Institution: University of Dundee

Unit of Assessment: UoA15 – General Engineering

Title of case study: Development of compact and efficient laser systems

1. Summary of the impact

This is an example of early economic impact where research on various aspects of laser engineering has resulted in the development of inexpensive, compact, efficient and user-friendly laser sources. An example is the incorporation of quantum dot structures into semiconductor laser architectures, with these replacing much larger and more expensive systems, with a range of applications in areas such as microscopy, biomedical diagnosis and therapy. This work has led to the generation of key know-how and patents that have been subsequently licensed as well as resulting in a variety of laser-related products being brought to market. Additionally, it has resulted in extra staff being employed at one of our partner companies.

2. Underpinning research

Since 1987, Professor Edik Rafailov has been engaged in the research and development of novel semiconductor lasers, nonlinear and integrated optics. On moving to Dundee in 2005 his group began to get involved with a number of new projects developing novel laser architectures and laser-based optical tools. Much of this research was carried out with industrial partners and these collaborations have led to a number of new devices being brought to market. This work has primarily been in the area of compact and efficient laser systems and their applications, underpinned by funding from a number of sources, especially the EU FP7, EPSRC and KTP funding (some representative grants are shown in section 3).

One of the major directions has been on cw and ultrafast semiconductor quantum-dot-based lasers, funded through a €13.7M grant called FASTDOT.

Ultrafast lasers are able to generate light pulses with durations spanning from a few femtoseconds (fs) to a few picoseconds, with applications in areas such as non-invasive diagnostics and therapeutic medicine, micromachining, spectroscopy and imaging (1fs to 1s is the same as 1s to 32 million years). The currently available ultrafast lasers are bulky, expensive, difficult to operate and often offer limited flexibility in how their pulse characteristics can be matched to a specific application. The Photonics and Nanoscience Group at the University of Dundee has undertaken a very significant programme of research in conjunction with many companies (in particular with Innolume GmbH, and M Squared Lasers) to manufacture and develop low-cost, compact and turn-key laser sources that can generate ultrashort optical pulses with tailored characteristics. Such operational characteristics are particularly critical in the development of novel optical tools for diagnostics and therapy in the biomedical sciences.

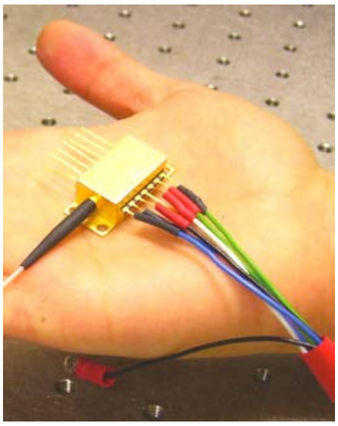

Figure 1 Compact laser system of the type developed in this case study

In order to achieve these goals, the Dundee group has focused on a novel class of materials – semiconductor quantum dots (QDs).

QDs consist of tiny clusters of semiconductor material with dimensions of only a few nanometers. The unique properties of these materials enable the manufacture of compact, efficient and environmentally stable semiconductor lasers.

This work produced a range of new mode-locked and cw laser sources based around quantum dot technology [1-3], which have enabled a number of applications in biomedical imaging and therapy, resulting in a patent on the use of a quantum-dot-based laser for photodynamic therapy [P1]. This then led to a number of spin off projects, such as the development of terahertz emitters [4] and devices producing widely tuneable visible light [5].

Another major research vector on the development of compact and efficient lasers has been the investigation of an old optical phenomena called 'conical refraction' in which light passing through a biaxial crystal leads to an output beam with an unusual cone shaped intensity profile and polarisation properties. This was used to make an incredibly efficient (close to 99% of the theoretical efficiency) laser [6]. This work led to a patent [P2], and subsequent KTP funding in collaboration with M Squared Lasers to further develop the concept to a marketable device.

The work on quantum dot lasers and the collaboration with M Squared Lasers has also led to the filing of a third patent, which is focused on the development of novel laser systems based on semiconductor disk and quantum dot lasers for nonlinear optical microscopy of biological organisms. The patent is shared between members of the FASTDOT consortium, including M Squared Lasers.

3. References to the research

*** Denotes key references**

1. K.G. Wilcox, M. Butkus, A. Tropper, I. Farrer, D.A. Ritchie, E.U. Rafailov, "Sub-Picosecond Quantum Dot Saturable Absorber Mode-Locked Semiconductor Disk Laser", Applied Physics Letters **94**, 251105 (2009). DOI: 10.1063/1.3158960
2. M. Butkus, K. G. Wilcox, J. Rautiainen, O. G. Okhotnikov, S. S. Mikhrin, I. L. Krestnikov, A. R. Kovsh, E. M. Hoffmann, T. Südmeyer, U. Keller, and E.U. Rafailov, "High-Power Quantum Dot Based Semiconductor Disk Laser", Optics Letters **34**, 1672 (2009). DOI: 10.1364/OL.34.001672
3. Y. Ding, R. Aviles-Espinosa, M. A. Cataluna, D. Nikitichev, M. Ruiz, M. Tran, Y. Robert, A. Kapsalis, H. Simos, C. Mesaritakis, T. Xu, P. Bardella, M. Rossetti, I. Krestnikov, D. Livshits, Ivo Montrosset, D. Syvridis, M. Krakowski, P. Loza-Alvarez, and E. U. Rafailov "High peak power picosecond optical pulse generation using a quantum-dot external-cavity passively mode-locked laser and a quantum-dot optical amplifier" Optics Express 20, 14308 (2012). DOI:10.1364/OE.20.014308
4. *****T. Kruczek, R. Leyman, D. Carnegie, N. Bazieva, G. Erbert, S. Schulz, C. Reardon, and E.U. Rafailov, "Continuous wave terahertz radiation from an InAs/GaAs quantum-dot photomixer device", Applied Physics Letters **101**, 081114-4 (2012). DOI:10.1063/1.4747724
5. *****K.A. Fedorova, G.S. Sokolovskii, P.R. Battle, D.A. Livshits, and E. U. Rafailov, "Green-to-red tunable SHG of a quantum-dot laser in a PPKTP waveguide", Laser Physics Letters **9**, 790 (2012). DOI: 10.7452/lapl.201210085
6. *****A. Abdolvand, K.G. Wilcox, T.K. Kalkandjiev, E.U. Rafailov, "Conical refraction Nd:KGd(WO4)(2) laser," Opt. Express **18** 2753 (2010). DOI:10.1364/OE.18.002753

Underpinning funding:

2008-2012: FP7 IP programme – lead and Coordinator: Compact ultrafast laser sources based on novel quantum dot structures (FAST DOT) - 18 partners (value €13.7M).

2008-2009: Resonator modes in the presence of passive element for conical refraction (value €10k) ACCORD Project with Cone-Refringent Optics, Barcelona.

2010–2013: EPSRC grant (EP/H015795/1): Compact diode-laser-pumped THz source based on a novel photomixer device." (value £620k).

2011-2014: KTP grant: Development of a novel class high power laser source based on conical refraction crystal technology (value £195k) (with M Squared Lasers Ltd.)

Related Patents

P1. **Quantum dot laser diode**
Patent number: USA – 2013/164452.

P2**. Novel photonic devices based on conical refraction**
Patent numbers: Europe – EP10708577.1; Canada – 2,750,297; China – 2010800125702; USA – 2013/145736.

4. Details of the impact

The laser systems developed have largely resulted in an economic impact based on licensing and sales of the products developed by two of the key partners in the research grants mentioned above. These companies are a German diode laser company, Innolume and a UK based laser manufacturer, M Squared Lasers. This extremely fruitful partnership of the Dundee Group with these manufacturers has led to a successful economic impact for both companies and the University over a very short period of time.

Innolume have significantly improved the performance of one of their key products called the “Gain Chip” thanks to the work carried out with the Dundee Group. The company estimate that this improved device has led to approximately €100k in annual income [REFa]. The gain chips are used by end users in a variety of applications from tuneable lasers [5], narrow linewidth external cavity diode lasers and in emerging applications using swept laser sources such as optical coherence tomography.

Additionally the quantum dot research has led to a range of new Innolume products being developed and the initial income is now starting to build despite the fact that the research on these topics has largely been carried out over the period 2008-2012. Innolume’s current revenues (2009-2013) from this research are: €20k from novel ultra short pulse laser sources; €25k from QD THz antennas designs and €10k from novel Semiconductor Saturable Absorber Mirror (SESAMs) designs [REFa].

The work with M Squared Lasers has also led to new products being brought to market [text removed for publication] [REFb]. This work was based on the research that was developed in the FASTDOT project.

The two patents mentioned in the references section [P1 and P2] have underpinned the second relationship of the Dundee group, this time with M Squared Lasers. M Squared Lasers have licensed both patents and are developing these into new product lines. They have developed a QD laser from the patent [P1] – the applications ultimately being for end users looking for compact sources in areas such as photodynamic therapy, and evolving into multiphoton imaging and microscopy (which has been demonstrated as viable by the Rafailov group, and patented along with authors from M Squared Lasers). The income to date (since 2009 when the license was taken up) is £10k [REFc].

Figure 2: Toptica prototype based on work at Dundee

The second license was based around the patent [P2] to be used to develop a new laser source based around the conical refraction effect. This has resulted in £16k of income [REFb] since the patent was licensed in 2009, with further development being funded through a £195k KTP award (2011-2014) with the company, demonstrating the early impact of this particular strand of work on highly efficient solid state laser sources. The relationship between Dundee and M Squared Lasers is significant; this has been underpinned with two other KTP projects in the last five years, to work on compact laser sources for near-infrared imaging (KTP 7071) and THz sources for imaging applications (KTP 7892). The value of this commercial interaction is substantial. It is the 9th highest supplier of industry income to the University, lying only behind eight large pharmaceutical companies. Income in the REF period is £363k, with £262k of this being in financial year 2012-13.

The interaction between the research at Dundee and M Squared Lasers has led to the growth of the company and they have employed two extra staff to help further develop products as a direct result of this work. The company is a SME with around 40 employees, so these hires are 5% of the total workforce.

Additionally Toptica (GmbH), another German laser company, has developed a prototype (figure 2) tuneable QD laser source based on the outcomes of the research conducted at the University of Dundee, but as yet no device has been brought to market based on these research outcomes [REFd].

5. Sources to corroborate the impact (indicative maximum of 10 references)

Further information on the company specific involvements can be obtained from the following sources:

- [REFa] CTO, Innolume GmbH (factual statement).
- [REFb] Business Development Manager, M Squared Lasers Ltd. (factual statement).
- [REFc] Business Development Manager, Research and Innovation Services, University of Dundee.
- [REFd] President, Toptica GmbH.