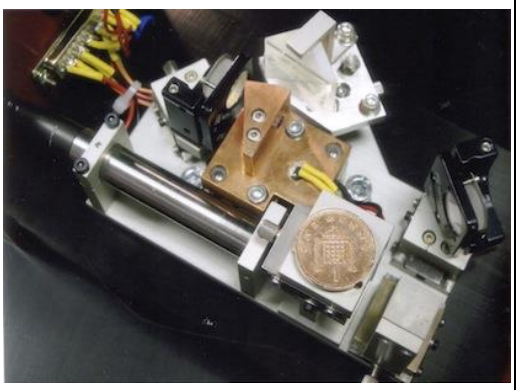
Institution: PHYESTA (Physics at Edinburgh and St.Andrews)

Unit of Assessment: UoA 9 - Physics

Title of case study: Ultrashort-pulsed lasers as the underpinning technology for ultrafast technology.

1. Summary of the impact

Impact: Economic gains / altered business practices.
Research on ultrafast lasers has led to the development of new products and services and has been pivotal in the development of a whole field of new technology.



Significance: The research underpins the product development of a range of world leading companies including Femtolasers, Newport Spectra-Physics and Menlo Systems.

Reach: The companies that use the technology represent all of the leading players in the solid-state femtosecond laser field, a marketplace worth more than $250M annually.

Beneficiaries: The impact presents economic gains to the companies involved and underlies many applications in e.g. biology and medicine, providing significant benefits to the public at large.

Attribution: The research was performed by Professor Sibbett's group.

2. Underpinning research

A large number of longitudinal resonator modes can reach threshold in broadband lasers and a choice can be made to impose an operational status that 'persuades' all of these lasing modes to oscillate together in phase – in a so-called *phase-locked* or *mode-locked* operation. The Ultrafast Lasers Group have been long-established pioneers in this field and have produced a range of laser sources that offer significant advantages over competing approaches. Within this period of assessment, work within PHYESTA has helped to improve the operational parameters of the most commonly deployed femtosecond Ti-sapphire lasers to achieve pulse durations as short as 5 femtoseconds and average powers of watts and peak powers up to megawatts[R1].

The Ti:Sapphire crystal gain medium, whilst remaining perhaps the key technology for solid-state ultrashort pulse lasers, suffers some major disadvantages, including the requirement for high-power pump lasers in the difficult-to-access green part of the spectrum reducing efficiency and driving up costs. To this end, work was undertaken by the Ultrafast Lasers Group in the mid-to late 1990s and 2000s on a range of other gain materials that demonstrated the potential for direct diode pumped femtosecond lasers in the near-infrared part of the spectrum (800 nm - 1100 nm) [R2-R4] opening up the potential for new products and application from sources that have the potential for much lower cost and higher operating efficiencies. A major drive in this period was also the development of advanced laser cavity designs that permitted the development of very compact ultrafast lasers that still offer attractive output performance levels [R3]. The research has continued and in the 2010s research and development relating to new spectral areas, including the important 2 μm region, offer exciting potential for an enlarged array of applications in surgery, communications and metrology [R5].

In addition to the development of new laser sources, the group also demonstrated in 1997 a range of original and innovative measurement techniques providing a step change in the simplicity and practicality of the measurement of ultrafast pulses through 2-photon based autocorrelation schemes [R6].

Personnel
Key PHYESTA researchers involved were Professor Wilson Sibbett (present as staff, and then emeritus, throughout period of assessment), Dr Derryck Reid (PDRA / EPSRC Advanced Fellow 1994 - 2000), Dr Alexander Lagatsky (PDRA 2001 - 2013) and Dr Tom Brown (PDRA 1999 - 2005, Lecturer / Senior Lecturer / Reader 2005 - present).

3. References to the research

The quality of the underpinning research is best indicated by R4, R5 and R6. *[Number of citations]*

[R1]	T Beddard, D T Reid, J Garduno-Mejia, N Jamasbi,M Mohebi and W Sibbett (1999) *'High-average power, 1-MW peak-power self-mode-locked Ti:sapphire oscillator'* , Optics Letters, **24**, p. 163, (1999) DOI: 10.1364/OL.24.000163, URL: tinyurl.com/kzdgfk2, *[20]*
[R2]	D Burns, M P Critten and W Sibbett (1996) 'Low threshold diode-pumped femtosecond $Cr^{3+}LiSrAlF_6$ laser', Optics Letters, **21**, p. 477, (1996) DOI: 10.1364/OL.21.000477, URL: tinyurl.com/l8cbqsu, *[11]*
[R3]	J M Hopkins, G J Valentine, B Agate, A J Kemp, U Keller and W Sibbett '*Highly compact and efficient femtosecond Cr:LiSAF lasers'*, IEEE J Quantum Electronics, **38**, p. 360, (2002) DOI: 10.1109/3.992549, URL: tinyurl.com/mr2sxwp, *[28]*
[R4]	A A Lagatsky, C T A Brown and W Sibbett *'Highly efficient and low threshold diode-pumped Kerr-lens mode-locked Yb:KYW laser'*, Optics Express, **12**, p. 3928, (2004) DOI: 10.1364/OPEX.12.003928, URL: tinyurl.com/kqq4uty, *[48]*
[R5]	A.A. Lagatsky, X. Han, M.D. Serrano, C. Cascales, C. Zaldo, S. Calvez, M.D. Dawson, J.A. Gupta, C.T.A. Brown and W. Sibbett, *'Femtosecond (191 fs) $NaY(WO_4)_2$ Tm,Ho-codoped laser at 2060 nm'*, Optics Letters, **35**, p. 3027, (2010) DOI: 10.1364/OL.35.003027, URL: tinyurl.com/l3qnuhg, *[37]*
[R6]	D.T. Reid, M. Padgett, C. McGowan, W.E. Sleat and W. Sibbett (1997) *'Light-emitting diodes as measurement devices for femtosecond laser pulses'*, Optics Letters, **22**, p. 233, (1997) DOI: 10.1364/OL.22.000233, URL: tinyurl.com/ln2mapy, *[102]*

4. Details of the impact

Ultrafast technology is an applications sector that is based in part on the laser sources developed by the Ultrafast Lasers Group (ULG) as described in section 2. The use of this technology underlies a wide range of applications that have emerged since the 1990s and have developed rapidly throughout the period of assessment (2008 - 2013.) These range from the development of ultraprecise measurements of frequency required for internet communications to the latest generation of techniques for corrective eye surgery. The importance of the work of the ULG is highlighted by the CEO of Femtolasers who states "*…the work of Professor Sibbett and more recently Dr Brown and Professor Sibbett has played a major role in leading the development and applications of ultrafast laser technology…"* [F1].

The development of practical technologies to achieve mode-locked laser operation was the underpinning requirement for the global development of ultrafast technology in the 1990s and its subsequent adaptation into a widely adopted technology from the early 2000s to the present day. Work in the field by the ULG was of major influence in defining product technologies for major multinational companies in the field including Coherent and Spectra Physics (now part of Newport) in the USA. This adoption led directly to the development of a suite of commercial devices (Coherent MIRA and Spectra Physics Tsunami) that continue to underpin the commercial sector. The scale of the success of these technologies can be estimated by the fact that *"…there are many thousands of Titanium Sapphire Kerr lens mode-locked lasers installed worldwide..."* [F2] A conservative estimate of $100k per system in 2013 shows that this market alone is worth many $100s million. The more recent work described above continues to have a major influence on the decision making processes of these leading international companies as the Advanced R&D Manager for Spectra-Physics states *"…the work of your St Andrews research group … has*

continued to be of interest and influence within the commercial laser community." [F3]

In addition to product development by major commercial players, the research highlighted above also has led to the development of laser systems by the smaller specialist laser companies such as M Squared in the UK, FemtoLasers, a multi-million € turnover SME in Austria [F1] and KML Inc in the USA with new product launches occurring throughout 2008 - 2013. Continuing through the period 2008 - 2013, new commercial laser systems, amplifiers and applications such as multi-photon microscopes have begun to further revolutionise fields as diverse as biology, medicine and manufacturing technology. Indeed, the source technology has now reached such a point of maturity that it is now routinely installed as OEM components within products such as systems for eye surgery [S1].

The impact of the research can also be identified through its influence on a range of applications that impinge on many areas of society. [Text removed for publication]. A major recent development has been the deployment of ultrafast lasers within medical treatments, particularly for surgery on the eye. For example, the IntraLase system now offers commercial refractive surgery to more than five million of patients worldwide and the latest generation of treatment for cataracts is based on the use of ultrafast laser systems related to those developed by Sibbett. [S2]

The measurement and characterisation of ultrafast pulses remains an area of key importance within this technology field. The ULG showed that a highly simplified method based on non-linear absorption in low cost semiconductor devices could be used to obtain basic pulse duration information. This innovation was patent protected (US6195167 B1 - granted 2001) and subsequently licensed by Elliot Scientific to produce an award winning commercial product, the Timewarp Autocorrelator. [S3]

A major impact of the work of the Sibbett group has been one of influence. A study in 2010 of emerging ultrahigh intensity laser facilities shows that there was more than $4.5 Bn of activities under development between then and 2015 and more than half of these are based on technology directly developed within PHYESTA [S4]. Notably, many major companies and individuals have highlighted the importance of the work in the 1 μm and 2 μm spectral regions from 2000 onwards and in diode-pumped femtosecond lasers to product development [F1, F3-5]. [Text removed for publication].

A 2008 survey showed that the ultrafast laser market was worth approximately $260M annually with a predicted year-on-year growth of up to 30% [S4]. Many of the developments in this field have been influenced and underpinned by the work of the Sibbett Group that retains a place of major world influence within the field both through its historic and on-going research. [F1-5]

5. Sources to corroborate the impact

[F1]	Factual statement provided by CEO Femtolasers. *Corroborates continued impact of research on company directions and overall underpinning importance of the group's research.*
[F2]	Factual statement provided by Director of Marketing – Scientific Market Segment, Coherent. *Corroborates importance of research in opening up new fields for industrial and commercial applications.*
[F3]	Factual statement provided by Advanced R&D Manager, Newport Spectra-Physics. *Corroborates overall importance of research to the technology field.*
[F4]	[Redacted Text]
[F5]	[Redacted Text]
[S1]	"Femto LDV Z Models", Special Supplement to Cataract and Refractive Surgery Today,

	September 2012. *Corroborates femtosecond lasers in commercial eye surgery equipment.*
[S2]	www.intralasefacts.com *Corroborates number of patients who have undergone IntraLase surgery.*
[S3]	www.laserfocusworld.com/articles/print/volume-36/issue-1/features/commercial-technology-achievement-awards-judges-name-2000-cta-award-winners.html *Corroborates industry prize award for commercialised autocorrelator device.*
[S4]	www.laserfocusworld.com/articles/oer/print/volume-15/issue-12/features/ultrafast-market-is-the-silver-lining.html *Corroborates market predictions for ultrafast lasers.*