Institution: University of Southampton

Unit of Assessment: 12 Engineering

Title of case study: 12-05 Delivering economic impact through the commercialisation of engineered nonlinear optical materials for laser and quantum technology systems

Period when the underpinning research was undertaken: 2000 – 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:
Peter G.R. Smith	Professor in Electronics and Computer Science	September 1994 – present
Corin Gawith	Professorial Fellow	October 2000 – present
James Gates	Principal Research Fellow	January 2006 – present
Lewis Carpenter	Research Fellow	October 2013 – March 2020

Period when the claimed impact occurred: August 2013 – December 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Researchers at the University of Southampton's Optoelectronics Research Centre (ORC) have developed and patented the engineering of nonlinear optical materials for highly efficient wavelength conversion with lasers. This has underpinned the original creation and ongoing development of spinout company **Covesion Ltd**. Over the impact period, Covesion has become a leader in the supply of crystals and packaged products for use in laser, anti-missile, imaging and quantum technology systems across the defence, communications, laser manufacturing and medical sectors. This has generated the following multi-faceted economic impact over the eligible period:

- Tripling of annual company turnover from 2014 to 2020 [text removed for publication]
- Doubling of the company workforce with the creation of six high-skilled roles.
- [text removed for publication]
- Enabling UK industry (mostly start-ups and SMEs) to win GBP5.48m in direct income from the UK Government's National Quantum Technologies Programme.
- Supporting the development of the UK's sovereign capability in quantum technologies.

2. Underpinning research

Engineered nonlinear optical materials are used to change the wavelength of laser light for numerous applications. 'Quasi-phase-matching' is a key technique for achieving efficient wavelength conversion. It involves compensating the relative phase between two or more frequencies of light as they propagate through a crystal. It is necessary for the phase relation between the input and generated photons to be maintained throughout the crystal so that the number of generated photons exiting the crystal is maximised. PPLN – periodically poled lithium niobate – is an engineered, quasi-phase-matched material; the orientation of the lithium niobate crystal is periodically inverted to avoid the photons slipping out of phase with each other. This means the number of generated photons will grow as the light propagates through the PPLN crystal, yielding a high conversion efficiency.

Research at Southampton's ORC optimised the use of PPLN for efficient power conversion at different wavelengths, including for near-infrared (long wavelength) operation [**3.1**]. The ORC team succeeded in developing a new technological process for the periodic poling of magnesium oxide (MgO) doped PPLN crystals that allowed them to be used in higher power laser applications and over a wider range of wavelengths. The MgO doping sits inside the crystal lattice and acts to compensate defects which reduce photorefractive damage and improve laser power-handling. Crucially, this new process allowed the MgO doped PPLN to be fabricated with sufficient reliability and at lower temperatures for commercial applications.

The MgO:PPLN process was patented in 2008 [**P1**] and licensed to a new university spinout company Covesion Ltd, co-founded by Smith and Gawith in 2009, in order to develop a PPLN business based on the new-generation MgO doped crystals. Smith is now a non-executive director; Gawith has been a part-time CTO since the company was founded, while remaining an academic at the ORC. The new IP covered the development of MgO doped PPLN, offering far superior power handling relative to undoped PPLN (up to tens of Watts compared to 100s of Milliwatts) and lower temperature device operation. The technology was explained, and its power further optimised, in a series of peer-reviewed publications involving Gawith [e.g. **3.2**].

Since Covesion's formation, ORC research has sought to optimise the performance of the company's PPLN crystals and develop new products. The ORC team has pioneered an approach to making optical waveguide devices in PPLN, utilising a combination of zinc diffusion and physical machining. The waveguide format in PPLN provides the capability of tightly focusing a laser beam, significantly boosting the efficiency of the wavelength conversion while maintaining a very high level of power handling. In 2005, ORC researchers first reported a technique for the fabrication of zinc-diffused channel waveguides using periodic poling, without degrading the nonlinearity [**3.3**, **G1**]. Research under the UK National Quantum Technologies programme [**G2**, **G3**] investigated the optimum dicing processes (a form of mechanical sawing used in photonics) required to achieve ultra-smooth surfaces for the zinc-diffused waveguide structures in order to optimise frequency conversion and eliminate the need for time consuming and costly lapping and polishing [**3.4**].

A patent for the waveguide fabrication method was filed [**P2**] and licensed to Covesion, allowing the company to launch, in June 2019 a new commercial range of PPLN waveguides that provide highly efficient and cost-effective frequency conversion. Customers are able to specify wavelengths that are not commercially available elsewhere. ORC researchers went on to demonstrate world record efficiencies and power handling for waveguides in lasers used to cool atoms close to absolute zero so they can be used as ultra-sensitive gravity sensors for earth systems monitoring, including changes in polar ice mass, ocean current and sea level [**3.5**, **3.6**].

3. References to the research

3.1 MA Watson, MV O'Connor, PS Lloyd, DP Shepherd, DC Hanna, CBE Gawith, PGR Smith, O Blachninaite, Extended operation of synchronously pumped optical parametric oscillators to longer idler wavelengths, Opt Lett, 27, 23, 2106-2108 (2002). https://doi.org/10.1364/ol.27.002106

3.2 K. Li, AY Yao, NJ Copner, CBE Gawith, IG Knight, HU Pfeiffer, B. Musk, Compact 1.3 W green laser by intracavity frequency doubling of a multi-edge-emitter laser bar using a MgO:PPLN crystal, Opt Lett, 34, 22, 3472-3474 (2009) https://doi.org/10.1364/OL.34.003472

3.3 L Ming, CBE Gawith, K Gallo, M O'Connor, GD Emmerson, PGR Smith, High conversion efficiency single-pass second harmonic generation in a zinc-diffused periodically poled lithium niobate waveguide, Opt. Exp., Vol 13 , pp4862-4868, Issue: 13 (2005). https://doi.org/10.1364/OPEX.13.004862

3.4 LG Carpenter, SA Berry, CBE Gawith, Ductile dicing of LiNbO3 ridge waveguide facets to achieve 0.29 nm surface roughness in single process step, Elec Letters, 53, 25, 1672-1673 (2017) https://doi.org/10.1049/el.2017.2863

3.5 L.G. Carpenter, SA Berry, AC Gray, JC Gates, PGR Smith, and CBE Gawith, CW demonstration of SHG spectral narrowing in a PPLN waveguide generating 2.5 W at 780nm, Opt. Express 28, 21382-21390 (2020). https://doi.org/10.1364/OE.395566

3.6 SA Berry, LG Carpenter, AC Gray, PGR Smith, and CBE Gawith, Zn-indiffused diced ridge waveguides in MgO:PPLN generating 1 watt 780 nm SHG at 70% efficiency, OSA Continuum 2, 3456-3464 (2019), https://doi.org/10.1364/OSAC.2.003456

Selected intellectual property

P1 Patent: EP2247981B1, A process for poling a ferroelectric material doped with a metal, CBE Gawith, PGR Smith, HE Major, Priority date 15th Feb 2008, Granted 29th June 2016.

P2 Patent application: GB2584877A, Method for fabrication of ridge waveguides, CBE Gawith, PGR Smith, L Carpenter, S Berry, Priority date 19th June 2019, Published 23rd December 2020.

Key underpinning grants

G1 EPSRC GR/S50700/01, Zinc-waveguide Enhanced Periodically Poled Lithium Niobate, Oct 2003 – Sept 2004, £162,042.

G2 EPSRC EP/M013294/1, UK Quantum Technology Hub for Sensors and Metrology (multi-institution grant), Dec 2014 –Nov 2019, £35,513,855. (Southampton share = £3.8M).

G3 EPSRC EP/M013243/1, UK Quantum Technology Hub: NQIT - Networked Quantum (multi-institution grant), Dec 2014 – Nov 2019, £38,029,961. (Southampton share = £1.6M).

4. Details of the impact

ORC research underpinned the formation of UoS spin out company Covesion and, over the REF 2021 impact period, has been integral to both the optimisation of the company's MgO PPLN crystals and the creation of new PPLN products. Covesion offers volume manufacture of bespoke crystals for Original Equipment Manufacturer systems; its PPLN devices allow customers to reach wavelengths that cannot be achieved with conventional solid state or diode lasers. The company's customers include world-leading companies and prestigious research institutes spanning the areas of defence, communications, laser manufacturing and medicine. Specific applications include: microscopy imaging, laser-based missile countermeasure systems, trace gas detection, LIDAR, precision navigation systems, seabed surveying, environmental monitoring and remote sensing.

There are three strands to the economic impact arising from ORC's underpinning research: direct impact on Covesion's commercial growth over the impact period; wider economic impact generated through sales, by Covesion customers, of systems reliant on Covesion's PPLN devices; commercial income unlocked for UK industry through the award of Innovate UK programmes that revolve around Covesion's technology.

Economic impact via the commercial growth of a university spinout company

ORC research underpins Covesion's two main products: MgO PPLN crystals and MgO PPLN packaged waveguides. These patented, market-leading technologies have resulted in Covesion securing customers that include major corporations [text removed for publication], government labs (e.g. NASA, US Naval Observatory, Fraunhofer Institute for Applied Optics and Precision Engineering, Korea Institute of Science and Technology, Indian Institute of Technology) and the majority of the world's leading universities (e.g. Harvard, Stanford, Caltech) [**5.1**, **5.2**].

Over the impact period, Covesion has almost tripled its annual turnover [text removed for publication]; 95% of sales constituted overseas exports, benefitting the UK economy [**5.2**, **5.3**]. The new PPLN waveguide devices launched in June 2019 accounted for 25% of commercial income as of December 2020; this is expected to rise to more than 50% by 2023 [**5.2**]. The company has more than doubled its workforce from 5 to 11 people, creating six high-skilled roles [**5.2**]. It has been able to plan strategically for annual growth of 30% for the period 2021-2024. This is demonstrated through its formal [text removed for publication] commitment, made in December 2020, to move to a larger high-value manufacturing facility at Adanac Park, Southampton to accommodate planned growth [**5.2**].

Economic impact via the sale of laser systems reliant on Covesion products

Global sales of laser and quantum technology systems have been enabled specifically through the incorporation of Covesion PPLN crystals. [text removed for publication]

Companies choose Covesion materials for a set of technical reasons and a range of commercial reasons that provide their OEM systems with a competitive advantage [**5.2**]. The former includes high laser damage thresholds (>500kW/cm2 for 2000 hours), nonlinearity of 16pm/V, dimension control (+/- 50 microns) and poling fidelity – all of which lead to reliable operation within design tolerances. The latter reasons for choosing to purchase from Covesion includes price, reliability of supply, delivery time, quality control and after-sales technical support [**5.2**]. Many of these features originate directly from ORC research into poling technology (specifically the development of MgO:PPLN poling), which provides very high poling fidelity, reliable yield (which is important to meet tight delivery schedules) and optimum nonlinearity [**5.2**]. Covesion's large volume manufacturing capabilities are key to offering its customers a significant price advantage [**5.2**]. When customers purchase crystals, they place orders via tenders or large call-off orders, which allows Covesion to reduce the prices of their crystals by increasing manufacturing volumes. [text removed for publication]

Covesion sells its products into laser systems that retail for anywhere between 40 and 1,000 times the value of the Covesion product; it is common for a pulsed laser system to sell for at least GBP100,000 [**5.2**]. [text removed for publication]

Taking the above details into account, Covesion can produce a quantitative estimate of the global economic impact arising from OEM product sales that <u>rely upon</u> the nonlinear properties of the company's PPLN crystals and waveguides: an average of GBP60,000,000 per year (cumulatively, GBP420,000,000) over the impact period. Covesion's CEO wrote [**5.2**]: '*Based on our direct sales figures and what we know of the retail value of the laser systems in which our products form an integral part, we can provide a confident, yet conservative, economic impact estimate of £60m per year as an average over the impact period. This relates to the sale of systems that would otherwise not be possible without our devices*.' There is also a wider societal impact in that anti-missile laser systems protect commercial, military and peace-keeping aircraft from attack.

Economic impact via direct income to UK industry through the UK Government National Quantum Technology Programme

In 2014, the UK Government announced its intention to develop a GBP1bn industry based on the commercialisation of quantum technologies. The UK National Quantum Technologies Programme was further expanded in 2018 when the Government announced it was one of 15 key areas for the Industrial Strategy Challenge Fund. UoS research into the development of PPLN waveguides [**P2**, **3.3**-**3.6**] has been a key enabling element of several Innovate UK grants that have provided direct income to not only Covesion but multiple UK companies, and have supported the development of the UK's sovereign capability in this area [**5.2**, **5.5**].

Covesion has been awarded over GBP1,000,000 in direct income from five Innovate UK projects over the impact period [**5.5**]. These include the Cold Atoms Space Payload (CASPA) project, which sought to develop a small satellite payload to generate cold atoms in space; it was highlighted by the Government as one of three case studies in its investment announcement in 2018 [**5.6**]. UoS and Covesion PPLN waveguide technology unlocked income for a range of UK companies or subsidiaries, many of which are start-ups and SMEs, from three Innovate UK projects: CASPA; QT Assemble, which is increasing the reliability and reducing the size and cost of laser components and systems; and MIRUS, which aims to develop and deliver a mid-infrared single-photon detector demonstrator system (for LIDAR and telecommunications systems) [**5.5**]. These have resulted in the awarding of GBP5,480,000 in direct income for companies that include BAE Systems, Edinburgh start-up Photon Force Limited, University of Sheffield spinout AegiQ and Newcastle-based naontechnology firm Inex [**5.5**]. UoS and Covesion technology was integral to the award of these projects [**5.2**, **5.7**]. For example, in QT Assemble, Covesion's PPLN waveguide technology is fundamental to the delivery of all the project's technical work packages [**5.7**]. As further evidence of the research supporting the UK's sovereign capability, the work of Covesion is cited twice in DSTL's 2020 report: *Quantum Information Processing Landscape 2020: Prospects for UK Defence and Security* [**5.8**]. The report's purpose was to encourage and guide MOD investment in quantum technologies.

5. Sources to corroborate the impact

5.1 Covesion webpages detailing product offerings and customers: https://www.covesion.com/products/; https://www.covesion.com/support/applications.html; https://www.covesion.com/company/customers-and-partners.html

5.2 Corroborating statement from the Chief Executive Officer, Covesion.

5.3 Filing history for Covesion Limited, Companies House. https://beta.companieshouse.gov.uk/company/06338847/filing-history

[text removed for publication]

5.5 List of Innovate UK grants based around ORC and Covesion technologies – direct income to UK industry demonstrated via 'project offer' grants under the 'organisations' tab:

QT ASSEMBLE: https://gtr.ukri.org/projects?ref=50414

CASPA: https://gtr.ukri.org/projects?ref=102805

QWISPS: https://gtr.ukri.org/projects?ref=102668

SNORQL: https://gtr.ukri.org/projects?ref=133980

MIRUS: https://gtr.ukri.org/projects?ref=133994

5.6 Press release on Gov.uk (2018): UK to lead second revolution in quantum technologies: https://www.gov.uk/government/news/uk-to-lead-second-revolution-in-quantum-technologies

5.7 Covesion company announcement (2020): QT Assemble: Covesion play integral part in exciting quantum technologies collaboration: https://www.covesion.com/news/qt-assemble-covesion-play-integral-part-in-exciting-quantum-technologies-collaboration.html

5.8 Quantum Information Processing Landscape 2020: Prospects for UK Defence and Security, DSTL (2020): https://uknqt.ukri.org/files/qipl2020prospects/ (pages 48, 113).