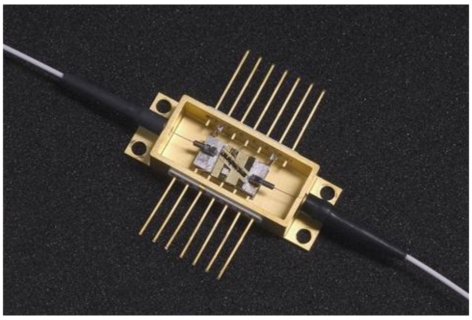
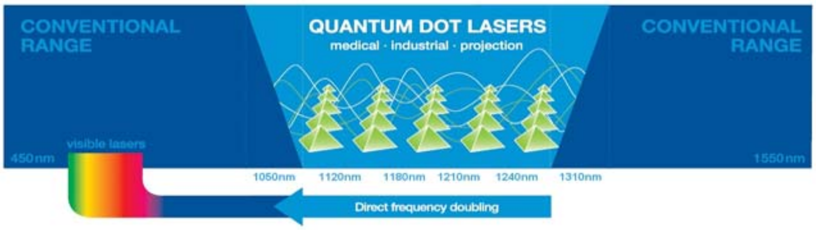
Publishable Summary



The laser systems that are traditionally used for biomedical applications are very expensive, bulky and complicated to use. The vision of the FAST-DOT project is to revolutionise the use of lasers in the biomedical field, providing both practitioners and researchers with matchbox-sized, ultra-high performance lasers at a substantially lower cost, making their widespread use more affordable.

FAST-DOT is a €14.75M project (EU contribution €10.1M) coordinated by the University of Dundee, with a project consortium consisting of 18 of Europe's leading photonics research groups and companies from 12 different countries. The aim of the project is to take advantage of the unique properties of nano-materials based on quantum dots (QDs) to develop a new class of miniature lasers designed specifically for biomedical and imaging applications such as multi-photon imaging and cell surgery. FAST-DOT has already delivered significant advances and world record performances in defining the unique properties of semiconductor nano-materials based on quantum dots to realise a new class of semiconductor lasers components.

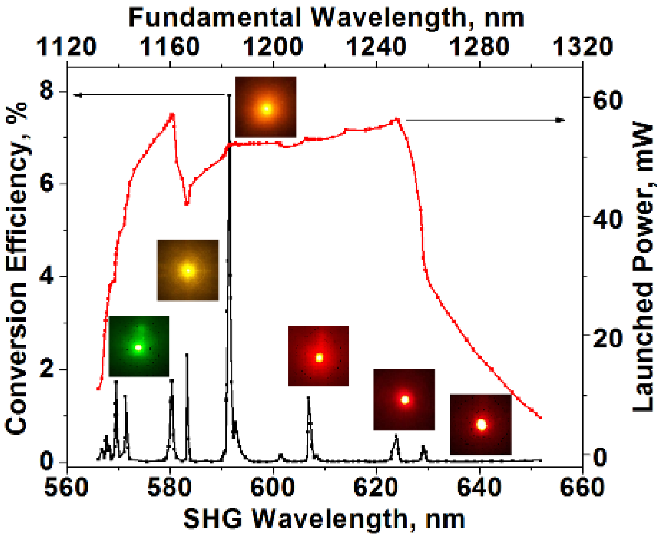
Quantum dots are special semiconductor materials which, when produced under highly controlled conditions can be custom designed and are sometimes called artificial atoms because of their nano-scale dimensions and unique properties. The high level of control that is possible over the size of the crystal produced means that it is possible to precisely design QD-based lasers with particular characteristics to produce specific wavelengths (or colours) that are difficult to reach using conventional laser technologies, ultrafast / ultra short pulses and generation of difficult to reach wavelengths.



With ultra short pulses, very high levels of energy can be delivered to a very small area, making this kind of laser very useful for applications such as cell surgery as there is not the undesirable heat generation association with normal lasers.

The lasers developed in FAST-DOT are mainly targeted towards compact sources of ultra short pulses. As such they are utilising semiconductor quantum dots and semiconductor laser technology. The real strength of these lasers is their compact size, potentially low production cost and good performance. The performance that FAST-DOT lasers can achieve is not sufficient to compete directly in terms of pulse duration or peak power with the Ti:Sapphire lasers currently used in many applications which can produce shorter pulses and higher peak powers, but with a high cost and complex system. However there are certain applications where the performance that has been obtained from FAST-DOT lasers in terms of average power, peak power, pulse duration, pulse energy and wavelength is high enough to make them excellent sources for some applications where the ultrahigh performance of a Ti:Sapphire laser is not necessary, and the lower cost and smaller footprint would be a major benefit.

The tunablility wavelength range has been extended beyond the state-of-the-art to ~202 nm (between 1122 nm and 1324 nm) and a new record has been achieved. This offers the prospect of users being able to tune the wavelength of the lasers to suit the needs of their particular applications and several prototype units have been assembled to demonstrate this capability. The potential to amplify ultrashort laser pulses has also been achieved using compact semiconductor optical amplifiers based on quantum-dot materials. Novel device architectures based on tapered devices have been fabricated and tested, and as a result, the generation of picosecond pulses with record high average power directly from "match-

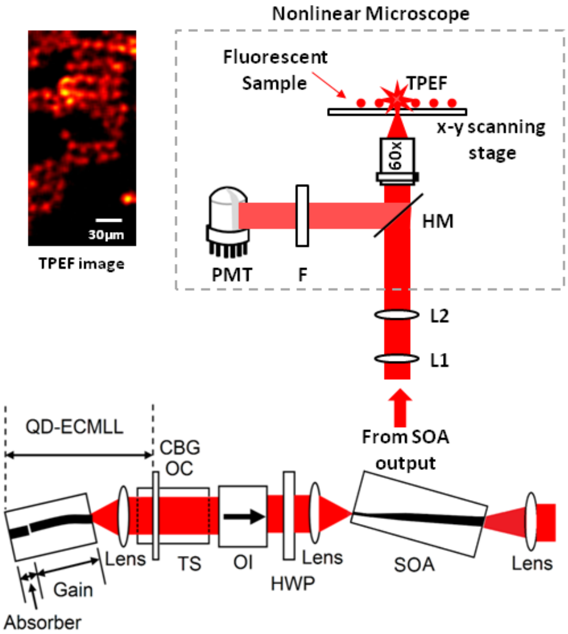


box" size electrically pumped devices has been demonstrated.

Fully tunable semiconductor lasers have been long time an aspiration of laser users, and FAST-DOT has made substantial; progress here with the realisation of picosecond pulse generation with broadband wavelength tunability (136.5 nm tuning range - between 1182.5 nm to 1319 nm) from a quantum dot external-cavity mode-locked laser (QD-ECMLL) providing the highest peak power of 870 mW.

Using similar QD-ECMLL with a tapered quantum-dot based semiconductor optical amplifier (QD-SOA), a broadly tunable master-oscillator power-amplifier (MOPA) picosecond optical pulse source was demonstrated with a wide tunability range between 1187 nm and 1283 nm and the highest output peak power of 4.39 W.

A tuneable device and a semiconductor optical amplifier (SOA) delivering approximately 12 W peak power enabled nonlinear imaging of fluorescent beads.



An external cavity configuration, using a chirped Bragg grating as an output coupler and a semiconductor optical amplifier was used to increase the system power up to 30.3 W. This configuration was then used to obtain two photon fluorescence from Crimson beads.

As shown the beads can be clearly identified and to the best of our knowledge this is the first demonstration of two-photon excited fluorescence (TPEF) imaging obtained with a 1.26 μm wavelength chip-scale semiconductor ultrashort pulsed laser and SOA. Although this system operates at a fixed wavelength it could be used to efficiently excite a wide range of commonly used fluorescent dyes via TPEF.

Tunable visible continuous wave (between 567.7nm and 629.1 nm) and picosecond (between 600 nm and 627 nm) laser emission was demonstrated using second-harmonic generation (SHG) in a PPKTP waveguide with a tunable quantum dot external cavity diode laser (QD-ECDL).

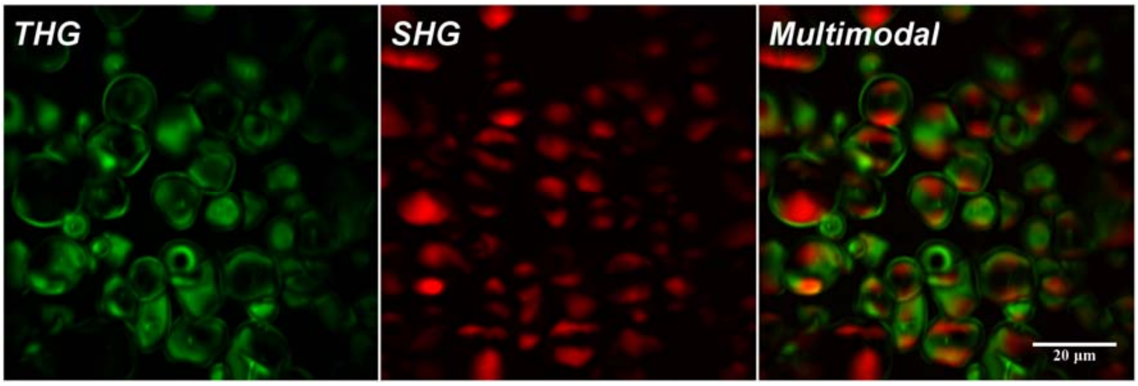
The theoretical model has been developed to explain the observed results. Frequency-doubling system generating up to 1W of orange light (at 589 nm) was demonstrated using a QD-ECDL and a quantum dot SOA as a pump source which produced more than 2W at 1178nm.

The FAST-DOT consortium have realised electrically pumped vertical external cavity surface emitting lasers (EP-VECSELs) in the 100mW range. These devices, being driven electrically rather than optically, are compact and potentially extremely low cost. For the first time, we have demonstrated sub 10ps pulse width in mode locked operation of these devices. The ability of an EP-VECSEL to emit short pulses, have the potential to be scaled to high powers and still be compact enough to simply fit in a handheld device are the unique features of this type of device. An example of the compactness of electrical pumping, showing the gain chip fitting comfortably in the O of the Euro can be seen in the picture opposite.

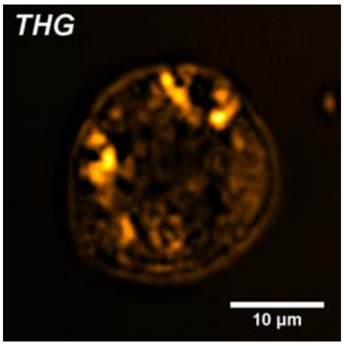
The unique properties of quantum dots have been shown to be especially relevant in developing SESAMs where the energy per unit area (saturation fluence) and very fast recovery times presents particular advantages over normal SESAM designs. The FAST-DOT consortium have successfully mode-locked a VECSEL to to produce up to 3 W of average output power with 5 ps pulse width.

The FAST-DOT consortium has taken these new high performance quantum dot based materials and components and implemented them in a range of prototypes for validation and demonstration in bio-photonic applications where the novel properties offer advances in terms of cost and performance to a number of biological imaging and intervention techniques.

By using a specific excitation line at 1560 nm, second- and third-harmonic generation images can be generated using the FAST-DOT technology. Traditionally the lasers used for this type of imaging would be very large and expensive, but the quantum-dot devices prove that this does not have to be the case.



Using the same specifications third-harmonic generation (THG) imaging measurements were performed on HeLa cancer cells.



The dark round region in the central area of the cell represents the nucleus which does not emit any THG signal due to its optical homogeneous composition. In contrast the cytoplasm and cell membrane generate moderate to high levels of signal.

Two photon imaging and cell-surgery are available as modules for use inside a demonstrator that has been realised within the project. As a result of this the multiphoton imaging will become compatible with other micromanipulation modules such as optical traps and capillary based micromanipulation. This type of flexibility has not been reached previously.

The demonstrator system shows that multiphoton imaging and cell-surgery have the potential to become available for biologists in the future. Taking into account that biology labs do not normally have access to laser specialists and typically have very limited lab space, the robustness and compactness of the system, in conjunction with the simplicity and usability of the demonstrator software are key to the system's success.

The FAST-DOT project has contributed significantly to advances in QD technology with 28 papers being published in high quality scientific journals and 23 papers presented at international conferences in the 4th year alone.

During the project duration excellent progress has been made: Novel Quantum Dot (QD) structures and devices have been designed, fabricated and evaluated by the project partners, detailed theoretical models have been developed for the simulation of QD mode-locked lasers, and novel operating regimes for the mode-locked lasers have been identified. The obtained results are enormously encouraging and confirm the great potential of this technology to enable future development of compact low-cost laser products capable of high power ultrashort pulse generation for applications in cell-surgery and multi-photon imaging.

For more information on the FAST-DOT project see www.fast-dot.eu .