Institution: University of Bath

Unit of Assessment: 9: Physics

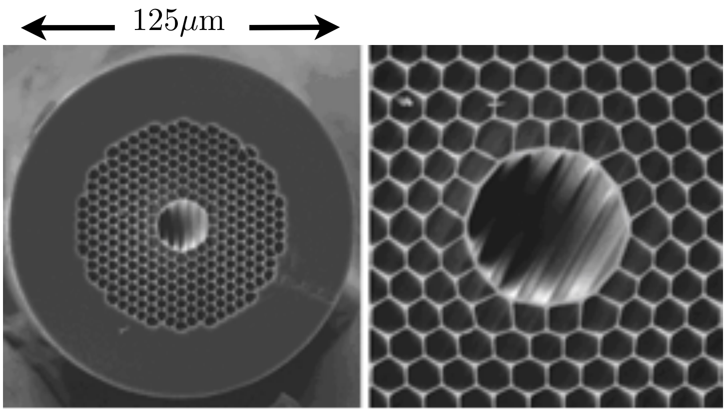
Title of case study: Photonic Crystal Fibre: Creation of a multi million dollar industry

1. Summary of the impact

Photonic crystal fibres are a new form of optical fibre developed at the University of Bath from 1996 to the present. Our work has led to the creation of new companies, new business sectors for established companies and stock products for large component suppliers. Our key patents (now sold) continue to dominate technological developments. The estimated annual world market for photonic crystal fibre is between \$35M and \$70M. Users include industries and academic institutions involved in physical and biomedical imaging, microscopy, spectroscopy, sensing, metrology and laser gyroscopes.

2. Underpinning research

Photonic crystal fibres (PCFs) are optical fibres incorporating carefully-controlled patterns of microscopic air holes. They have characteristics that are impossible in conventional fibres, such as the ability to guide light along a hollow core (see figure). The fibre's inventors Birks, Knight and Russell[§] established what is now the Centre for Photonics and Photonic Materials (CPPM) at the University of Bath in 1996. They were later joined by Wadsworth, Benabid and Skryabin[§]. This group pioneered the design and fabrication of these fibres with funding from DERA Malvern, EPSRC and JIF and support from the University of Bath. They have led what has since developed into a continuing worldwide academic research field and industrial technology.



The cross section of a hollow-core PCF developed at Bath

The research took place from 1996 and continues to this day. Key scientific milestones underpinning the impact include:

- Demonstration and understanding of endlessly single-mode PCFs, which propagate light of any wavelength at a well-defined speed [1]. All conventional fibres are only single-mode over a limited range of wavelengths, leading sometimes to a poor profile for the delivered beam.
- Demonstration and understanding of low-loss optical fibres that guide light in a hollow core surrounded by a "photonic band gap" cladding [2-4]. This enables delivery of pulse lengths, optical powers and wavelengths, which are truly unthinkable using conventional fibres.

- Prediction and demonstration of the necessary properties for the control of strong non-linear interactions in PCFs [5]. This revitalised the field of nonlinear fibre optics, resulting in a range of technological and commercial developments as well as new scientific insights.

§ T.A. Birks (Professor 1996-present), J.C. Knight (Professor 1996-present), P. S-J. Russell (Professor 1996-2005), Wadsworth (Reader 1999-present), Benabid (Reader 1999-2011) and Skryabin (Professor 2000-present).

3. References to the research

[1](*) TA Birks, JC Knight, PStJ Russell, *Endlessly single-mode photonic crystal fiber*, Optics Letters **22** 961-963 (1997) (1703 citations, 2nd most cited paper in the journal's history). http://dx.doi.org/10.1364/OL.22.000961

[2](*) JC Knight, J Broeng, TA Birks and PStJ Russell, *Photonic band gap guidance in optical fibers*, Science **282** 1476-1478 (1998) (824 citations). DOI:10.1126/science.282.5393.1476

[3](*) RF Cregan, BJ Mangan, JC Knight, TA Birks, PStJ Russell, PJ Roberts, DC Allen, *Single-mode photonic band gap guidance of light in air*, Science **285** 1537-1539 (1999) (979 citations). *DOI: 10.1126/science.285.5433.1537*

[4] F Benabid, JC Knight, G Antonopoulos, PStJ Russell, *Stimulated Raman scattering in hydrogen-filled hollow-core photonic crystal fiber*, Science **239** 399-401 (2002) (374 citations). *DOI:* 10.1126/science.1076408

[5] WH Reeves, DV Skryabin, F Biancalana, JC Knight, PStJ Russell, FG Omenetto, A Efimov, AJ Taylor, *Transformation and control of ultra-short pulses in dispersion-engineered photonic crystal fibres*, Nature **424** 511-515 (2003) (246 citations). doi:10.1038/nature01798

(*) Best indicators of research quality

4. Details of the impact

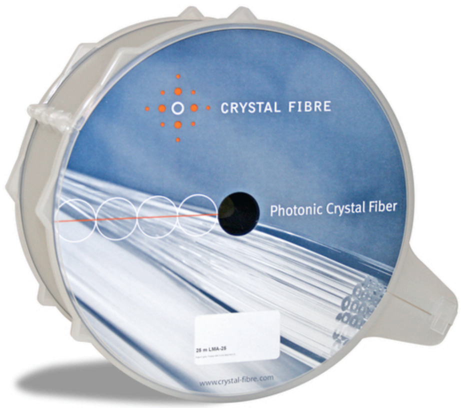
The unique properties of PCFs (described above) open up new ways to manipulate and control light, benefiting applications such as medical imaging (eg. fluorescence lifetime imaging, optical coherence tomography and optical molecular imaging) [6], spectroscopy, physical and biomedical sensing [7], laser gyroscopes (used in critical navigation and defence systems) [8] and materials processing.

Commercial activity at Bath began with several key patents filed from 1998 with Birks, Knight and Russell as inventors [9]. Together with a Bath spin-out company BlazePhotonics, these patents were sold to Danish firm “Crystal Fibre” for $3.3M in 2004. Now part of NKT Photonics [10], Crystal Fibre's capability also derived directly from Bath know-how following our collaboration with its co-founder Broeng [2,11]. The PCFs sold by NKT Photonics during the REF period were therefore based on our original expertise and patents. The company also incorporate PCF as a key enabling component in many of their fibre laser products. In their 2010 Annual Report, NKT state that the “addressable market for crystal fibers is valued at around 200-400 mDKK annually” [12], equivalent to $35M-$70M annually. “Addressable market” is the total size of a market [13].

CPPM remain engaged with the needs of industry and indeed some of NKT Photonics’s newest custom fibre products were supplied directly by us under contract. Commenting on this deal, the CEO of NKT Photonics said “We are pleased that we can continue to serve our customers with these leading edge fibers, and along with the help and expertise of the University of Bath, demonstrate our continued leadership and commitment in the area of hollow core fibers” [11].

Several other companies sell systems incorporating types of PCFs invented, designed and demonstrated by the Bath team, such as Leukos SA (France) [14] and B&W Tek (USA) [15]. A major PCF application is microscopy, and the market leading Leica TCS SP8 X confocal microscope employs PCF in the excitation source [16]. Another key application is the optical comb marketed by Menlo Systems for precision metrology and standardisation [17]. Menlo itself arose from the laboratory of one of our German collaborators, in part because of our contribution to the work for which he was awarded the Nobel Prize in 2005 [18]. The US military uses PCF for high-power military sensors and gyroscopes [19].

Throughout the REF period, the leading optical components vendors Newport Corporation [20] and Thorlabs [21] sold “off-the-roll” PCFs made by BlazePhotonics and NKT Photonics and based on our designs. They offered 15 and 25 PCF products respectively, priced between £80 and £1100 per metre, for a variety of industrial and academic applications such as those described above.



PCF on a spool, sold by Newport Corporation

In summary:

- Photonic crystal fibres represent a revolutionary waveguide technology that was pioneered and developed by the University of Bath team
- Their unique properties have a multitude of applications
- Businesses derived directly or indirectly from our research outputs serve a worldwide market worth several tens of millions of dollars annually

5. Sources to corroborate the impact

[6] F. Begum and Y. Namihira *Photonic Crystal Fiber for Medical Applications,* in "Recent Progress in Optical Fiber Research", Edited by Moh. Yasin, Sulaiman W. Harun and Hamzah Arof ISBN 978-953-307-823-6, DOI: 10.5772/27739

[7] A.M.R. Pinto and M. Lopez-Amo, *Photonic Crystal Fibers for Sensing Applications*, Journal of Sensors, vol. 2012, Article ID 598178, 2012. doi:10.1155/2012/598178

[8] http://www.nktphotonics.com/gyro (accessed 15/7/13)

[9] For example patents: EP 1340725, EP 1153324, EP1388018, EP1153325, viewable via http://www.google.com/patents

[10] www.nktphotonics.com (accessed 22/4/13)

[11] NKT Photonics press release at www.nktphotonics.com/news_2010 (accessed 22/4/13)

[12] NKT Photonics: 2010 Annual report page 30: http://www.nkt.dk/uk/Materials/Annual+reports/2010 (accessed 22/4/13)

[13] http://en.wikipedia.org/wiki/Total_addressable_market (accessed 22/4/13)

[14] http://www.leukos-systems.com (accessed 22/4/13)

[15] http://bwtek.com/ (accessed 22/4/13)

[16] http://www.leica-microsystems.com/products/confocal-microscopes/leica-tcs-sp8-configurable-confocal/details/product/leica-tcs-sp8-x/ (accessed 12/7/13)

[17] www.menlosystems.com (accessed 22/4/13)

[18] See page 165 of Ted Hänsch's Nobel lecture: http://www.nobelprize.org/nobel_prizes/physics/laureates/2005/hansch-lecture.pdf (accessed 22/4/13)

[19] http://www.darpa.mil/NewsEvents/Releases/2013/07/17a.aspx (accessed 18/7/13)

[20] www.newport.com (accessed 22/4/13)

[21] www.thorlabs.com (accessed 22/4/13)