for publication] and a workforce of [text removed for publication] [A]. Bath's CPPM is a world leader in fibre supercontinuum research and, although not the only research team in this active field, Fianium chose to collaborate closely only with Bath in this area. Fianium's first supercontinuum source (Product # SC450) was based directly on CPPM research [3] and had a spectral range from about 460 nm (blue) to about 2000 nm (infrared). This remained an important component of Fianium's product line up to the sale of the company in 2016. Knight, Stone and Skryabin patented and licenced the design of a new supercontinuum-generating fibre to Fianium [4] which gave rise to new products with enhanced output in the blue and UV. These were [text removed for publication]products in the Fianium lineup between 2013 and 2016. [text removed for publication]. The workforce increased to [text removed for publication] by 2016, and total sales between August 2013 and 2016 were more than GBP[text removed for publication] [B].

In 2016 Fianium Ltd was sold to NKT Photonics A/S (Denmark) for GBP21,000,000 [D]. This gave NKT access to Bath and Fianium technologies in supercontinuum. Between 2016 and 2020 NKT revised its supercontinuum product range, [text removed for publication]. The flagship product with highest power in the blue/UV [text removed for publication]carries the Fianium brand name [C]. [text removed for publication]. This shows that Bath research has been pivotal in driving supercontinuum laser development [text removed for publication] at Fianium [text removed for publication]. NKT Photonics has become the only major supplier of supercontinuum lasers, supplying them for the majority of original equipment manufacturer (OEM) integrators [B,G].
[text removed for publication]

Summary of impact

- Development of a world-leading new technology: Supercontinuum laser sources.
- [text removed for publication] annual sales revenue of Fianium Ltd from 2013 until its sale in 2016: more than GBP[text removed for publication] total sales revenue [A,B].
- Fianium's workforce of [text removed for publication] employees in October 2013 [A] grew to [text removed for publication] in 2016 [B].
- Sale of Fianium Ltd to NKT Photonics A/S for GBP21,000,000 in 2016 [D].
- [text removed for publication] NKT Photonics SuperK series from 2016 onwards. Aggregated direct sales of EUR[text removed for publication] and direct employment of [text removed for publication] FTE employees [E,F].
- NKT Photonics are by far the largest supplier of supercontinuum products [G]; these lasers are incorporated by OEMs into products with annual sales of EUR[text removed for publication] [F].

5. Sources to corroborate the impact

[A] Statement from [text removed for publication], Fianium Ltd, 8 October 2013.

[B] Statement from [text removed for publication], Fianium Ltd, until sale in 2016, 14 January 2021.

[C] Promotional video for NKT Photonics 'SuperK Fianium' product, 2020. https://www.nktphotonics.com/lasers-fibers/2020/11/27/the-superk-fianium-is-broad-as-a-lamp-bright-as-a-laser/

[D] NKT Photonics press release 31 March 2016.

[E] NKT Annual Report 2018.

[F] Statement from [text removed for publication]of NKT Photonics A/S, 8 December 2020.

[G] Feature article: Super Lasers, Electro Optics **270**, p32, February 2017. https://www.electrooptics.com/feature/super-lasers