Institution: University of Southampton

Unit of Assessment: 13 Electrical and Electronic Engineering, Metallurgy and Materials

Title of case study: 13-13 Commercialisation of Engineered Nonlinear Materials for Optoelectronics.

1. Summary of the impact

Covesion, the company spun out of the University of Southampton's research into materials for use in high-powered lasers, has grown into a multi-million pound business that has created high-technology jobs, attracted more than £1 million in US investment and won UK export orders around the world. Covesion's nonlinear crystals are used by the world's leading companies and research institutes in cutting edge applications that include fibre lasers, medical imaging, aircraft anti-missile defences, display projectors and the remote sensing of airborne hazardous materials. The global value of Covesion-enabled operations since the company's inception in 2009 is estimated to be in excess of US$100 million.

2. Underpinning research

Nonlinear optical materials are used to manipulate some of the fundamental properties of light (almost invariably laser light) in terms of its wavelength, bandwidth or spectral content, by the judicious choice or manipulation of their nonlinear optical coefficients. The field of nonlinear optical research has grown rapidly following the invention of the laser in 1960. Although it may be comparatively easy to demonstrate laser action in a particular material, unless the laser wavelength produced is optimum for the end application, nonlinear optical techniques are needed to convert the primary wavelength into the one required, and to do this with the highest efficiency possible.

One technique for achieving such efficient wavelength conversion is called 'quasi-phase-matching', which involves the manipulation of a crystal structure by periodically modifying its internal crystalline axes at length scales that fall into the few micron range. Suggested first in the early 1960s, little practical progress was made in the area until the early 1990s, when techniques emerged to successfully fabricate these engineered crystals with the correct periodicity and quality. Three research groups at Sony corporation in Japan, Stanford University in California, and the ORC at Southampton, independently developed and refined the fabrication techniques required, using lithium niobate crystals as the optimum starting material, to produce the final product known as PPLN (periodically poled lithium niobate). In 1994, Southampton published a key result using a novel approach which involved periodic structuring using liquid electrodes [3.1] which produced the small periods required with excellent fidelity, a result that followed soon after the first reports from Sony in 1993 and from Stanford University in 1994. Research followed into the use of light to control periodic poling [3.2, G1, G3] and fundamental work on structures within periodically poled materials was undertaken via collaborative research [3.3] to further refine all aspects of the final material precision and quality.

Progress in the underpinning research extended to the use of periodically poled materials for efficient wavelength conversion into the blue (short wavelength), where 450mW of blue light was generated [3.4] and near-infrared (long wavelength) operation [3.5, G2] as well as the adoption of optical waveguide technology which was developed in conjunction with periodic poling [3.6] all of which presented further opportunities to expand the range of future products. In particular, one of the ORC's important contributions to the technology lay in developing a simple process for periodic poling of magnesium oxide doped crystals, which allows them to be used in high-power applications and at higher temperatures. Grants G4, G5, G6 cover much of the subsequent recent research work, before these activities were spun out via Stratophase and then Covesion, which was formed in 2009, initially with just two staff members, to develop a PPLN business that revolved around these new-generation magnesium oxide doped crystals. Researchers who made significant contributions to this work include:

- Professor David Hanna, who instigated the research into periodic poling technology, deputy director of the ORC until his retirement in 2007.
- Professor Robert Eason, researching in the ORC 1989- date.
- Professor Peter G.R. Smith, joining the ORC in 1994 as Research Fellow, and founder of Covesion.
- Dr Corin Gawith, joining the ORC in 1998, an now CTO of Covesion. 2009 - Present
- Dr Huw Major, a former PhD student who is now senior engineer at Covesion. 2000 - Present

3. References to the research

*[3.1] Webjörn, J., Pruneri, V., Russell, P.St.J., Barr, J.R.M. and Hanna, D.C. (1994) Quasi-phase-matched blue light generation in bulk lithium niobate, electrically poled via periodic liquid electrodes. Electronics Letters, 30, (11), 894-895.

[3.2] P.T. Brown, G.W. Ross, R.W. Eason, A.R. Pogosyan (1999) Control of domain structures in lithium tantalate using interferometric optical patterning, Optics Communications, Volume 163, Issues 4–6, p310-316.

[3.3] Z. H. Hu, P. A. Thomas, A. Snigirev, I. Snigireva, A Souvorov, P. G. R. Smith, G. W. Ross, S. Teat (1998) Phase-mapping of periodically domain-inverted LiNbO3 with coherent X-rays, Nature 392, 690-693 (16 April 1998).

*[3.4] G.W. Ross, M. Pollnau, P.G.R. Smith, W.A. Clarkson, P.E. Britton, D.C. Hanna (1998), Generation of high-power blue light in periodically poled LiNbO3, OPTICS LETTERS Volume: 23 Issue: 3 Pages: 171-173.

*[3.5] M.A. Watson, M.V. O'Connor, P.S. Lloyd, D.P. Shepherd, D.C. Hanna, C.B.E. Gawith, P.G.R. Smith, O. Blachninaite (2002), Extended operation of synchronously pumped optical parametric oscillators to longer idler wavelengths, OPTICS LETTERS Volume: 27 Issue: 23 pp. 2106-2108.

[3.6] L. Ming, C.B.E. Gawith, K. Gallo, M. O'Connor, G.D. Emmerson, P.G.R. Smith (2005) High conversion efficiency single-pass second harmonic generation in a zinc-diffused periodically poled lithium niobate waveguide, OPTICS EXPRESS Volume: 13 , pp4862-4868, Issue: 13.

Underpinning research grants

The research was funded by grants from EPSRC between 1994 and 2011, as detailed below. Funding specifically attributable to PPLN research was approximately £480,000, and funding was also provided via larger portfolio grants [G4, G5, G6].

[G1] GR/K28251/01, OPTICALLY INDUCED PERIODIC DOMAIN GRATINGS, R.W. Eason, 26/9/1994 to 25/9/1996, £103,506.

[G2] GR/M40301/01, NEW QUASI PHASE MATCHED NONLINEAR MATERIALS AND THEIR APPLICATION TO OPTICAL PARAMETRIC OSCILLATORS, D.C. Hanna, P.G.R. Smith, 01/10/1998 to 31/03/2002, £196,437

[G3] GR/S47373/01, Light-induced domain engineering in ferroelectrics: a route to sub-micron poling, R.W. Eason, 1/10/2003 to 30/9/2004, £152,050

[G4] GR/M81854/01 Advanced optical fibre and waveguide devices and microstructured optical materials, EPSRC, DN Payne, DC Hanna, RW Eason, JS Wilkinson, WS Brocklesby, E Taylor, HN Rutt, D Hewak, PGR Smith, M Zervas, 1/10/1999 to 30/9/2003, £2,056,683.

[G5] GR/T11746/01 Fabrication of Microstructured Glass & Crystal Photonic Materials &

Devices, EPSRC, DN Payne, DC Hanna, RW Eason, JS Wilkinson, PG Kazansky, T Monro, HN Rutt, DJ Richardson, D Hewak, DP Shepherd, PGR Smith, 1/4/2004. Subsumed into Portfolio Partnership in Photonics, 30/9/2004, £2,741,404.

[G6] EP/C515668/1 Portfolio Partnership in Photonics, EPSRC, DN Payne, WA Clarkson, RW Eason, D Hewak, N Broderick, PGR Smith, 1/10/2004 to 31/3/2011, £7,179,095.

4. Details of the impact

The process (from research to impact)

The spin-out company Covesion was itself spun out from a parent company, Stratophase (another spin-out company of the University started in 2003) in 2009, to better focus on research and development of its nonlinear optical materials product line [5.1]. With fresh venture capital investment, Covesion developed new Intellectual Property around poling of magnesium oxide-doped PPLN for high power applications, technology that had been pioneered within the ORC. At its inception Covesion comprised only the two former Stratophase staff members working on PPLN. Since then it has created five high-tech jobs and achieved sales worth £2.1m over three years, 95 per cent of these sales being to overseas customers [5.2].

Economic impact

Covesion customers include some of the world's most successful companies and prestigious research institutes, (including some University-based former PPLN research groups), which span the areas of defence, communications, laser manufacturing and medicine. *New business has therefore been created.* The list includes major corporations such as [text removed for publication]. From recent measurements of the performance of these nonlinear engineered crystals, where 45W of green light has been generated from an input near- infrared laser beam, (reported by Stanford University, in 2012 [5.3]) it is clear that high-power lasers can now be built in a far more cost-effective manner using Covesion components, and such impressive results have led to significant patent activity [5.4].

Another area that demonstrates *economic impact* relates to the use of these engineered crystals in laser projection systems for presentations and displays. This laser-based technology provides brighter, clearer colours and uses less energy than conventional light bulb-based units, and therefore represents an activity that has an impact on the environment also (*management of energy*). Consumer demand in this area is growing rapidly, as products are marketed for home cinema, desktop projectors and rear-projection displays. Future opportunities include pico-projectors integrated into mobile phones and laptops, as well as use in medical screening and aero defence equipment. Covesion has entered into a license agreement and technology transfer programme with a leading projector company [text removed for publication].

The final claim under economic impact is that the crystals sold by Covesion have become essential parts of new laser systems and applications, which has *improved the performance of existing businesses.* The crystals are integrated into high-end products which are sold by Covesion customers, so the leverage effect is considerable, and vital to the success of these companies. The company's own analysis of sales of these systems and the volume of products shipped suggests that the total worldwide market value of Covesion-enabled commerce is greater than US$25m per year (hence $100m since 2009) [5.2]. A ready example concerns Covesion products that are used in short-pulse fibre lasers which are sold by at least three manufacturers [text removed for publication]. Publicised users to date include Oclaro Inc., one of the world's largest suppliers of optical communications equipment, top universities Harvard and Stanford and leading governmental research organisations such as NASA.

Other key applications for Covesion products lay in the area of medical imaging, where 2-photon fluorescence microscopy that uses Covesion crystals enables imaging of living tissue, an area of immediate concern for real-time medical diagnostics. Covesion have also played a key role in the consortium working on the EU-funded CROSS TRAP (Coherently-enhanced Raman One-beam Standoff Spectroscopic Tracing of Airborne Pollutants) project [5.5] which addresses the development of a novel laser remote sensing technique for probing air at a distance for hazards such as biochemicals, bacterial threats and explosive materials.

A final area concerns the impact *on society* through provision of essential components in systems that protect the public and armed forces of several nations – preventing future loss of life. Under UK export licenses, Covesion crystals are used as wavelength conversion components in laser countermeasure systems on over 90 commercial aircraft [5.2]. These involve direction of laser beams towards an approaching missile, causing it to veer off course. [text removed for publication][5.6].

In conclusion, for the sake of completeness, a reference has been included that describes the global technical impact, which provides a list of publications from Covesion customers [5.7].

5. Sources to corroborate the impact

5.1 www.covesion.com

5.2 contact to confirm sales figures, details on Projector license and [text removed for publication]: COO of Covesion Limited

5.3 http://dx.doi.org/10.1364/OL.37.003861

5.4 Southampton has applied for the following US patents: No. 8,064,129 (Process for poling a ferroelectric material doped with a metal), filed 2009, issued 2011, No. 8,054,536 (Electric field poling of ferroelectric materials), filed 2008, issued 2011, 2011/0064,719, filed 2009 (Compensation for the Gouy phase shift in quasiphase matching), pending.

5.5 http://www.crosstrap.eu/index.php?option=com_content&view=article&id=3&Itemid=5

http://www.southampton.ac.uk/ris/kt/proof2_38982_KTScasestudy.pdf

http://spie.org/exhibitor/company/Covesion-Ltd./SPIE-Defense,-Security,-and-Sensing-2012

Contact: Knowledge Transfer Scheme Collaboration Manager, University of Southampton

5.6 [text removed for publication]

5.7 References to impact globally in technical terms (providing a list of peer review publications by customers) http://www.covesion.com/news/