NEWSLETTER Y4b

"COMPACT ULTRAFAST LASER SOURCES BASED ON NOVEL QUANTUM DOT STRUCTURES"

INTEGRATED PROJECT

Funded by the European Commission
under SEVENTH FRAMEWORK PROGRAMME: Photonic Components and Subsystems

FAST-DOT is a 7th Framework European Integrated Project targeting at development of new generation of quantum dot based lasers for use in Biophotonics applications. Being compact and efficient these lasers will improve the performance of procedures such as precision cutting and imaging.

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www.fast-dot.eu

Project overview

FAST-DOT is a €13.7M project (EU contribution €10.1M), aimed at developing a new generation of lasers for biomedical applications. Led by the University of Dundee, Scotland, 18 of Europe's leading photonics research groups and companies from 12 countries are working together to realise miniature lasers designed specifically for bio-photonics 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 pocket-sized ultra-high performance lasers at a substantially lower cost, making their widespread use affordable.

The new lasers have been designed for use in microscopy and nano-surgery, where high-precision cutting, imaging and treatment therapies will be made possible. The project has used novel nano materials called quantum dots, and exploited their unique light generating properties to produce devices with tuneable wavelengths and ultra-fast light pulses while cutting the cost of lasers and making them more portable. Quantum-dots are sometimes called artificial atoms because of their nanoscale dimensions and unique properties.

The very short, high energy pulses delivered by these lasers means they can be used in new ways like cutting cells and tissues without the undesirable heat generation associated with normal lasers. Furthermore, the wavelengths available from the new lasers will potentially open new areas of bio-photonic applications.

Partners

1.	(CO) University of Dundee (UNIVDUN)	UK
2.	Innolume GmbH (SME) (INNOLUME)	Germany
3.	University of Sheffield (USFD)	UK
4.	Tampere University of Technology (TUT)	Finland
5.	Swiss Federal Institute of Technology Zurich (ETH)	Switzerland
6.	Royal Institute of Technology Stockholm Sweden (KTH)	Sweden
7.	Institute of Photonic Sciences (ICFO)	Spain
8.	The Foundation for Research and Technology – Hellas (FORTH)	Greece
9.	Alcatel Thales III-V Lab (ALCATELTHALES)	France
10.	Vilnius University (VUFC)	Lithuania
11.	M Squared Lasers Limited (SME) (M2)	UK
12.	Philips (PFLA)	Germany
13.	Technical University of Darmstadt (TUD)	Germany
14.	TOPTICA Photonics AG (SME) (TOPTICA)	Germany
15.	Time Bandwidth Products (SME) (TBWP)	Switzerland
16.	Politecnico di Torino (POLITO)	Italy
17.	National and Kapodistrian University of Athens (NKUA)	Greece
18.	Molecular Machines and Industries GmbH (SME) (MMI)	Germany

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Project highlights

Quantum Dot Technology is moving fast from the research labs to the production lines. A broad range of application sectors profit from the advantages of the new technology, covering areas from electronics, optics and extending to cellular imaging and therapeutic detection capabilities for life sciences and biomedicine. According to a recent technical market research report[a, b] (BCC Research of Wellesly Mass. Sept. 2008) the global market value for QD technology is $28,6 million (mainly colloidal particles) and is expected to rise to $721,1 million in 2013 covering apart from colloidal dots applications, sectors in optics ($212 million in 2013), electronics ($61 million in 2013, mainly for QD flash memory applications), and optoelectronics ($245,7 million in 2013).

In view of the above data, FAST-DOT is strategically placed very well, being temporally in phase with the expanding market wave but also targeting at QD based devices of the optoelectronics sector. The objective of the project is to provide compact, high performance and low cost lasers for biophotonics applications such as laser microsurgery and imaging.

The activities during the project were, according to the initial schedule, devoted mainly to the detailed setting of the target specifications for the planned devices and subsystems and the development of the underlying technology needed for their realization. Furthermore, the realized devices have been optimized and used for specific applications related to biomedical imaging. In this respect, significant progress has been made in the following areas:

- ***Mode-locked QD edge-emitting lasers and amplifiers***
- ***Optically pumped VECSELs***
- ***Electrically pumped VECSELs***
- ***Mode-locked solid state and fiber lasers***
- ***Biomedical imaging***

This newsletter concludes with the dissemination activities of the project including summer schools and conferences organized by FAST-DOT and selected publications.

The FAST-DOT partners at the kick-off meeting in Barelona, 2-3 June, 2008.

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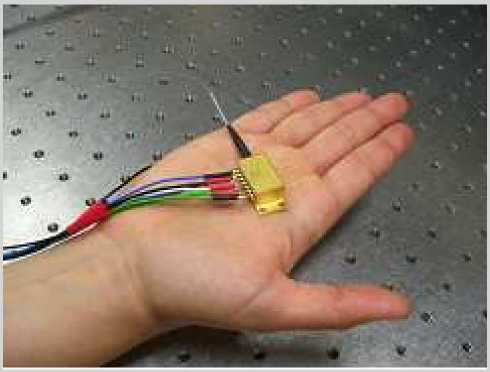
[a] "Quantum Dots: Technical Status and Market Prospects", Report Number: NAN027B

[b] "Quantum Dots point to a $721.1 million market" Photonics Spectra, Nov. 2008, pp 28.

Mode-locked QD edge-emitting lasers and amplifiers

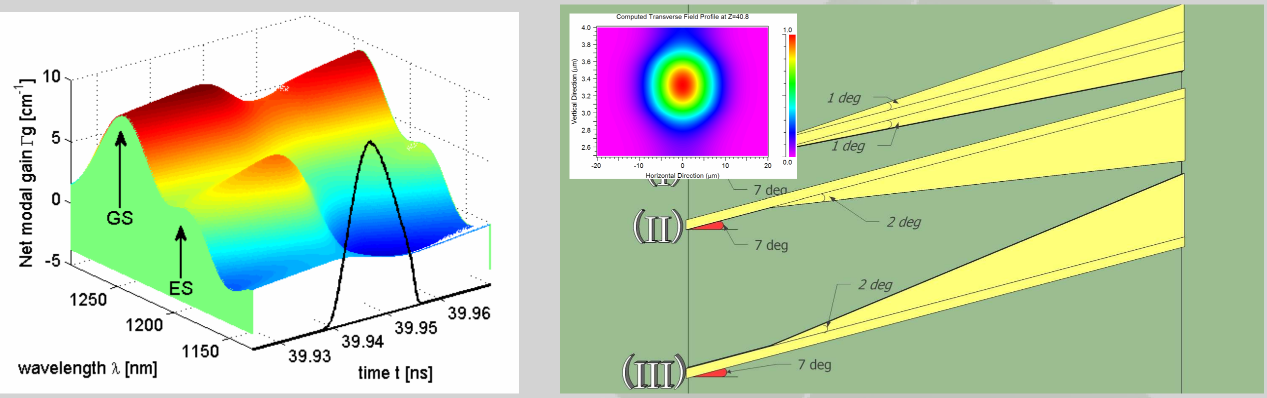


The project aim is to develop high-power, tunable, ultrafast edge-emitting quantum dot lasers, based on novel compact monolithic and external cavity configurations and subsequent frequency conversion to generate visible light, for key biophotonic and medical applications.

Our goal: ultrafast and ultra-compact electrically-pumped QD lasers

Design and simulation of passively mode locked edge emitting quantum dot lasers and semiconductor optical amplifiers for high power short pulse generation

Within the context of FAST-DOT, the teams at Politecnico di Torino (PoliTo) and the National and Kapodistrian University of Athens (NKUA) have successfully collaborated in the design and modelling of passive mode-locking in quantum-dot (ML QD) lasers and semiconductor optical amplifiers (SOAs). Various theoretical models have been developed (Time Domain Travelling Wave, Delay Differential Equation and Modified DDE etc). The outcome of this activity is the accurate description of passive mode-locking dynamics, the investigation of novel ML regimes (dual wavelength ML, reverse state emission etc), the high power short pulse amplification in SOAs. Furthermore, PoliTo has successfully designed and simulated passively mode locked lasers with tapered gain sections and together with NKUA, novel tapered waveguide multi-section QD SOAs have been designed and studied. This work was very essential for the achievements of FAST-DOT goals and gave the guidelines to the FAST-DOT partners for the realization of chips delivering high power short pulse generation. A large number of results from this activity have been published [1, 2, 3, 4].



Calculations of passive mode-locking in a two section QD laser (left) and design of a QD semiconductor optical amplifier (SOA) with tapered sections (right).

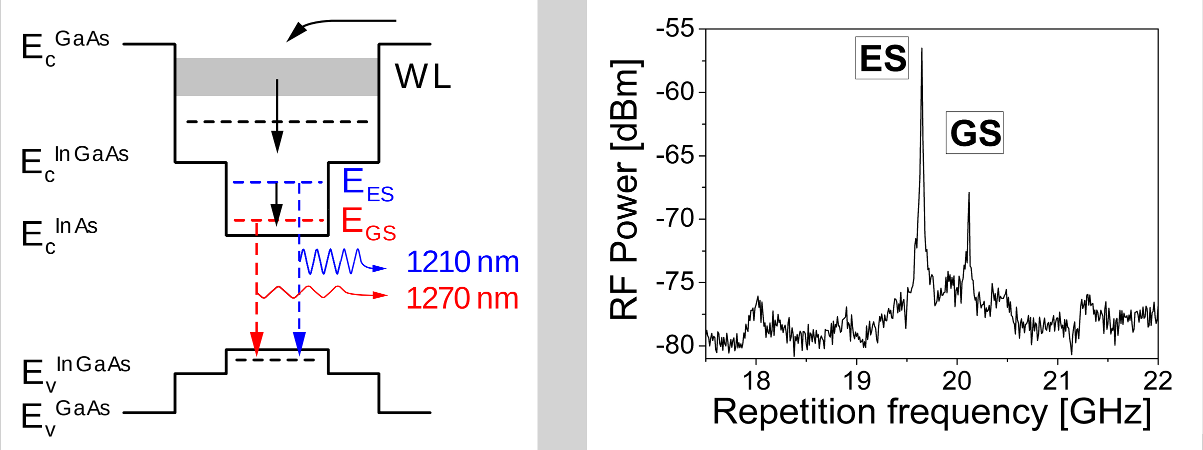
FAST-DOT researchers have identified novel operating regimes for the mode-locked QD lasers

In QD lasers, emission can occur via ground-state (GS) or excited-state (ES) transitions. The presence of the ES is a unique feature of QD lasers, and offers much potential that only recently started to be explored. FAST-DOT partners investigated the role of the ES transitions in the stability of mode locking in the GS, as new degree of freedom to control ML. Furthermore, the possibility to achieve switchable or simultaneous ML operation from GS and ES has been investigated. FAST-DOT partners form University of Dundee (UNIVDUN), National and Kapodistrian

University of Athens (NKUA), Politecnico di Torino (PoliTo), Technical University of Darmstadt (TUD) and Innolume GmbH (INNOLUME) have investigated in depth theoretically and experimentally the GS/ES emission effects.

The teams form UNIVDUN, NKUA and INNOLUME demonstrated both theoretically and experimentally a dual-wavelength passive mode-locking regime where picosecond pulses were generated from both ES (λ=1180nm) and GS (λ=1263nm), in a two-section GaAs-based QD laser[4]. This is the widest spectral separation (83nm) ever observed in a dual-wavelength ML non-vibronic laser. The teams from TUD and PoliTo have also investigated the dual wavelength emission dynamics; the influence of different biasing conditions on the emission properties has been investigated both experimentally and theoretically and identified the origin of the experimentally observed ML regimes[5]. The exploitation of this novel ML regime could enable a range of applications extending from dual-wavelength nonlinear imaging modalities to frequency mixing, time-domain spectroscopy and ultrafast optical processing.

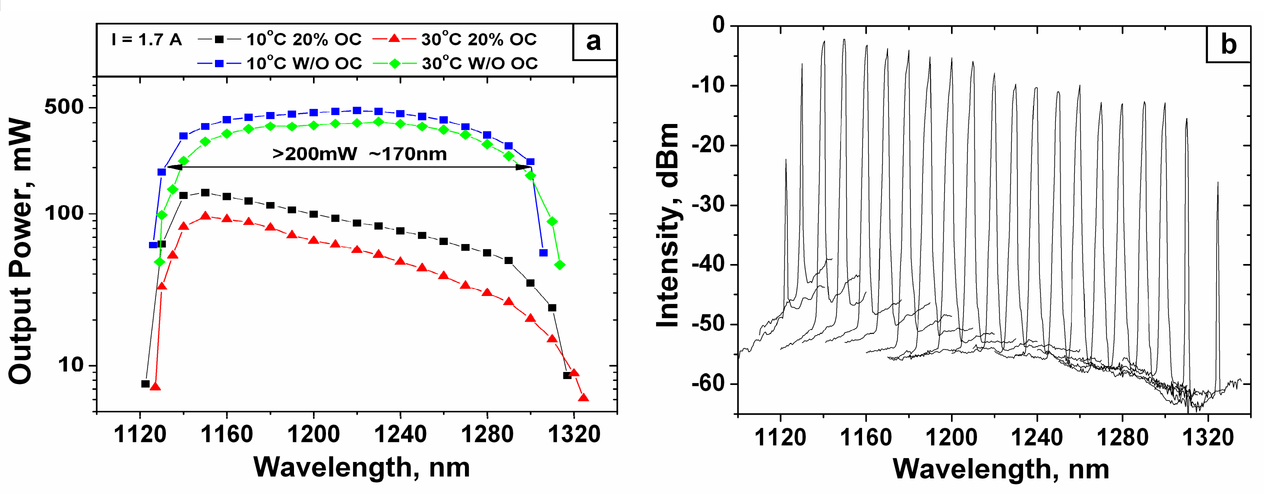
These results have been complemented by the very recent observation of the so-called reverse-state dynamics in a particular designed (strongly inhomogeneously broadened) two-section QD structure by TUD, where lasing first started on the ES and then, with increasing current, a transition from ES to ES+GS emission took place. This fascinating novel concept allows tailored emission wavelengths and picosecond-short mode-locked pulses quasi "on demand" interesting for a lot of applications[6].



Lest: Schematic of GS/ES emission in QD lasers. Right: Experimental demonstration of simultaneous GS and ES emission in a passively QD ML laser (electrical spectrum).

Record-breaking tunability achieved from an external-cavity laser diode with chirped quantum-dot layers

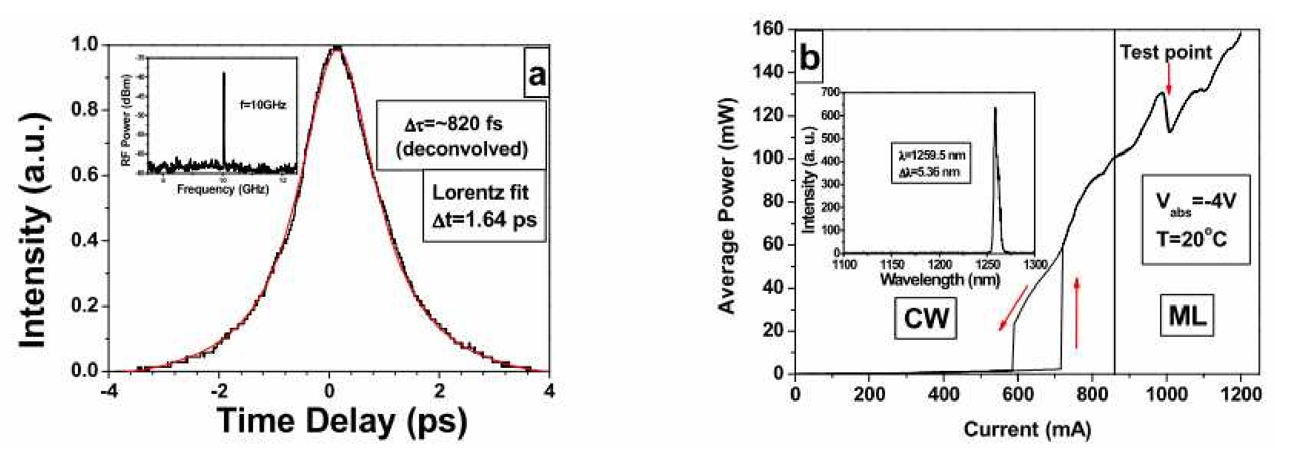
A record broadly tunable high-power external cavity InAs/GaAs quantum-dot diode laser with a tuning range of **202 nm** (1122 nm-1324 nm) has been demonstrated - as a result of a FAST-DOT research collaboration between the University of Dundee (UNIVDUN) and Innolume GmbH (INNOLUME)[7]. A maximum output power of 480 mW and a side mode suppression ratio greater than 45 dB are achieved in the central part of the tuning range[7]. Such laser performance is poised to have an impact in biomedical applications such as optical coherence tomography, where there is a growing interest in the development of broadly-swept tunable laser sources due to their high spectral bandwidth and output power. Furthermore, the spectral region encompassing 1.1 - 1.3 µm is particularly useful for biomedical imaging due to the low absorption and minimal scattering in human tissue, which can significantly enhance the penetration depth. Other important applications for this spectral range include the generation of coherent radiation in the visible spectral region via second harmonic generation or sum frequency generation, particularly into the yellow-orange spectral region, for which compact and efficient sources are relatively scarce.



Left: Dependence of output power of the quantum-dot external cavity laser on wavelength for different temperatures (10°C, 30°C) and configurations (without and with 20% output coupler). Right: Optical spectra of the quantum-dot laser, tuned across the 1122.5 nm – 1324.5 nm wavelength range, under an applied constant current of 1.7 A.

Record-breaking high power and sub-ps pulse generation from a passively mode-locked monolithic two-section gain-guided tapered quantum-dot laser

FAST-DOT partners UNIVDUN, TUD, Alcatel-Thales III-V Lab, PoliTo, and INNOLUME have been involved in the design and the realization of high-power two-section monolithic mode-locked Quantum-Dot lasers with gain-guided tapered sections. Within this activity they have demonstrated the highest peak power of **15 W** directly from a monolithic quantum-dot tapered laser, with sub-picosecond pulse width [8]. In detail, the gain-guided tapered laser was grown on a GaAs substrate by Molecular Beam Epitaxy, incorporating 10 identical layers of InAs quantum dots. The investigated gain guided tapered laser consists of two sections: a straight one and a tapered one (angle of 2°), to which reverse bias and forward bias are applied, respectively. The lengths of the straight and tapered sections are 800 μm and 3.2 mm respectively (repetition rate: 10 GHz). A longer tapered section and higher absorber-to-gain lengths ratio (1:4) were chosen to boost the power and generate shorter pulses. The shortest pulse generated (820 fs), was observed at a high

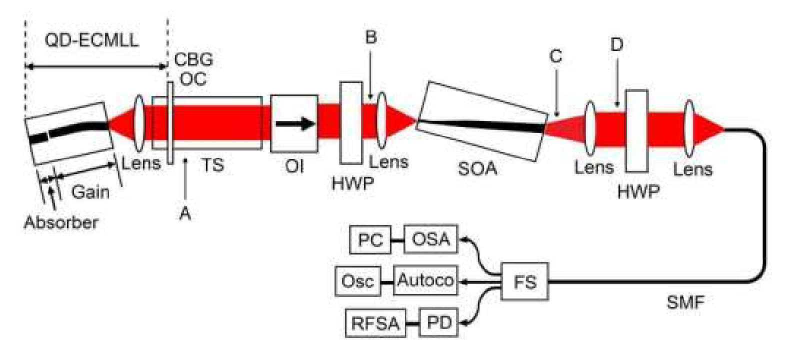


Left: autocorrelation trace for an injection current of 1A and reverse bias -4V for sub-ps regime (inset: Corresponding RF spectrum). Right: light-current characteristic at 20 °C for reverse bias of -4V (inset: Optical spectrum for I=1A and V=-4V).

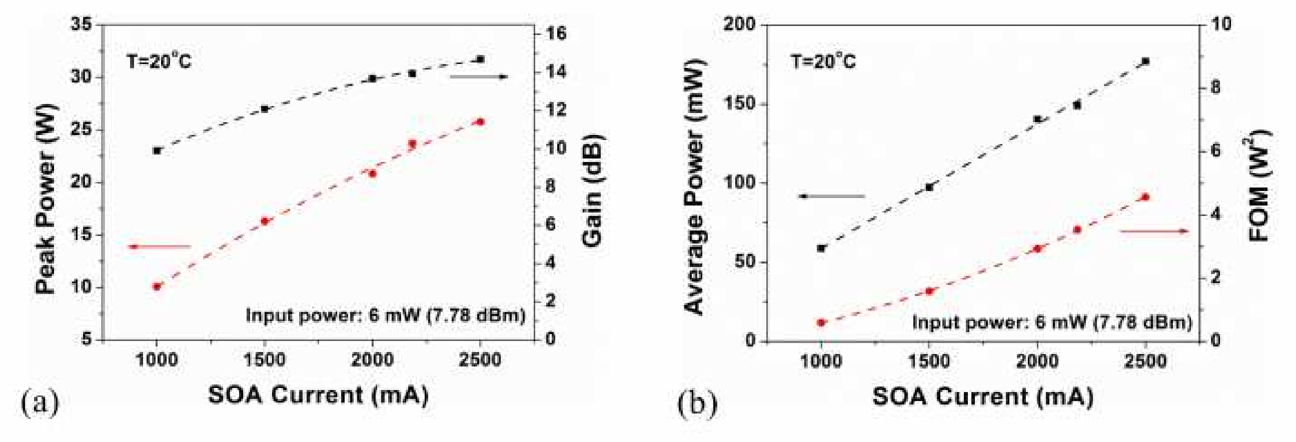
average power of 123 mW, which was made possible due to the increasing width of the tapered sectio, resulting in a peak power of 15 W and a time-bandwidth product of 0.83. Noise measurements show that timing jitter can be as low as 3 ps.

High peak-power picosecond pulse generation at 1.26 µm using a quantum-dot-based external-cavity mode-locked laser and tapered optical amplifier

FAST-DOT partners UNIVDUN, ICFO, III-V Lab, PoliTo, NKUA and INNOLUME presented the generation of high peak-power picosecond optical pulses in the 1.26 µm spectral band from a repetition rate tunable quantum-dot external-cavity passively mode-locked laser (QD-ECMLL), amplified by a tapered quantum-dot semiconductor optical amplifier (QD-SOA)[9]. The ultrashort-pulsed MOPA system presented is the first demonstration of a low-cost, chip-scale based device in the spectral region 1.0 µm - 1.3 µm, with power levels compatible with NLM. The system generates high-peak power picosecond optical pulses centered at 1.26 µm, which is located within the infrared penetration window of most biological tissues. This asset could potentially offer greater penetration depths and reduced sample damage compared with the ultrashort-pulsed semiconductor laser systems previously demonstrated, which could lead to major progress and a more widespread adoption of nonlinear imaging technology. Moreover, and unlike previous demonstrations of nonlinear imaging with ultrafast laser diode systems, we present for the first time a system which incorporates only a single amplification stage, and does not include external dispersion compensation, enabling a rather more compact and less complex laser system.



The laser emission wavelength was controlled through a chirped volume Bragg grating which was used as an external cavity output coupler. An average power of 208.2 mW, pulse energy of 321 pJ, and peak power of 30.3W were achieved. Preliminary non-linear imaging investigations indicate that this system is promising as a highpeak-power pulsed light source for nonlinear bio-imaging applications across the 1.0 µm - 1.3 µm spectral range.



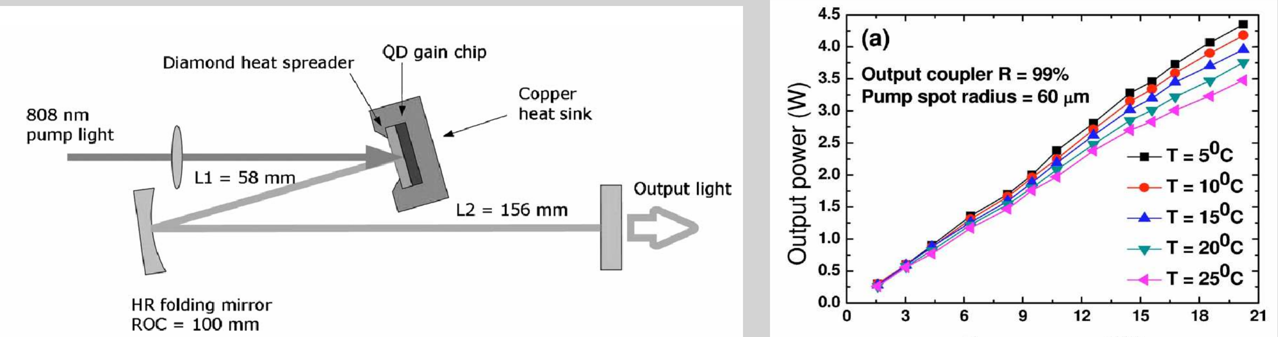
(a) Peak power (red), gain (black), (b) average power (black), and FOM (red) against SOA current for a 648-MHz repetition rate.

Optically pumped VECSELs

One of the key activities of the project was the development of optically pumped vertical-external-cavity surface-emitting lasers (OP-VECSELs) for multi-photon imaging, RGB generation and sub-picosecond pulses for continuum generation. Major achievements include:

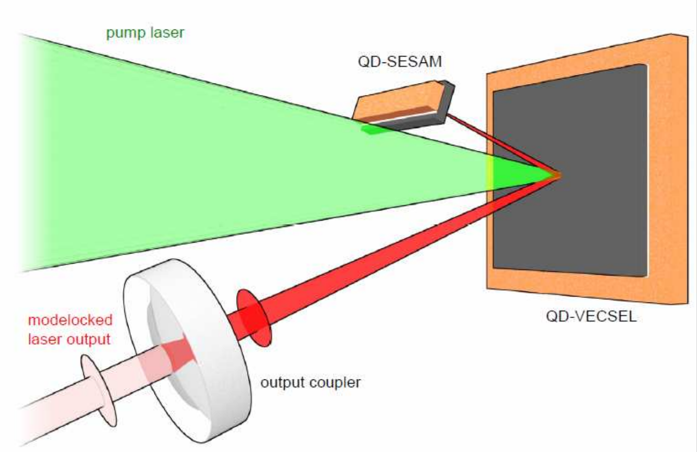
High-power quantum-dot-based semiconductor disk laser

The teams from Univ. Dundee, ORC Univ. Tampere, Innolume and ETHZ have demonstrated multi-watt cw output power from an optically-pumped quantum-dot VECSEL[10]. Continuous-wave output power of 4.35 W with 22% slope efficiency was demonstrated at a center wavelength of 1032 nm. This represents an increase in power of 15 times and an increase in slope efficiency of 10 times from the previously published results using Stranski–Krastanow grown quantum dots. An intracavity diamond heat spreader was used for thermal management. The maximum output power was limited by the available pump power, and no sign of thermal rollover was observed.



Schematic of the V-cavity laser configuration and right output power versus pump power characteristics of diamond heat spreader optically pumped VECSEL.

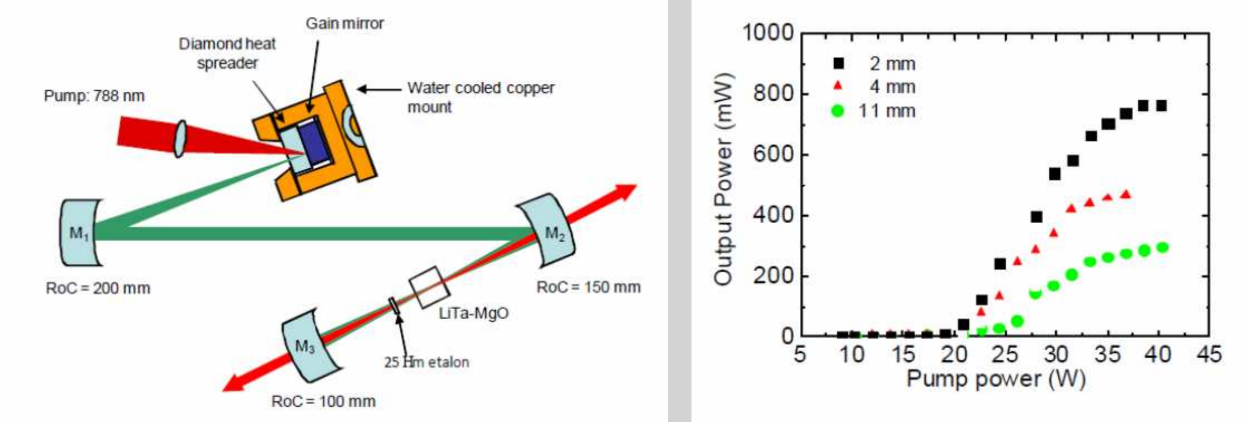
Femtosecond operation of a high power VECSEL



Pertners ETHZ and INNOLUME reported on the first femtosecond vertical external cavity surface emitting laser (VECSEL) exceeding 1 W of average output power[11]. The VECSEL is optically pumped, based on self-assembled InAs quantum dot (QD) gain layers, cooled efficiently using a thin disk geometry and passively modelocked with a fast quantum dot semiconductor saturable absorber mirror (SESAM). They have developed a novel gain structure with a flat group delay dispersion (GDD) of ±10 fs^2 over a range of 30 nm around the designed operation wavelength of 960 nm. This amount of GDD is several orders of magnitude lower compared to standard designs. Furthermore, an optimized positioning scheme of 63 QD gain layers has been used to broaden and flatten the spectral gain. For stable and self-starting pulse formation, a QD-SESAM with a fast absorption recovery time of around 500 fs has been employed. An average output power of 1 W with 784-fs pulse duration at a repetition rate of 5.4 GHz hs been achieved. The QD-SESAM and the QD-VECSEL were operated with similar cavity mode areas, which is beneficial for higher repetition rates and the integration of both elements into a modelocked integrated external-cavity surface emitting laser (MIXSEL).

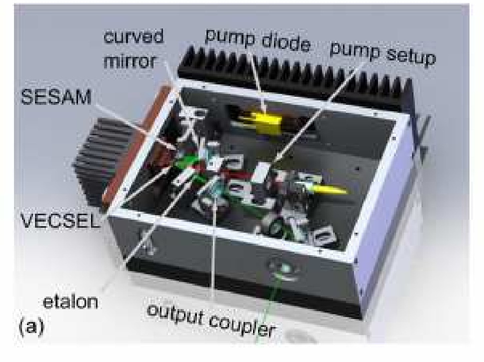
Efficient frequency conversion using a optically pumped VECSEL

Compact coherent laser sources emitting red light are required for several applications such as photodynamic therapy, laser projection displays, and biophotonics. An optically pumped semiconductor disk laser (OP-SDL or OP-VECSEL) can produce high power with nearly diffraction-limited beam and by using proper semiconductor compounds they can be designed to emit from 650 nm to midinfrared (midIR). However some wavelengths are hard to achieve; particularly, direct generation of visible light at nm from SDL is problematic due to the shortage of efficient semiconductor gain materials and the limited availability of short-wavelength high power pump sources. Alternatively, visible wavelengths can be generated from an infrared SDL by second-harmonic generation (SHG). FAST-DOT team of TUT (Finland) in collaboration with the team from UNIDUN (UK) have demonstrated an OP-SDL frequency doubled with periodically poled lithium tantalate crystal[12]. The semiconductor disk laser exploited GaInNAs-based active region with GaAs–AlAs distributed Bragg mirror to produce emission at 1.2 µm. Crystals with various lengths were tested for intracavity frequency conversion and the achieved frequency doubled output power was 760 mW at 610 nm (red wavelength) with a 2-mm-long crystal.



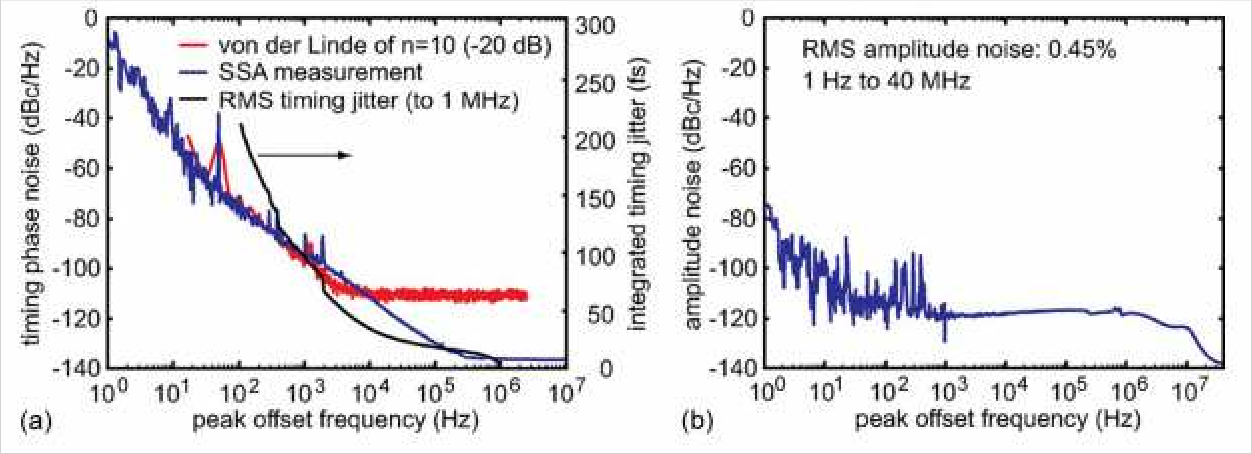
Left: Experimental setup for the frequency doubling with the OP-SDL. Right: Output power at red wavelength with different lengths of nonlinear crystal.

Low timing jitter of a free-running SESAM mode-locked VECSEL



FAST-DOT partner ETHZ presented timing jitter measurements of an InGaAs quantum well vertical external cavity surface emitting laser (VECSEL) passively mode locked with a quantum dot semiconductor saturable absorber mirror (SESAM) at 2-GHz repetition rate[13]. The VECSEL generates 53-mW average output power in 4.6-ps pulses at 953 nm. The laser housing was optimized for high mechanical stability to reduce acoustic noise. A fiber-coupled multimode 808-nm pump diode which is mounted inside the laser housing is used. No active cavity length stabilization is employed. The phase noise of the free-running laser integrated over a bandwidth from 100 Hz to 1 MHz corresponds to an RMS timing jitter of ~212 fs, which is lower than previously obtained for mode-locked VECSELs. This clearly confirms the superior noise performance expected from a high-

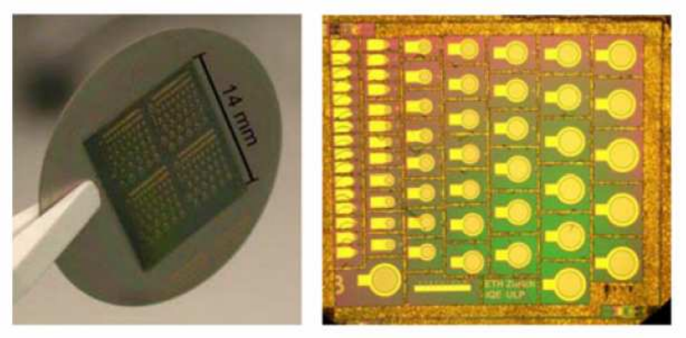
Q-cavity semiconductor laser. In contrast to edge-emitting semiconductor diode lasers, the cavity mode is perpendicular to the quantum well gain layers, which minimizes complex dispersion and nonlinear dynamics.



Noise characterization. (a) Two-sided power density of the phase noise (dBc/Hz) and integrated timing jitter (fs) integrated from f_{low} to f_{high} = 1 MHz as a function of f_{low} and (b) amplitude noise with an integrated RMS amplitude noise of 0.45% in [1 Hz, 40 MHz].

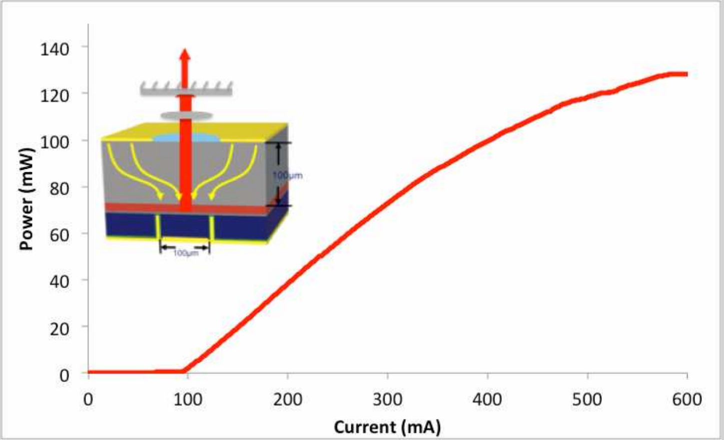
Electrically pumped VECSELs

Realization of an electrically-pumped Vertical External Cavity Surface Emitting Laser for passive mode-locking



Modelocked optically pumped vertical external cavity surface emitting lasers (VECSELs) have generated up to 6.4-W average power, which is higher than for any other semiconductor lasers. Electrical pumping of mode-locked VECSELs is the next step toward a higher level of integration. With continuous wave (cw) electrically pumped (EP) VECSELs, an average output power of 900 mW has been demonstrated from the undisclosed proprietary novalux extended cavity surface emitting laser (NECSEL) design. In contrast, mode-locked NECSELs have only been demonstrated at 40 mW. FAST-DOT partner ETH demonstrated the first realization of previously designed EP-VECSELs suitable for mode-locked operation[14]. Power scaling is achieved with a lateral mode size increase. The competing electrical and optical requirements are, on the electrical side, low ohmic resistance, and on the optical side, low optical losses and low dispersion. Additionally, the device needs to operate in a fundamental mode for stable modelocking. 60 EP-VECSELs with varying dimensions have been fabricated and characterized. The tradeoff between good beam quality and output power is a point of discussion with an outlook to the modelocking of these EP-VECSELs. Initial EP-VECSEL devices have generated >100 mW of cw output power.

Design and fabrication of an electrically-pumped Vertical External Cavity Surface Emitting Laser based on substrate emission

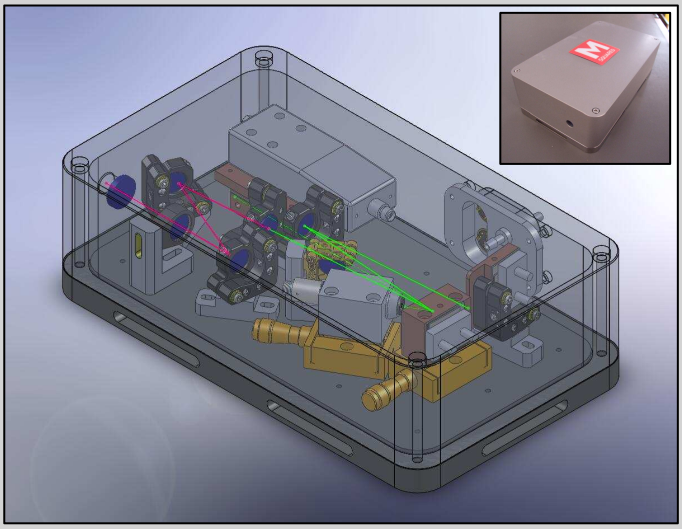


Within FAST-DOT, USFD have designed, grown, fabricated and tested electrically pumped VCSELs based on a substrate emission and carrier spreading layer[15]. The gain medium consists of six strain balanced QWs for high round trip gain. A range of device geometries have been investigated, and high output powers have been achieved from size scaling up to 100um diameter. In this case, a threshold current of 1200A/cm2 with external quantum efficiency of 30% and 30K/W heat dissipation leads to 130mW CW output power. This power is limited by uniformity of lateral carrier injection and efficiency of heat extraction. There is scope for both of these to be further improved.

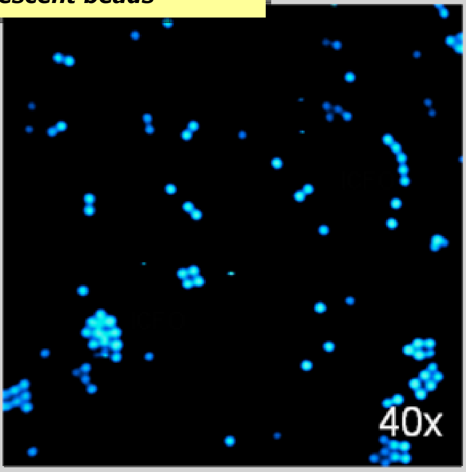
Mode locking of these USFD devices has been successfully achieved at DUNDEE in a Z-cavity configuration. The cavity round trip time led to a pulse repetition rate of 1.49GHz. In order to increase the internal cavity power incident on the SESAM, an output coupler of 2% was used, which led to an average output power of 1mW. In order to increase output power, the output coupler reflectivity can be reduced, in this case, a maximum of 8 mW was achieved with 10% output coupling before the device became unstable. Further improvements to both the EP-VECSEL and the SESAM are being carried out to greatly improve this performance. Nonetheless, this result represents a significant step forward in realising ultra compact low cost ultra fast pulsed lasers suitable for battery operated handheld devices. The figure above shows a schematic of the EP-VECSEL device yielding 130mW CW power in a straight cavity with 20% out-coupling mirror.

Mode-locked solid state and fiber lasers

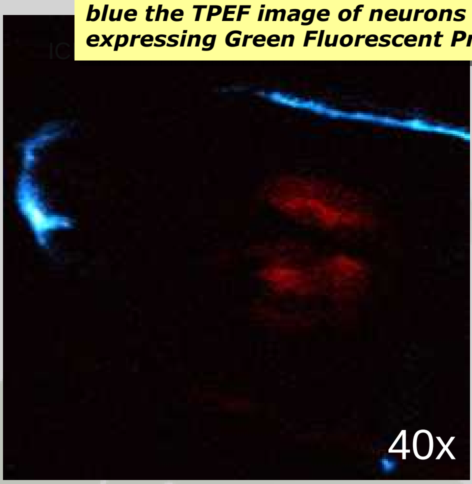
Development of an optically pumped VECSEL/SESAM mode-locking prototype



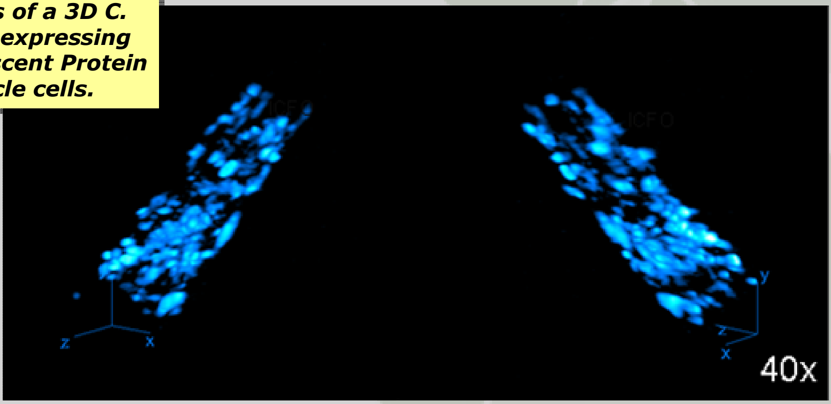
Compact packaging of Watt-level average power mode-locked lasers is an important issue affecting stability of the laser and eventually the usability in nonlinear imaging systems. Efficient solutions for heat-load management, are crucial for reliable hands-off laser operation. FAST-DOT partner M-Squared Ltd has developed a unified compact packaging technology platform for high-repetition rate watt-level mode-locked solid state lasers and optically-pumped VECSELs. The new prototype laser is mode-locked by employing QD-SESAM designed and fabricated by FAST-DOT partners. The laser, envisioned for nonlinear imaging applications, generates pulses shorter than 1.5 ps at a repetition rate of 500 MHz and average powers exceeding 1 W. The laser center wavelength is 965 nm, which lies at the maximum of the two-photon action cross section of the widely used GFP marker. Some biomedical imaging samples taken at ICFO with the M-Squared prototype are shown below.



TPEF images of green fluorescent beads



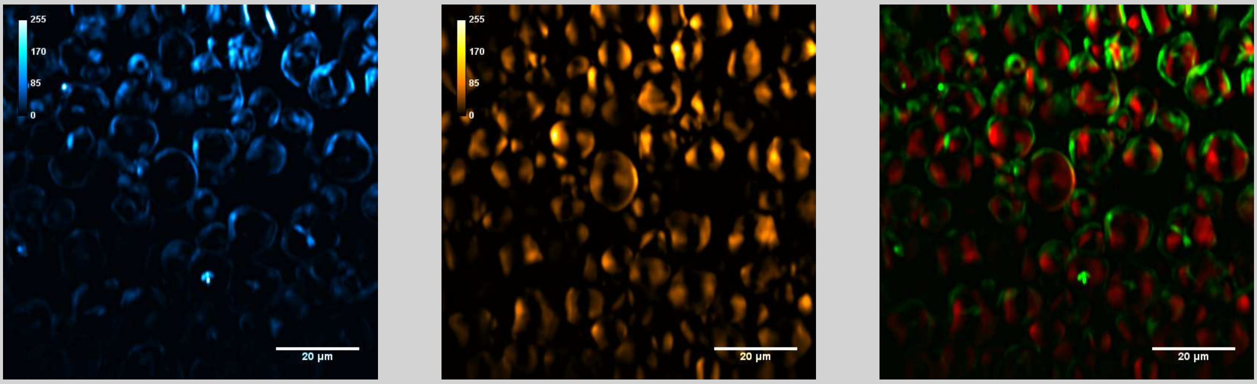
C. elegans nematode head. In red is the Second-Harmonic Generation (SHG) image of pharyngeal muscles and in blue the TPEF image of neurons expressing Green Fluorescent Protein.



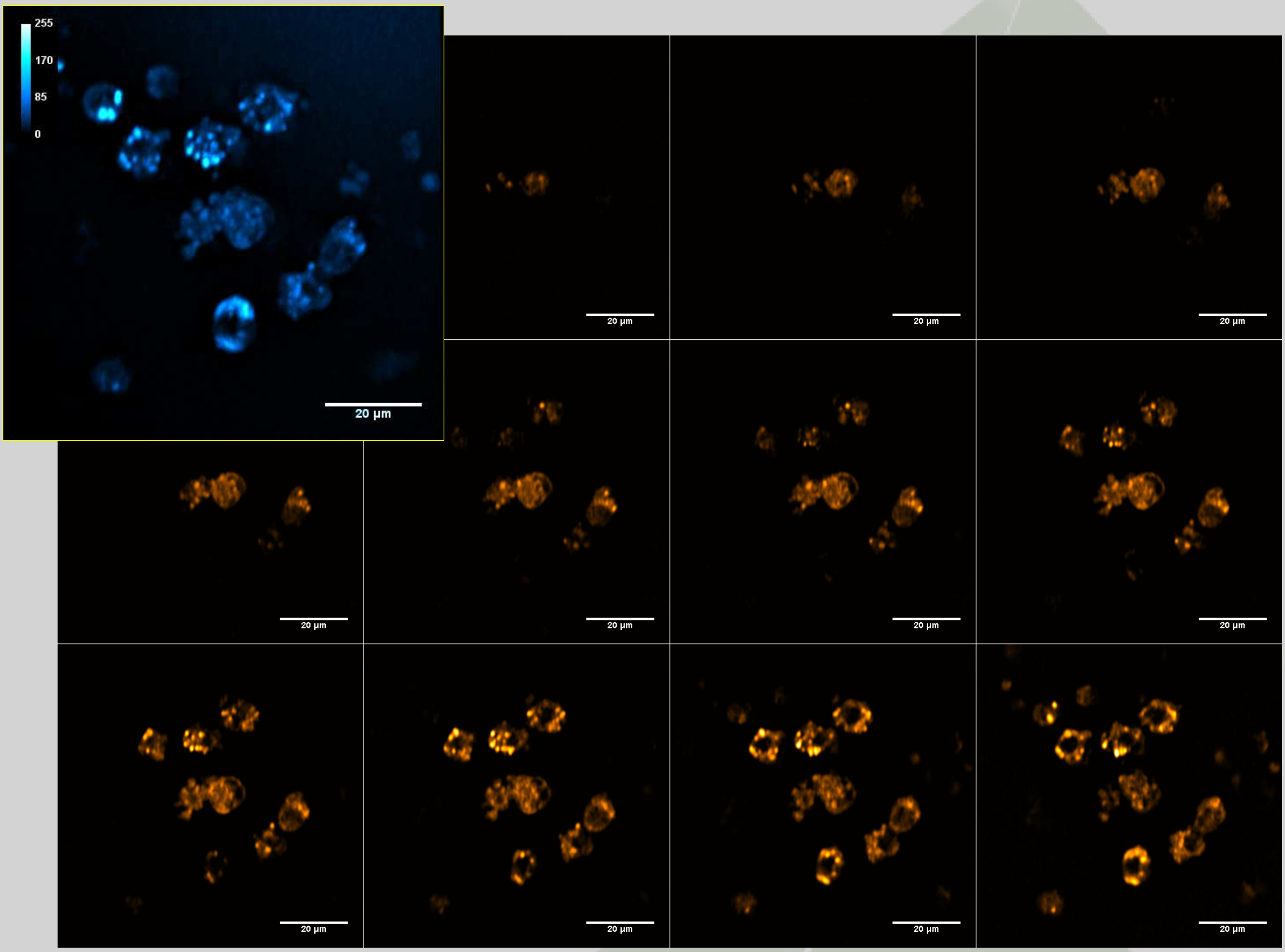
Rotated views of a 3D C. elegans head expressing Green Fluorescent Protein (GFP) in muscle cells.

Development of a solid state laser for multiphoton imaging and cell surgery

FAST-DOT partner Time-Bandwidth Products has developed a laser for multiphoton imaging and cell surgery, both to be done with the same laser. The prototype Yb based solid state laser is built and tested with 83 MHz repetition rate, >2.5 W of average power and <200 fs pulse duration. The laser is delivered and installed at FORTH. The collaboration of the two partners on TPE imaging and cell surgery took place in FORTH and some representative results are shown below:

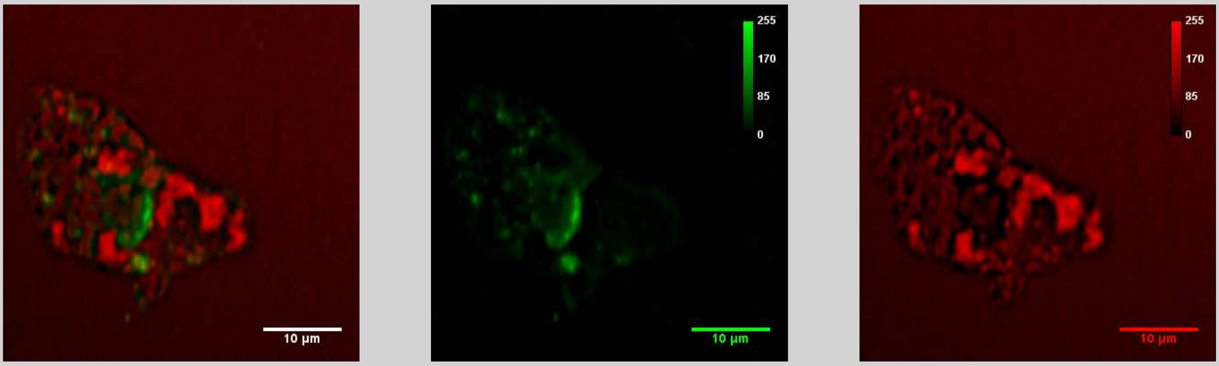


Starch 2-D Imaging. Left: THG, middle: SHG, right: multimodal (Green: THG, Red: SHG)



HeLa Cancer Cells THG Slice Imaging.

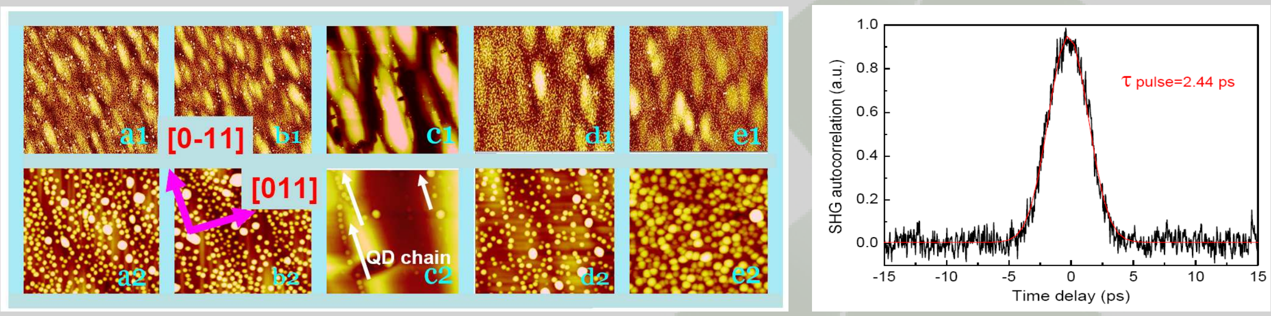
Inset: HeLa Cancer Cells 3-D THG Imaging (14 sequential slices combined)



HeLa Cancer Cell (THG) – Gold Nanorods (TPL).
Left: THG, right: TPL, right: multimodal (Green: THG, Red: TLP)

1.55 µm InAs/GaAs Quantum Dots and High Repetition Rate Quantum Dot SESAM Mode-locked Laser

The team from The University of Sheffield have developed a novel epitaxial process for the realization of high optical quality 1.55 µm In(Ga)As quantum dots (QDs) on GaAs substrates and their incorporation into a semiconductor saturable absorber mirror (SESAM)[16]. Using this SESAM, Time-Bandwidth Products, and ETH, have realized the first 10 GHz high repetition rate QD-SESAM modelocked laser at 1.55 µm, exhibiting ~2 ps pulse width from an Er-doped glass oscillator (ERGO)[17]. The low Q-switching threshold suggests the potential to increase the beam waist diameter on the SESAM in an improved and possibly simpler laser design, enabling simpler manufacturing of even higher repetition rate (e.g. >25 GHz) fundamentally modelocked lasers, highly desired in telecom applications. In addition, with a high areal dot density and strong light emission, this QD structure is a very promising candidate for many other applications, such as laser diodes, optical amplifiers, non-linear and photonic crystal based devices.

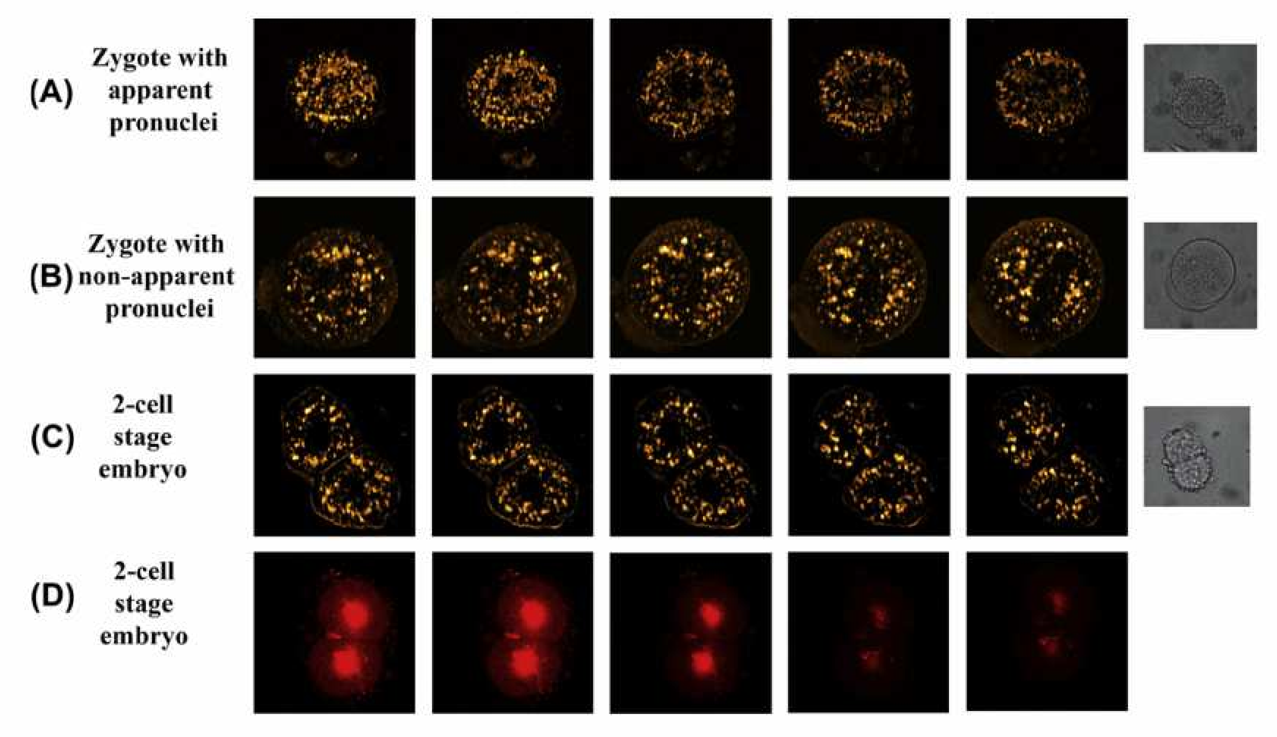


Left: AFM images of 1.55µm InAs/GaAs quantum dot samples. Right: 10 GHz ERGO laser output: second harmonic generation (SHG) autocorrelation trace.

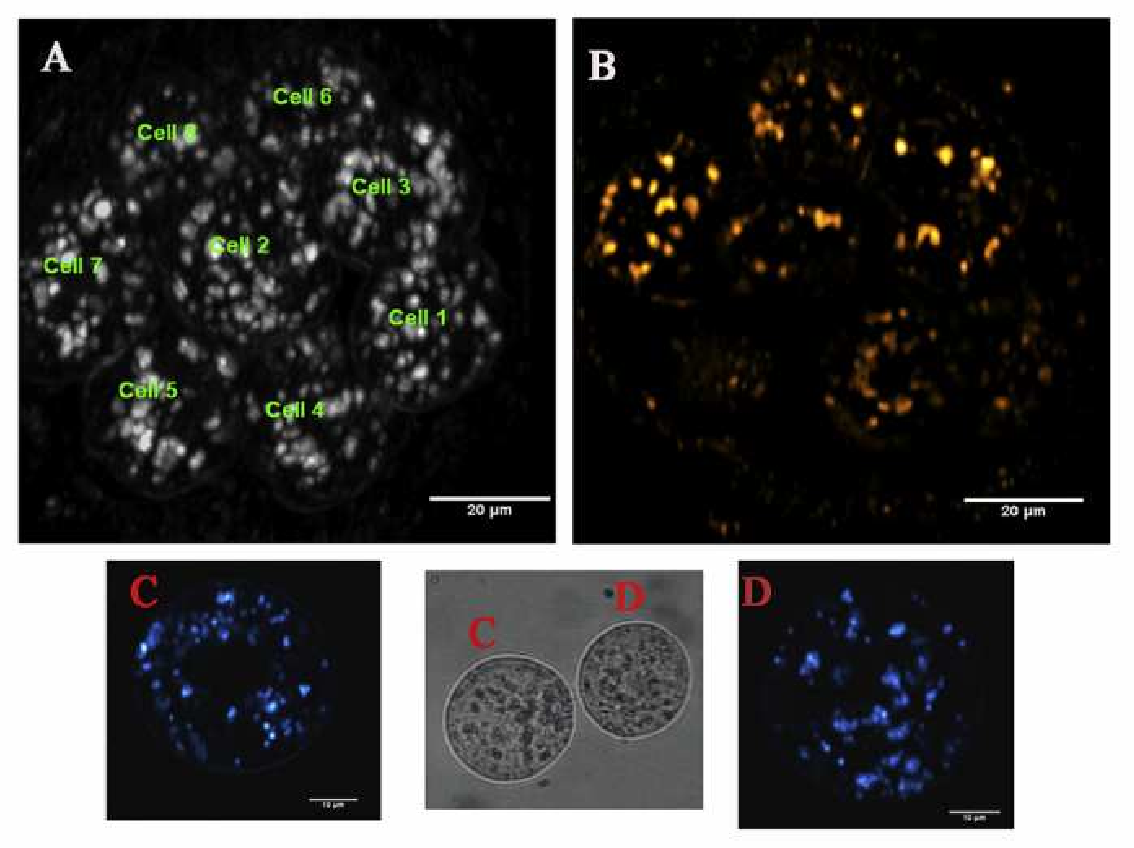
Biomedical imaging

Study of the pre-implantation embryo patterning based on Third Harmonic Generation (THG) using a femtosecond t-pulse laser.

Embryo patterning is subject to intense investigation. So far only large, microscopically obvious structures like polar body, cleavage furrow, pro-nucleus shape can be evaluated in the intact embryo. Using non-linear microscopic techniques, FAST-DOT partner FORTH describes new methodologies to evaluate pre-implantation mouse embryo patterning[18]. Third Harmonic Generation (THG) imaging, by detecting mitochondrial/lipid body structures, could provide valuable and complementary information as to the energetic status of pre-implantation embryos, time evolution of different developmental stages, embryo polarization prior to mitotic division and blastomere equivalence. Quantification of THG imaging detected highest signalling in the 2-cell stage embryos, while evaluating a 12–18% difference between blastomeres at the 8-cell stage embryos. Such a methodology provides novel, non-intrusive imaging assays to follow up intracellular structural patterning associated with the energetic status of a developing embryo, which could be successfully used for embryo selection during the in vitro fertilization process.



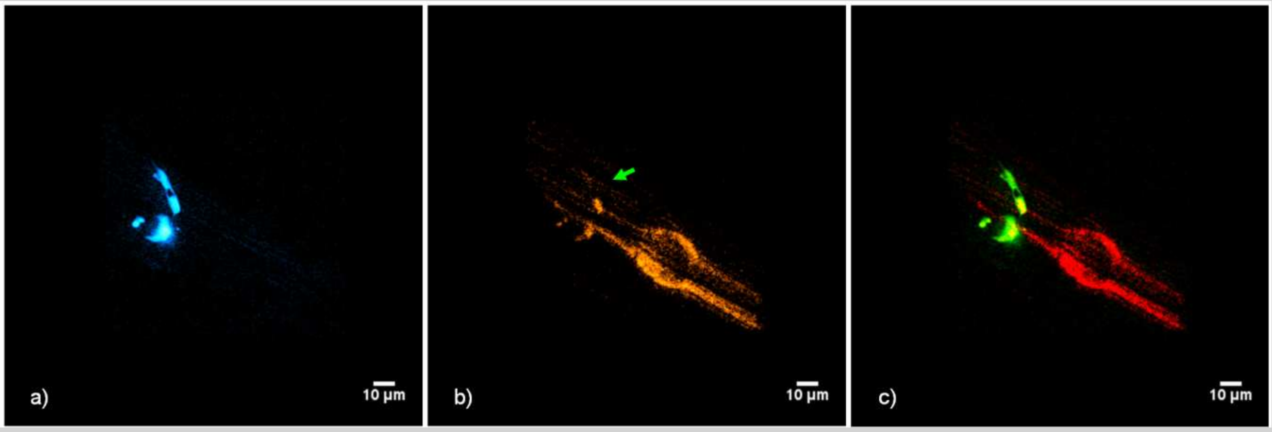
Serial sections from a zygote with apparent pronuclei at 18 h post-hCG (A), a zygote with no apparent pronuclei at 21 h 30 min post-hCG (B), a 2-cell stage embryo at 45 h 30 min post-hCG (C) visualized by THG imaging and a 2-cell stage embryo stained with TOPRO-3 for the detection of nuclei (D). Mouse embryos were generated from BALB/c mice upon in vivo fertilization procedures and submitted to THG imaging without any further manipulation.



THG signal of blastomeres in 8-cell stage embryos with their zona pellucida (A: 3D reconstruction, B: central slice image) and in isolated blastomeres from 4-cell stage embryos (C and D). Signal quantification in blastomeres C and D (calculated as described in Section 3) reveals a 16% difference.

Imaging with Semiconductor Disk Laser - I

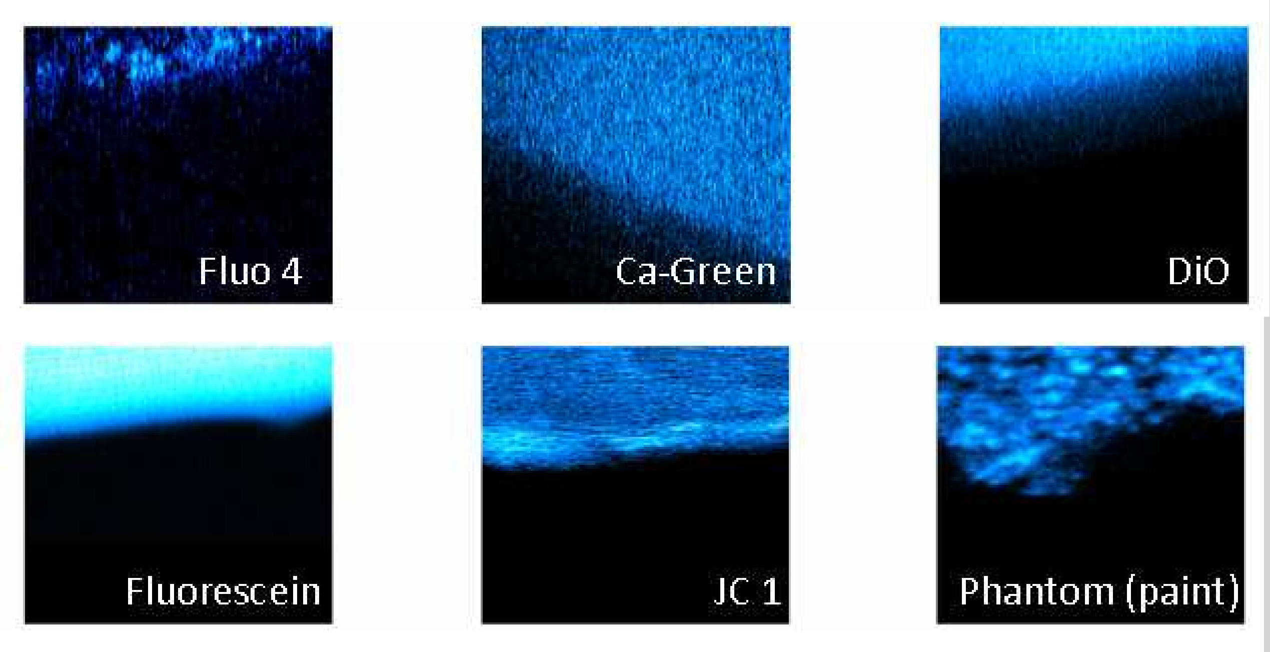
FAST-DOT partners ICFO, FORTH, M2, TBWP, ETHZ presentd a portable ultrafast Semiconductor Disk Laser (SDL) (or vertical extended cavity surface emitting laser—VECSELs), to be used for nonlinear microscopy in the journal Biomedical Optics Express[19]. The SDL is modelocked using a quantum-dot semiconductor saturable absorber mirror (SESAM), delivering an average output power of 287 mW, with 1.5 ps pulses at 500 MHz and a central wavelength of 965 nm. Specifically, despite the fact of having long pulses and high repetition rates, they demonstrated the potential of this laser for Two-Photon Excited Fluorescence (TPEF) imaging of in vivo Caenorhabditis elegans (C. elegans) expressing Green Fluorescent Protein (GFP) in a set of neuronal processes and cell bodies. Efficient TPEF imaging is achieved due to the fact that this wavelength matches the peak of the two-photon action cross section of this widely used fluorescent protein. The SDL extended versatility is shown by presenting Second Harmonic Generation images of pharynx, uterus, body wall muscles and its potential to be used to excite other different commercial dyes. Importantly this non-expensive, turn-key, compact laser system could be used as a platform to develop portable nonlinear bio-imaging devices.



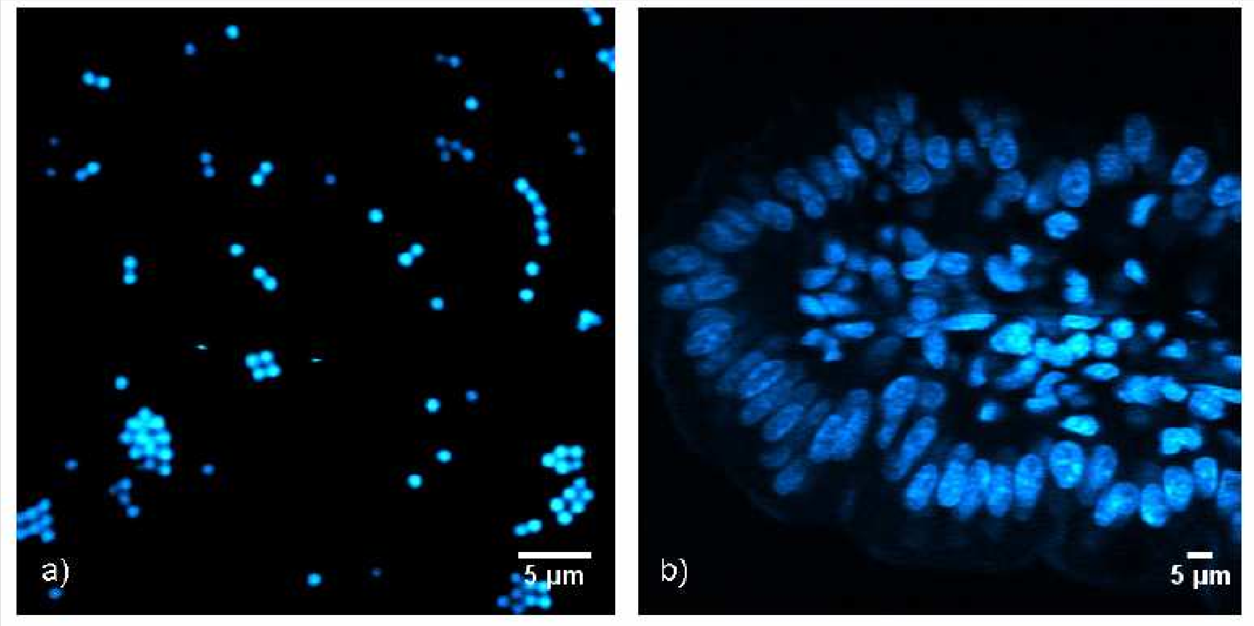
3D projections of a) TPEF signal from neurons forming the nerve ring expressing GFP (blue) and b) SHG signal from the pharyngeal region (orange) of the C. elegans nematode. c) Merged TPEF (Green) and SHG (red) images of both structures.

Imaging with Semiconductor Disk Laser - II

The second and third Quantum Dot-based laser prototypes where tested at ICFO to extend the versatility of the system for obtaining multiphoton images from different samples containing different biological dyes. The second and third iterations of the Quantum Dot based semiconductor disk laser systems developed by M2 were tested at ICFO (with the participation of M2 personnel). The new lasers could deliver up to 1 W average output power. The obtained results have enabled to demonstrate to extend the versatility of this device for efficient excitation not only of green fluorescent protein (GFP) but also of different biological dyes. These results (including the first demonstration of Two-Photon Excited Fluorescence (TPEF) and Second Harmonic Generation (SHG) of in-vivo C. elegans nematodes) have been published in several conference papers and journals[19-22]. This work was highlighted on Biophotonics magazine[23].



TPEF images from different biological dyes in solution that can also be efficiently excited using Msquared quantum dot based systems.



Two-Photon Excited Fluorescence images from a) green fluorescent beads and b) mouse intestine section labeled with different dyes.

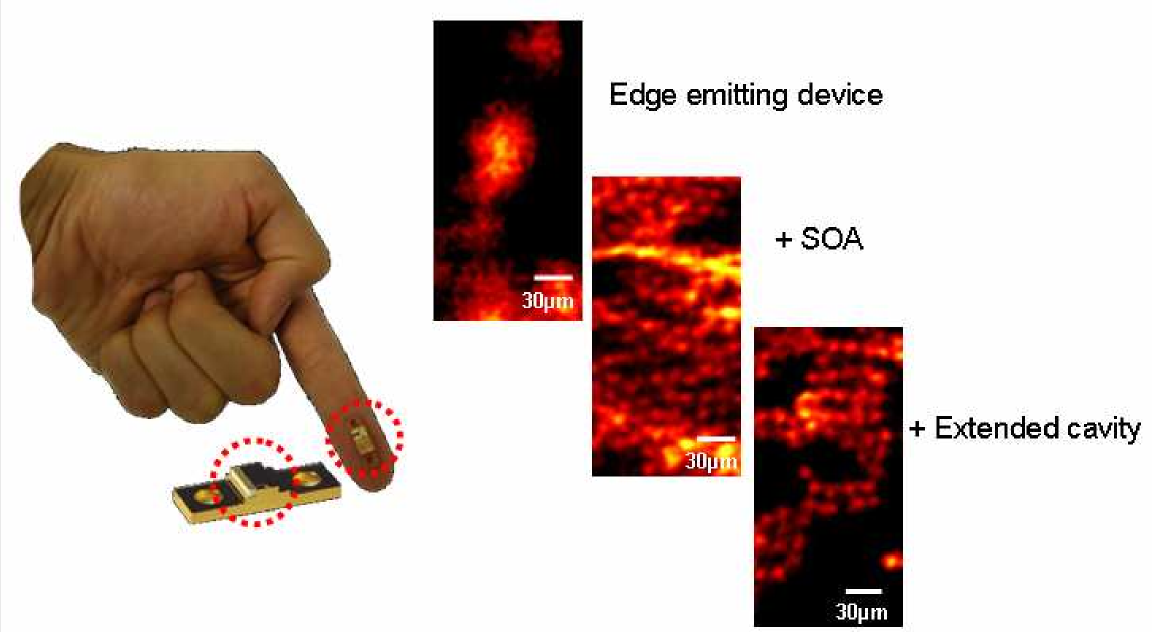
Imaging Mode-locked QD edge-emitting lasers and amplifiers

Fast-Dot partners ICFO and University of Dundee presented the first demonstration of TPEF imaging obtained with 1.26-m wavelength chip-scale semiconductor ultrashort pulsed edge emitting devices and SOAs. This was achieved using different configurations to increase the output peak power.

The first device had pulse duration of 1.0 ps, an output average power of 100 mW, and a repetition rate of 10 GHz, corresponding to ~10-W peak power. In this case the peak power of the laser system has been up scaled considerably (compared with the previous devices), thus being able to deliver a couple of watts into the sample plane. Fluorescent bead samples (suitable for NL excitation at 1260 nm) were imaged.

The second system to be tested consisted on an edge emitting device and a SOA where the pulse duration was 3-4 ps, the repetition rate was 10 GHz and the output average power from the system ranged between 290-370 mW. As it can be observed, the system output peak power has been considerably increased up to ~12 W by employing an amplification stage consisting of a QD based SOA. In this case it is evident more power directly enables to efficiently obtain a nonlinear image.

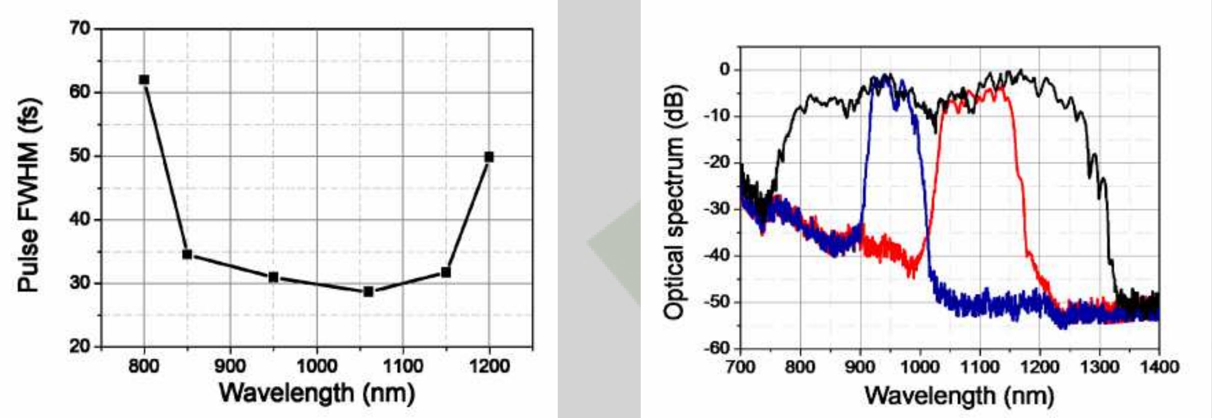
For further increasing the peak power, an external cavity configuration was employed. The repetition rate of QD-ECMLL was decreased to 648 MHz. The system had a pulse width of ~ 9 ps. As before, this configuration was amplified through a QD-SOA. In this experiment the highest peak power was ~30.3 W. The obtained TPEF image shows how the increase on peak power directly gives an improvement in the image quality. These results have been published in several conference papers and journals[24-26].



Experimental setup and TPEF image of 15µm Crimson fluorescent beads for blood flow determination imaged using the chip-sized based ultra-short pulsed laser systems in different configurations. The resulting images were obtained by averaging 10 frames to improve the signal-to-noise ratio.

Near-infrared tunable 30-fs system with optional multi-spectral output for multi-photon microscopy

FAST-DOT partner TBP demonstrated a novel low-cost, low-noise, tunable, high-peak-power, ultrafast laser system based on a SESAM-mode locked, solid-state Yb tungstate laser plus spectral broadening via a microstructured fiber followed by pulse compression[27]. The spectral selection, tuning, and pulse compression are performed with a simple prism compressor. The spectral broadening and fiber parameters are chosen to insure low-noise and short pulse operation of the tunable output. The long-term stable output pulses are tunable from 800 to 1200 nm, with a peak power up to 30 kW and pulse duration down to 26 fs. The generation of an output beam with 30 fs pulsewidth and multiple colors in infrared is also demonstrated. In particular, selected spectral



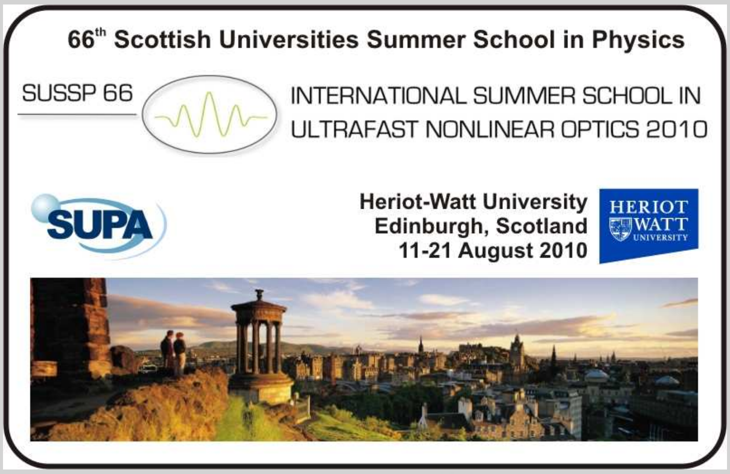
Left: Laser system output compressed pulse duration versus central wavelength of the selected spectral slice. Right: Multicolor imaging option: total optical output spectrum (black curve), selected spectral slice centered at 960 nm (blue), and slice centered at 1100 nm (red).

slices centered at 960 and 1100 nm are compressed suitable for imaging with green fluorescent protein and red dyes. Such a multicolor, 30 fs laser is ideally suited for simultaneous multispectral multiphoton imaging. This system is attractive for variety of applications including multiphoton (TPE, SHG, THG, CARS) and multimodal microscopy, nanosurgery, and optical coherence tomography (OCT). Such system is simpler, lower-cost, and much easier to use (fully turn-key) compared to a currently available solutions for near-infrared ultrashort pulses, typically a Ti:sapphire laser-pumped OPO.

Exploitation and dissemination activities

Organization of summer school on ultra-fast non-linear optics (2010)

FAST-DOT organized an international summer school in collaboration with Heriot-Watt University (SUSSP 66) held on 11-21 of August 2010 in Edinburgh, Scotland. The ten-day summer school topic was the "ultrafast non-linear optics" and brought together PhD students and young postdoctoral researchers from a diverse range of fields relevant to the study of ultrafast nonlinear optics, enabling the exchange of new ideas across these fields. The core program consisted of lectures by internationally renowned experts, supplemented by workshops, poster presentations and informal discussion sessions.



66th Scottish Universities Summer School in Physics

SUSSP 66

INTERNATIONAL SUMMER SCHOOL IN
ULTRAFAST NONLINEAR OPTICS 2010

SUPA

Heriot-Watt University
Edinburgh, Scotland
11-21 August 2010

HERIOT WATT UNIVERSITY

Organization of summer school entitled "Photonics meets biology" (2011)

FAST-DOT organized successfully a 2nd summer-school with title "Photonics meets Biology". The summer school was held during 15 - 18 September 2011 in Hersonissos on the Crete island, Greece. The school was organized by FAST-DOT partners IESL/FORTH (Greece) and the University of Dundee (UK).

FAST-DOT

FAST-DOT SUMMER SCHOOL
"PHOTONICS meets BIOLOGY"

15th - 18th September, 2011
Creta Maris Hotel
Hersonissos, Crete, Greece

DURATION:
4 DAYS
15th - 18th September, 2011

REGISTRATION DEADLINE:
31st July, 2011

FEE:
200€
Some scholarships available

SCHOOL ORGANIZERS

Dr. Maria Farsari
IESL-FORTH

Prof. Edik Rafailov
University of Dundee

KEYNOTE SPEAKERS

Sir Alfred Cuschieri
University of Dundee, UK

Paras N. Prasad
SUNY at Buffalo, USA

Valery Tuchin
Saratov State Univ., RUSSIA

Organization and implementation of a new conference at Photonics West

The scientific and industrial importance of the research performed in the FAST-DOT project was highlighted by the successful implementation of a new conference at Photonics West, January 21-26, 2011 in San Francisco, USA. The conference LA116, which was initiated and organized by FAST-DOT member Ursula Keller, focused on current work in the rapidly developing field of optically and electrically pumped vertical external cavity surface emitting lasers (VECSELs). These lasers, which are also referred to as optically pumped semiconductor lasers (OPSLs) or semiconductor disk lasers (SDLs) have gained a strong interest for power scaling. In a VECSEL, the light is emitted perpendicular to the epitaxial layers, unlike edge-emitting lasers, where the beam propagates in the epitaxial layers. In contrast to a VCSEL (i.e. a vertical cavity surface emitting laser) the external cavity of the VECSEL offers additional mode control for excellent transverse beam quality even at highest power levels and enables the integration of elements for nonlinear intracavity frequency conversion, wavelength tuning elements or passive mode-locking. An extensive selection of tutorial and invited papers provided a comprehensive overview of the latest progress in this new field. In addition, many submitted papers treated various state-of-the-art technologies, such as:

- power scaling of VECSEL, OPS, SDL and MIXSEL
- heat management
- spectral coverage; material systems, quantum dots, epilayer design
- intracavity nonlinear frequency conversion
- epilayer growth challenges
- numerical modeling of gain, dynamical behavior, thermal behaviour
- optical in-barrier and in-well pumping
- electrical pumping
- mode-locked operation
- single frequency operation
- integrated extended cavities and wafer processing
- specific applications.

As the conference was a large success with high attendance, it will be again organized in the next year. Approximately 40% of the committee members are FAST-DOT partners, illustrating the high impact of our research. The link to next year’s conference: http://spie.org/LA116.

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