Institution: PHYESTA (Physics at Edinburgh and St.Andrews)

Unit of Assessment: UoA 9 - Physics

Title of case study: Manufacture and Commercialisation of Novel Laser Devices, and their Applications.

1. Summary of the impact

Impact: **Economic**
Based on research carried out within PHYESTA, a range of novel laser devices have been produced and sold under licence by M Squared Lasers Ltd Glasgow.

Significance: The products have significantly expanded the M Squared product range and have led to increased sales and new customer relationships.

Reach: M-Squared have marketed these lasers worldwide and has had major sales from customers in the defence and oil and gas sectors. New collaborations have been enabled with international partners including the Fraunhofer Centre for Applied Photonics (Glasgow).

Beneficiaries: M-Squared Lasers

Attribution: The devices were developed by PHYESTA Researcher Professor Malcolm Dunn's research group

2. Underpinning research

The research underpinning the impact was carried out by the Nonlinear Optics group within PHYESTA. The nonlinear optical process of parametric generation is the basis of a technology of unprecedented flexibility for the production of widely-tuneable coherent light from the ultraviolet to the THz region. Such sources can generate coherent light of unprecedented optical quality, both with regard to spectral (continuously-tuneable, single-frequency light), and spatial (single transverse mode) characteristics, thereby opening up an increasing range of applications.

The particular research insights and findings underpinning the impact described here relate to optical parametric oscillators operating (a) in the terahertz (THz) and (b) in the mid infrared (mid-IR) spectral ranges. In the former case novel photonic devices have been developed for generating continuously and widely tuneable THz. The novel intersecting cavity geometry (patented) employed allows the nonlinear medium to be located in both the resonant cavity of the pump laser and the resonant cavity of the parametric oscillator, referred to as an intra-cavity geometry, while still retaining wide and continuous tuning. This results in substantially increased efficiencies compared to the former state-of-the art, thereby leading to compact and portable devices. [R1, R2]. This work has resulted in a range of filed and granted patent applications.

The research insights relating to the mid-IR spectral range includes lasers incorporating high-repetition rate intra-cavity parametric oscillators, in particular for hyperspectral imaging applications [R3]. These developments allowed the development of devices particularly suited for real-time video imaging [R4]. Two patents have been awarded in connection with these developments.

Our work has also focussed on solving problems involved in operating lasers incorporating intra-cavity parametric oscillators in continuous-wave mode. In this case, insights have been gained into the problem of severe relaxation oscillations that occur in such devices. In the case where gain media with long upper state lifetimes (compared to cavity decay times) are used, we have shown

that the incorporation of a nonlinear medium for second harmonic generation in the cavity of the pump laser suppresses such oscillations with little loss in the down conversion efficiency [R5]. An alternative approach that we have demonstrated is that the using semiconductors as gain media eliminates the problem as a result of the very short upper laser state lifetime [R6]. Two patents have been filed in connection with these research insights.

Personnel:
Key PHYESTA researchers involved were Professor Malcolm H Dunn (present throughout period of assessment) with Dr Cameron F. Rae (PIC Technical Manager, present throughout) and Dr David J. M. Stothard (PDRA 2000-2013)

3. References to the research (indicative maximum of six references)

The quality of the underpinning research is best illustrated by R2, R4 and R6. *[Number of citations]*

[R1]	D.J.M. Stothard, T.J. Edwards, D. Walsh, C.L. Thomson, C.F. Rae, M.H. Dunn, P.G. Browne, *'Line-narrowed, compact, and coherent source of widely tuneable terahertz radiation*', Applied Physics Letters, **92**, art. no. 141105. (2008), DOI: DOI: 10.1063/1.2907489, URL: tinyurl.com/nwrsoqo, *[17]*
[R2]	T.J. Edwards, D. Walsh, M.B. Spurr, C.F. Rae, M.H. Dunn, P.G. Browne, *'Compact source of continuously and widely-tuneable terahertz radiation'*, Optics Express, **14**, p. 1582, (2006), DOI: 10.1364/OE.14.001582, URL: tinyurl.com/pjmrym4, *[48]*
[R3]	D.J.M Stothard, C.F. Rae, M.H. Dunn, *'An intracavity optical parametric oscillator with very high repetition rate and broad tuneability based upon room temperature periodically poled MgO: LiNbO3 with fanned grating design'* IEEE Journal of Quantum Electronics, **45**, p. 256, (2009), DOI: 10.1109/JQE.2009.2013086, URL: tinyurl.com/nd4au26, *[6]*
[R4]	D.J.M. Stothard, M.H. Dunn, C.F. Rae, '*Hyperspectral imaging of gases with a continuous-wave pump-enhanced optical parametric oscillator'*, Optics Express, **12**, p. 947, (2004), DOI: 10.1364/OPEX.12.000947, URL: tinyurl.com/pc7bkve, *[20]*
[R5]	D.J.M. Stothard, M.H. Dunn, *'Relaxation oscillation suppression in continuous-wave intracavity optical parametric oscillators'* Optics Express, **18**, p. 1336. (2010), DOI: 10.1364/OE.18.001336, URL: tinyurl.com/k4j32zm, *[6]*
[R6]	D.J.M. Stothard, J-M. Hopkins, D. Burns, M.H. Dunn, 'Stable, continuous-wave, intracavity, optical parametric oscillator pumped by a semiconductor disk laser (VECSEL)', (2009) Optics Express, **17**, p. 10648 (2009), DOI: 10.1364/OE.17.010648, URL: tinyurl.com/q32ggk5, *[22]*

4. Details of the impact

The primary impact has been and continues to be the successful manufacture and commercialisation with growing worldwide sales of two innovative photonic products by the company M Squared Lasers Ltd, based in Glasgow. [F1] In addition the commercial availability of such technologically advanced devices through M Squared Lasers Ltd, continues to have a worldwide secondary impact on user communities, such as those engaged in applied research. Particular examples of this latter include the Defence Science & Technology Laboratory (DSTL) at Porton Down [F2], the Oil and Gas Sector in general, and Defence R & D Canada (DRDC).

In order to achieve maximum impact from our work, the University filed patents in key areas of licensable technology based on such insights prior to publication through the usual academic routes [S1]. In parallel, the intellectual property residing within the patent portfolio was widely promoted through personal contacts. As a result of these activities M Squared Lasers Ltd approached the University which led to licensing agreements for manufacture/commercialisation, accompanied by a continuing interaction to effectively attain total technology transfer. The licensing to M Squared Lasers Ltd in 2008 of the intellectual property /know-how based on the above identified key research insights has resulted in two emergent product lines based on our

intellectual property (among a total of five product lines currently on offer by the Company). These are the "Firefly-THz" range of Pulsed Tuneable Terahertz Lasers, and the "Firefly-IR" range of Widely Tuneable Mid- and Near-IR Pulsed Lasers [S2]. In the case of the Firefly-IR a hyperspectral imager based on the licensed intellectual property has also been developed as a complementary product.

Annual Net Sales for the two Firefly systems in 2012-13 have amounted to £432K to date; with Net Sales showing an average compounded annual growth rate over the four years of the licence of 90%/annum. Overall 50% of company sales are in North America, with a further 30% in Asia [F1]. The income to the University from royalties arising from the above commercialisation activity in 2012-13 was £60K.

The technology transfer activity overall was summed up by the CEO of M Squared Lasers Ltd in the following statement*:* *"St Andrews have been instrumental in allowing M Squared to develop this important new technology and their approach to ensuring "impact" from their research is in our opinion the gold standard for such activities. M Squared is highly collaborative and our team has been involved in many technology transfers from universities but the St Andrew's team's thorough, collaborative, and energetic approach has been our best experience in such endeavours."* [F1]

The commercial availability of the Firefly-IR product through M Squared Lasers Ltd has had significant impact on the research and development work of the DSTL Detection Department at Porton Down. Hyperspectral imaging systems based upon the Firefly-IR laser have been used extensively in trials for the remote sensing and imaging of hazardous chemicals and compounds. As the Principal Scientist, DSTL comments: *"The unique compact OPO design you pioneered has enabled the realisation of a prototype IR imager for the stand-off detection of chemical warfare agents."* [F2] This resulted in a further impact advantage for M Squared Lasers Ltd in that DSTL have placed a number of contracts with them for the further development and refinement of the laser and the associated hyperspectral imaging system to a total value of £1.5M.

This work was highlighted at the Centre for Defence Enterprise Showcase Event held in London on 13th January 2011, leading to a half-page, illustrated article in the Daily Star [S3] and inclusion on the British Forces News Channel. In October-November 2012 field trials were extended to the USA in a collaboration involving personnel from DSTL, M Squared Lasers and the US-Army Edgewood Chemical & Biological Center (ECBC); this work was selected for publication by the SPIE Newsroom Website [S5].

In 2012 M Squared Lasers was ranked eighth by accountants Deloitte in a list of the UK's 50 fastest-growing technology firms; being placed top in Scotland. The Firefly laser range was identified as a key technology in enabling growth of more than 1600% in the last 5 years [S4]. An additional impact associated with the licensing of the key research insights has been to enhance the ability of M Squared Lasers Ltd to access venture capital. Additional funding of £3.85M for development has been received from the Business Growth Fund with the role of firefly particularly highlighted: *"In particular, we are looking at new market opportunities in remote sensing, and will specifically focus on developing our Firefly laser product, which has a clear application for the security and defence, oil and gas and food and drink industries."* [S6] In October 2012 the UK Technology Strategy Board funded two hyper-spectral imaging projects based on the company's Firefly optical parametric oscillators under a strategy aimed at promoting innovation in the Oil & Gas Sector.

In a recent development (January 2013), the partnership between M Squared Lasers Ltd and PHYESTA has been enhanced by the involvement of the newly-established Fraunhofer Centre for Applied Photonics based in Glasgow. This centre offers new opportunities for enhanced technology transfer activity, in particular with regard to the "Firefly" product range, through collaborative effort involving all three partners. As remarked by the Head of the Fraunhofer Centre: ***"We are enthusiastic supporters of this work because of the combination of scientific excellence, commercial relevance and its potential in addressing real world problems."*** [F3]

5. Sources to corroborate the impact:

[F1]	Factual Statement: Chief Executive Office, M Squared *Corroborates All aspects of M Squared Lasers involvement in the case study and authorises quotations used.*
[F2]	Factual Statement: Principal Scientist - Spectroscopy, DSTL, Porton Down *Corroborates All aspects relating to the involvement of DSTL (Porton Down).*
[F3]	Factual Statement: Head of Fraunhofer Centre for Applied Photonics *Corroborates All aspects relating to the Fraunhofer Centre for Applied Photonics.*
[S1]	Patent portfolio for OPO based devices. *Corroborates IP developed within this technology area.*
[S2]	www.m2lasers.com/products/laser-systems.aspx *Corroborates products within M Squared Laser's catalogue*
[S3]	Daily Star, p. 23, 23/01/2011 (tinyurl.com/kpbavnx) *Corroborates Daily Star publication of details of the devices.*
[S4]	www.bbc.co.uk/news/uk-scotland-scotland-business-20269751 *Corroborates growth figures for M Squared Lasers.*
[S5]	spie.org/x93757.xml *Corroborates story present in SPIE Newsroom.*
[S6]	www.bbc.co.uk/news/uk-scotland-scotland-business-17905847 *Corroborates BGF funding for M Squared lasers and the role of the Firefly product.*