Institution: The University of Glasgow

Unit of Assessment: B9: Physics

Title of case study: Development of ultra-stable lasers for metrology, spectroscopy and imaging

1. Summary of the impact

Pound-Drever-Hall (PDH) locking, developed into a practical technique by researchers at the University of Glasgow, is the ubiquitous method for the precise frequency control of stable laser systems. This control is central to laser products from companies such as Toptica and Newport, and has an estimated global annual market in excess of £5M. The PDH stabilisation technique is essential for the operation of the time standards maintained in all of the world's Governmental Metrological Standards Laboratories (e.g. NPL, NIST, BIPM) and finds applications in inspection tools in the semiconductor industry and deep UV lasers for UV-Raman spectroscopy.

2. Underpinning research

All lasers exhibit fluctuations in the frequency of light they emit due to factors such as temperature variations and electronic noise. In many applications, such as metrology, a stable laser is essential. Prior to the developments described here, the use of optical cavities as stable references to which lasers could be locked in frequency, was limited – both in terms of the spectral purity of the resulting laser light and the duration over which this stability could be maintained. Consequently, until work at the University of Glasgow, the widespread opinion was that optical stabilisation cavities were impractical for commercial use.

The first step in the advancement of the field was the development of the Pound-Drever-Hall (PDH) approach by the University of Glasgow, the Joint Institute for Laboratory Astrophysics in Colorado and Caltech. While the promise of this approach was embodied in the 1983 publication, the technique remained of only academic interest because of the short timescales over which the stability could be demonstrated.

The pivotal transformation of PDH arose from innovative research carried out in the mid-late 1990s [1-4] at the University of Glasgow by Professor Jim Hough (Lecturer 1972-83, Senior Lecturer 1983-86, Professor 1986-current), Dr Henry (Harry) Ward (Lecturer 1989-95, Senior Lecturer 1995-current) and Professor Ken Strain (PPARC Adv. Fellow 1995-99, Lecturer 1999-2003, Professor 2003-present). This research showed for the first time that stable operation over long periods of time was possible. The robustness of PDH as applied to gravitational wave detection established the viability of the method for use in realistic applications. For example, the paper by Robertson, Strain, Hough and Ward et al. [3] reported excellent performance of highly stabilised optical cavities obtained using the PDH technique. Moreover, the group further demonstrated and assessed the robustness and long-term stability of an optical system using multiple instances of this technique [4] and published a demonstration that the technique could be completely automated [1].

The demonstration and promotion of this research had two direct consequences. The first was the adoption of the technique as the state-of-the-art (which it remains) in laser research laboratories around the globe. The second was the adoption of this technique by industry, where the key demonstration of its automation and robustness led to the desire to incorporate PDH into commercial products, (particularly in the frequency doubling of light) starting in the late 1990s and continuing today.

Although lasers had been widespread since the 1970s, only certain wavelengths were available. In particular, lasers in the blue and UV regions of the spectrum were difficult to obtain. Blue and UV wavelengths required for metrology applications can often only be produced by second harmonic generation by frequency doubling of a visible or near-infra red laser in a non-linear crystal within an optical cavity. To ensure that the frequency doubling works, the laser frequency must exactly match the peak of the cavity resonance and the PDH technique is the best way to achieve this. It was not until the research reported by the University of Glasgow in the mid 1990s that the robustness and long-term stability of this frequency matching was realised.

Furthermore, the PDH technique is particularly suited to diode lasers as the frequency modulation used can be directly applied to the drive current of the laser without the need for an external modulator. There are a number of niche markets for these systems where a particular wavelength is required or a continuous wave laser at a short wavelength is necessary.

3. References to the research

Key references to the research are [1], [2] and [3], marked by a *.

[1] P. W. McNamara, H. Ward, J. Hough and D. Robertson, Laser frequency stabilisation for spaceborne gravitational wave detectors, *Classical and Quantum Gravity* 14 (1997) 1543-1547 DOI: 10.1088/0264-9381/14/6/025 *

[2] K. D. Skeldon, K. A. Strain, A. I. Grant and J. Hough, Test of an 18m long suspended modecleaner cavity, *Review of Scientific Instruments* 67 (1996) 2443-2448, DOI: 10.1063/1.1147194 *

[3] D. I. Robertson, E. Morrison, J. Hough, S. Killbourn, B. J. Meers, G. P. Newton, N. A. Robertson, K. A. Strain and H. Ward, The Glasgow 10 m prototype laser interferometric gravitational wave detector, *Review of Scientific Instruments* 66 (1995) 4447-4452, DOI: 10.1063/1.1145339 *

[4] K. D. Skeldon and K. A. Strain, Response of a Fabry Perot optical cavity to phase modulation sidebands for use in electro-optic control systems, *Applied Optics* 36 (1997) 6802-6808, DOI: 10.1364/AO.37.004936

The importance of this work has been recognised globally. In 2001, Prof J. Hough FRS was elected a Fellow of the American Physical Society, cited for 'devising and developing the necessary implementing technologies for gravitational wave detection' and was awarded the Duddell Prize of the Institute of Physics in 2004. In 2005 Prof K. Strain became an External Member of the Max Planck Institute for Gravitational Physics, the Albert Einstein Institute.

4. Details of the impact

The development of practical PDH laser stabilisation by the University of Glasgow has created global economic impact of many millions of pounds in the period 2008-13. Although the University of Glasgow did not commercialise the PDH technique, the researchers were active in the dissemination of its benefits to audiences both in academia and industry. During the 1990s, the laser and gravitational wave communities shared an interest in stable and rugged high power optics and members of the commercial laser community routinely attended scientific conferences such as the 7th Marcel Grossman Conference (Stanford, 1994) where Ward presented results on the stability of the University of Glasgow 10m interferometer using PDH locking.

Moreover, owing to the high profile of the work carried out at Glasgow, the group maintained collaborations with leading universities and research institutes worldwide who in turn also trained students, collaborated with industry and engaged in commercial activities providing an international dimension to the widespread dissemination of the benefits of the PDH technique which ultimately led to industrial adoption. For example, the Glasgow group has an historically close link with Prof. Robert L. Byer at Stanford University and through him to companies adopting PDH in products. For example, New Focus, (subsequently bought by Newport) was a Stanford spin-out which utilised PDH in its products. There were also links between gravitational waves and atom optics groups particularly in Germany and it is from here that companies such as Toptica were founded. Prof. Hough and Prof. Ted Haensch had close links through working on the Scientific and Technical Advisory Committee for the Virgo interferometric gravitational wave detector in 1994-97. Prof.

Haensch subsequently founded Menlo Systems in 2001 that produces stable and ultra-stable laser systems.

The impact of the University of Glasgow work has occurred on three different scales.

a) Sales of dedicated high-speed frequency/phase modulators

Implementation of the PHD technique within specialist research establishments and commercial products requires the use of dedicated high-speed frequency/phase modulators that can be inserted into the laser beam and highly stable optical cavities to which the frequency of the laser can be locked.

The global number of units sold every year to enable implementation of PDH stabilisation is commercially sensitive but estimates fix revenue at a level of £6-10M per annum. This is broadly similar to revenues generated from sales of complete systems. Companies such as New Focus, Leysop, Thorlabs, and Gsaenger have significant sales due to the widespread adoption of the PDH technique and as confirmed by Newport in 2011, who said: *"In particular, Pound Drever Hall (PDH) r-f locking has become the accepted standard technique for locking high finesse resonant optical cavities, and Newport has used it in a range of commercial products. For more than 10 years, New Focus and Newport have sold a large number of r-f electro-optic modulators and high stability cavity mechanics to researchers building PDH systems for laser stabilisation and wavelength conversion."*

b) Sales of complete laser systems

Complete laser systems incorporating PDH stabilisation give turn-key output of laser light with stabilised, and / or predetermined frequency. In addition, the PDH technique is central to enhanced harmonic conversion of laser frequency (e.g. from IR to visible) where the non-linear optical conversion is enhanced within a frequency-matched, resonant cavity.

Companies such as Toptica and Sacher Lasertechnik sell green, blue and UV laser systems that depend upon PDH. Newport sells a sub-system that is used with the customer's own laser to produce the required light. Menlo Systems has developed an Optical Reference System based on PDH stabilisation for use in metrology, high precision spectroscopy and interrogation of optical clocks. The reach of this impact is world-wide with the companies above selling into European, North American, Japanese and Asian markets. The market for relevant lasers in such systems is currently worth in excess of £5M per annum, and totalling between £15M and £20M since 2008. One company alone (Toptica) has sales of PDH-enabled frequency-converted systems, with current revenue from the sale of approximately 60 systems per annum being estimated at more than £3M per annum. Their sales are increasing year on year.

Moreover quoting from a testimonial from Toptica: *"Laser frequency stabilisation to cavities or cavity length stabilisation – both by the Pound-Drever-Hall (PDH) method – are important applications of our customers. Commercial adoption of this method was made practicable after demonstrations in the mid-90's by the Glasgow group and collaborators that reliable, long-term locking of optical systems was possible – a must for industrial use. Our business benefits from the PDH method in mainly three ways…we developed and sell individual Pound-Drever-Hall detector modules directly to the market… Secondly, these modules are one of the key components of our frequency-converted product family… Thirdly, the PDH method is implemented in our new guide star laser system called SodiumStar20…"*

Scottish SME M Squared Lasers said: *"Although the original publication of the technique was in the 1980s, it was only the further work in the early 1990s that Glasgow University clearly showed for the first time that robust and stable operation over long periods of time was possible. This was key in establishing the method as being of real value for use in practical optical applications."* Also from M Squared Lasers: *"Throughout the period between 1993 and 2013 the work done in Glasgow University on the PDH locking technique had led to a significant portion of the scientific laser companies adopting PDH within their products and this has led to laser manufacturers achieving tens of millions of pounds in product revenue."*

c) **Enabling advanced applications in metrology and the semiconductor industry**

The commercial availability of PDH stabilised lasers are central to a number of applications beyond research. All of the world's national standards laboratories (e.g. NPL, NIST, BIPM) use PDH stabilised lasers in their time/frequency standards. In addition to these precise absolute optical frequency standard which allow precise distance measurement, PDH is used for precise frequency control with respect to a doubling cavity, allowing laser sources such as the Sony Chicon to generate low noise, continuous wave 266nm light for sophisticated semiconductor inspection tools.

The Chicon, emitting deep-UV light at 266 nm with maximum output power of 1W, was originally developed by Sony as a core technology for in-house wafer inspection systems. The main advantage of a short wavelength for wafer-inspection tools is the ability to detect particles as small as 30 and 40 nm on bulk-Si and Silicon on Insulator (SOI) wafers, respectively. In 2009 Sony decided to commercialise the product for the market of laser inspection systems and UV-Raman spectroscopy. The product line was subsequently taken over by Oxide Corporation which is currently offering four product lines under the Frequad brand.

5. Sources to corroborate the impact

Testimonial from Director Scientific Sales, Toptica Photonics AG (available from HEI) corroborates the importance of Glasgow University research carried out in the 1990's to the industrial adoption of the Pound-Drever-Hall (PDH) technique and details product lines implementing PDH including sales figures.

Testimonial from General Manager, New Focus, Newport Corporation (available from HEI) corroborates the industrial importance of the Pound-Drever-Hall (PDH) technique and details product lines implementing PDH including financial figures.

Testimonial from Chief Executive Officer, M Squared Lasers Ltd (available from HEI) provides evidence for the importance of Glasgow University research in the 1990's in the industrial adoption of Pound-Drever-Hall (PDH) technique and the mechanisms by which the company became exposed to the research. It also corroborates market figures for the PDH-related market.

Testimonial from Director of Stanford Photonics Research Center (available from HEI) provides evidence of the mechanisms by which Glasgow University research was disseminated, absorbed by industry and translated into products.

Sony Chicon Laser applications
http://optics.org/article/37737

Oxide Corporation takes over Sony Chicon
http://www.soliton-gmbh.de/?id=147&L=1

Oxide Frequad product line
http://www.opt-oxide.com/en/uvlaser/266nm-duvlaser-products/frequad-hp/