NEWSLETTER Y3a

"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.

CONTENTS

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 will be designed for use in microscopy and nano-surgery, where high-precision cutting, imaging and treatment therapies will be made possible. The project will use novel nano materials called quantum dots, and exploit 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.	University of Athens (NKUA)	Greece
18.	Molecular Machines and Industries GmbH (SME) (MMI)	Germany

Coordinator

Dr Edik Rafailov
University of Dundee
email: e.u.rafailov@dundee.ac.uk
phone: +44 1382 384 391
www.fast-dot.eu

Summary of the third year's highlights (first-half)

The activities during the first-half of the third year of the project were, devoted to the implementation of advanced laser systems using the already realized chips and their application to bio-imaging systems. In parallel, optimized devices have been designed. In this respect, significant progress has been made in the following areas:

- ***A record-breaking tunability and high-power CW operation and high peak power/pulse energy from external cavity InAs/GaAs quantum-dot diode laser has been achieved by the collaboration between the University of Dundee (UK) and Innolume GmbH (Germany).***
- ***3.6W peak-power from passively mode-locked tapered InAs/GaAs quantum-dot lasers.***
- ***Development of theoretical models, design and simulation of passively mode locked lasers with tapered gain sections (PoliTO).***
- ***Design of quantum dot amplifiers based on tapered gain sections.***
- ***Broadband emission from two-section Fabry-Perot quantum dot diode lasers.***
- ***Collaboration among FAST-DOT partners ICFO, ETHZ and M2 led to the generation of biomedical imaging using a VECSEL modelocked with a quantum dot SESAM.***
- ***ETHZ demonstrated a femtosecond VECSEL with up to 1-W average output power.***
- ***The collaboration of FAST-DOT partners ICFO and TOPTICA led to the demonstration of Third Harmonic Generation (THG) for the study of morphological evolution of living C. elegans.***
- ***TOPTICA Photonics has delivered the first two prototypes of broadly tuneable external cavity diode lasers (ECDL) to be used for biomedical applications like triplet oxygen detection.***

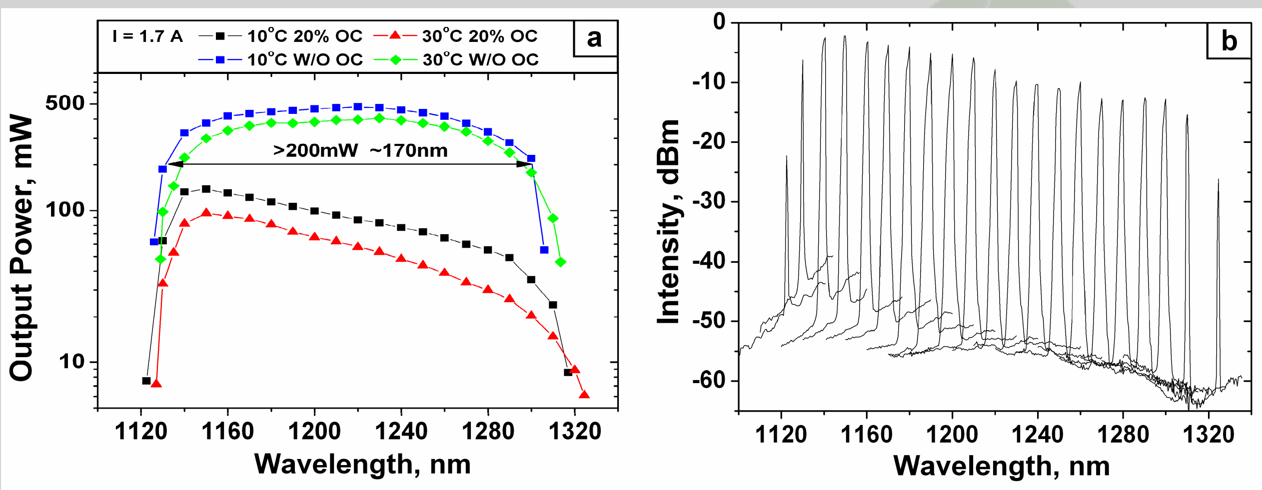
In conclusion, the project is proceeding according to the original schedule and, in the first-half of the third year, has already produced a number of novel and interesting results which have been published in ***10 journal publications, 15 international conference publications*** and ***1 book chapter***.

Mode-locked QD edge-emitting lasers and amplifiers

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 (UK) and Innolume GmbH (Germany). 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 [1].

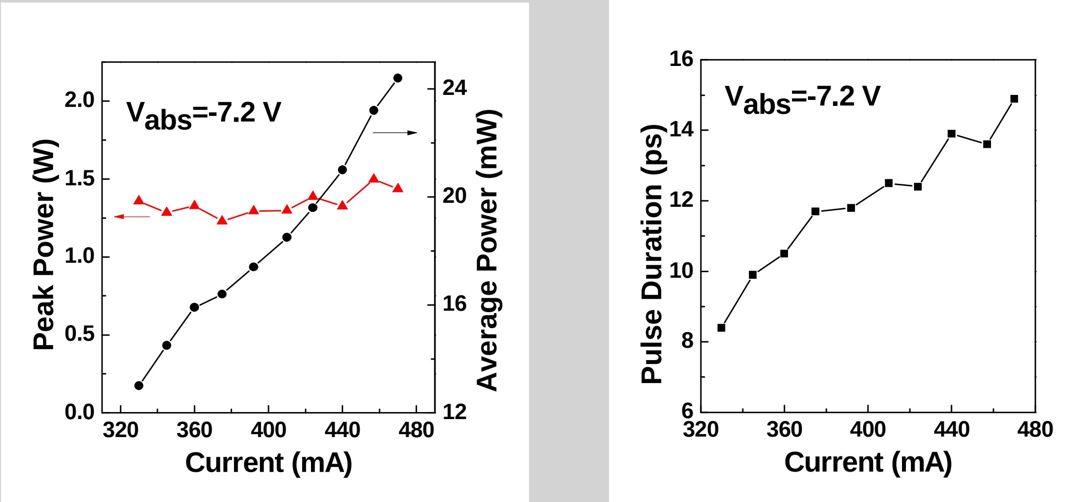
Such laser performance is poised to have an impact in biomedical applications such as optical coherence tomography, where there is a growing interest in the development of broadly-swept tunable laser sources due to their high spectral bandwidth and output power. Furthermore, the spectral region encompassing 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.

Ultrashort pulse generation with high peak power and pulse energy from a mode-locked external-cavity InAs/GaAs quantum-dot laser

A high-peak-power 1.27 µm quantum-dot external-cavity mode-locked laser has been demonstrated by the University of Dundee (UK) in collaboration with Innolume GmbH (Germany)[2]. Stable mode-locking with an average power up to 60 mW was obtained at a repetition frequency of 2.4 GHz. This performance corresponds to a 25 pJ pulse energy obtained directly from the oscillator, which represents a 55-fold increase in the pulse energy when compared to the current state-of-the-art for semiconductor lasers. At a repetition frequency of 1.14 GHz, picosecond optical pulses with 1.5-W peak power are also demonstrated, representing the highest peak power achieved from an external-cavity laser at the 1.3 µm waveband, without the use of any pulse compression or optical amplification.



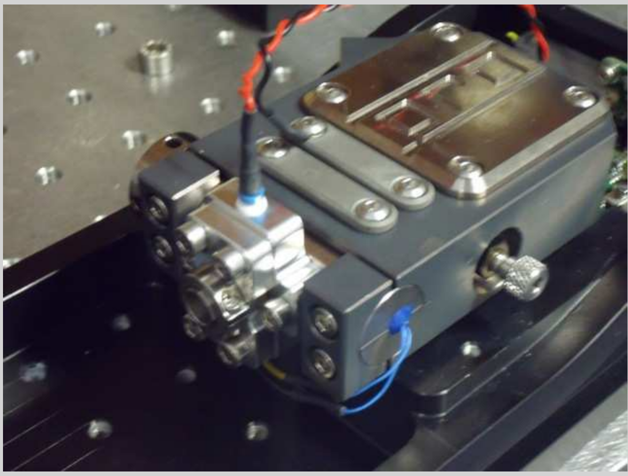
Peak power, average power (left) and pulse duration (right) versus forward current with a 7.2 V reverse bias applied to the saturable absorber of the external-cavity mode-locked quantum-dot laser.

---

[1] K. A. Fedorova et al., Optics Express 18, 19438-19443 (2010).
[2] Y. Ding et al., Electronics Letters 46, 1516-1518 (2010).

Two prototypes of broadly tuneable external cavity diode lasers have been delivered

TOPTICA Photonics has delivered the first two prototypes of broadly tuneable external cavity diode lasers (ECDL). Both lasers went to University of Dundee (UK) where they are used for biomedical applications like triplet oxygen detection.

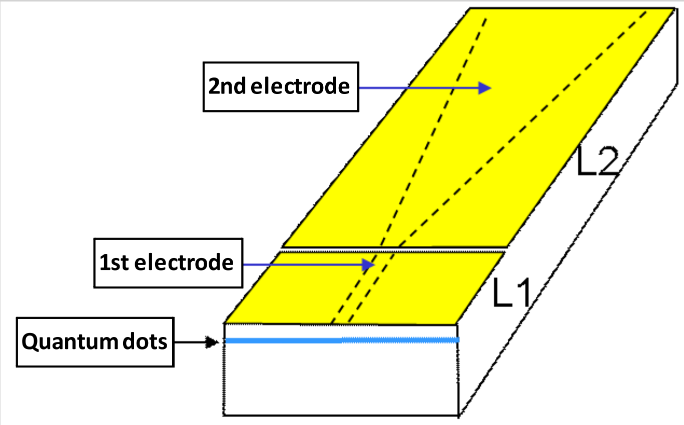


The laser systems are based on TOPTICA's well established "pro Technology" and employ a quantum dot based broad gain semiconductor gain chip supplied by Innolume. Output power is more than 300 mW in free beam and more than 150 mW in single mode fiber-coupled configuration. The lasers are continuously tuneable over more than 200nm in the 1200nm range.

Right now, TOPTICA is upgrading the system in order to operate it in a passive mode-locked mode. As already shown by other FastDot partners, this will allow the generation of widely tunable picosecond pulse trains with gigahertz repetition rates. High peak powers of those lasers facilitate nonlinear processes used for optical coherence tomography or second harmonic generation of visible light.

High-power passively mode-locked tapered InAs/GaAs quantum-dot lasers

A collaboration between Alcatel-Thales III-V Lab (France), University of Dundee (UK) and Innolume GmbH (Germany) has resulted in the demonstration[3] of picosecond pulse generation with high peak power in the range of 3.6 W from monolithic passively mode-locked tapered quantum-dot laser diodes, exhibiting low divergence and good beam quality. These results were achieved using a gain-guided tapered laser geometry, as shown in the figure below. Edge-emitting

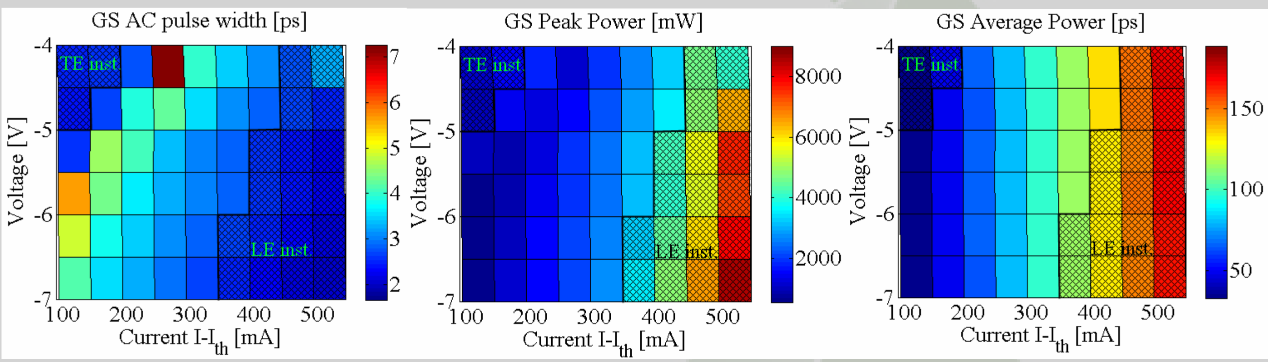


mode-locked semiconductor lasers with tapered waveguides are well-known for their capability to deliver high output power as well as ultrashort pulses. Tapered lasers typically consist of a straight ridge-waveguide section coupled to a tapered section (see schematic on the left). While the straight waveguide acts as a spatial filter in the cavity, the tapered section of increasing width delivers high power. As a result, tapered lasers show a great potential for providing single spatial mode, good quality beams with high power. The generation of picosecond pulses with high average power up to 209 mW directly from such tapered lasers was also demonstrated, corresponding to 14.2 pJ pulse energy (14.65 GHz repetition rate).

[3] D. I. Nikitichev et al. Applied Physics B (2010), http://www.springerlink.com/content/f12q8vk18465311p/

Simulation and design of passively mode locked lasers with tapered gain sections

POLITO proposed two different numerical models to accurately describe the QD gain and absorption dynamics in the gain and SA section of tapered devices. The models have been previously applied to the simulation of passive ML in QD straight lasers and performance comparisons have been carried out [4]. In the first model, the non-linear dynamics of the field within the laser cavity was computed via the finite-difference solution of one-dimensional time-domain travelling-wave equations [5]; the second approach was based on delayed differential equations (DDE) with improved features with respect to models available in the literature has been instead proposed [4]. POLITO team demonstrated that, with respect to standard DDE models, the newly proposed multi-section DDE model allows for a widely improved agreement with the finite difference travelling wave (FDTW) model when applied to the simulation of two section Fabry-Perot ML lasers. Furthermore, compared to the FDTW model, the proposed multi-section DDE model preserves an extremely small computational cost of the simulations.



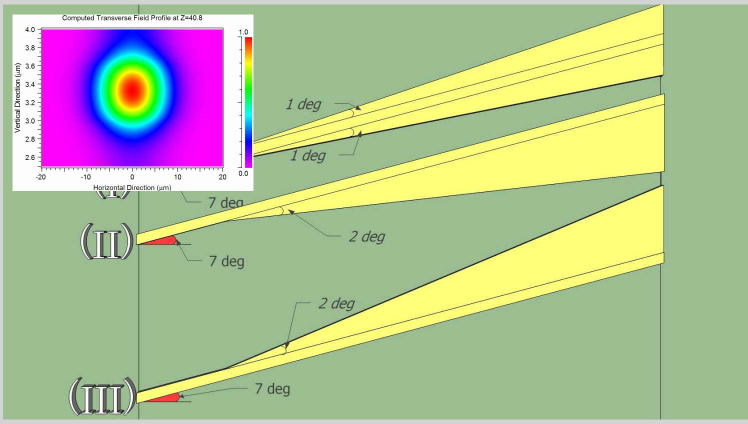
Simulation of mode-locking in a tapered gain guided QD ML laser with 4 mm total length, 800 µm straight saturable absorber section, tapered gain section with 2° full angle and active region consisting of 10 QD layers. Dashed regions highlight unstable ML due to either trailing edge instability (TE inst.) or leading edge instability (LE inst.)

Both the proposed models have been successfully applied to the simulation and design of tapered gain-guided QD ML lasers for high average and peak power ML operation. The dependence of the electromagnetic field on the transverse coordinates was eliminated by assuming a single transverse mode in the waveguide [4, 5]. This assumption is in general not strictly valid in devices with tapered waveguides. To accurately simulate such devices, two-dimensional (2D) numerical models would be in principle required, significantly increasing however the computational cost of the simulations and preventing their application on extensive parametric analyses of the ML regimes. To overcome this problem, POLITO team has proposed a simplified approach based on a 2D static beam-propagation method (BPM) to verify the adiabatic transformation of the amplified field in the cavity and to extract the propagation parameters to be used in the 1D dynamic QD ML laser models. With this approach, the evolution of the ML regimes as a function of the bias and structural parameters have been evaluated and the ML stability to noise perturbations has been studied (fig. above), providing useful insights for the design of optimized devices that have been successfully realized by ALCATEL-THALES and recently characterized at UNIDUN and TUD.

[4] M. Rossetti et al., IEEE Journal of Quantum Electronics, in press (2011)
[5] M. Rossetti et al., IEEE Journal of Quantum Electronics, 47, 2 (2011)

Design of quantum dot amplifiers based on tapered gain sections

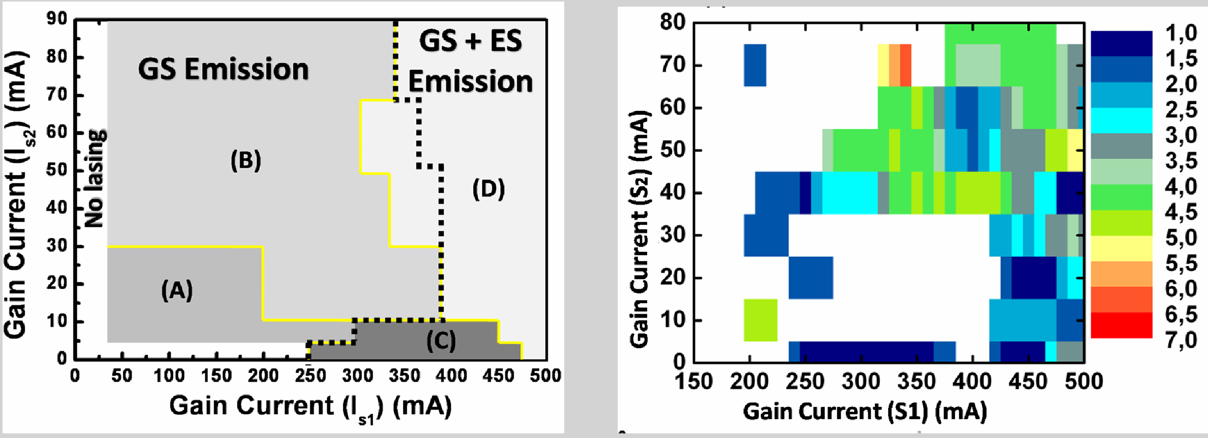
NKUA has been involved in the design of quantum dot semiconductor optical amplifiers (QD-SOAs) for amplification of short-pulses with high peak power. Several configurations regarding quantum dot amplifier structures were examined using state of the art simulation software for light propagation in optical media. Various design aspects were taken into careful consideration such as tolerance in input misalignment and spot size variations, saturation of the propagating field, maintenance of single mode operation, sufficiently high gain and excellent far field behaviour in terms of a small output field size. By twisting various design parameters such as the shape of the SOA, angles and width of different sections, a small set of optimized structures has been proposed which maximizes the gain/beam quality factor thus ensuring from the simulation point of view an optimal coupling into an optical fiber.



Broadband emission from two-section Fabry-Perot quantum dot diode lasers

NKUA has recently carried out an experimental study on the intrinsic instabilities of a two electrode InAs/InGaAs Fabry-Perot quantum dot laser in the absence of optical feedback [6]. By individually controlling the current injected in each electrode, regimes of operation with different dynamics were observed (see left figure below) including tunable self-sustained pulsations and coherence collapse resulting to possible chaotic emission. The origin of these effects does not resign in the presence of optical feedback but are associated to the carrier dynamics of the quantum dot device. For certain biasing conditions, high complexity regimes of operation have been identified - though correlation dimension contour plot mapping of the time traces collected from the device - that indicate coherence collapse operation (right figure below).

[6] C. Mesaritakis et al., accepted for publication in Applied Physics Letters.

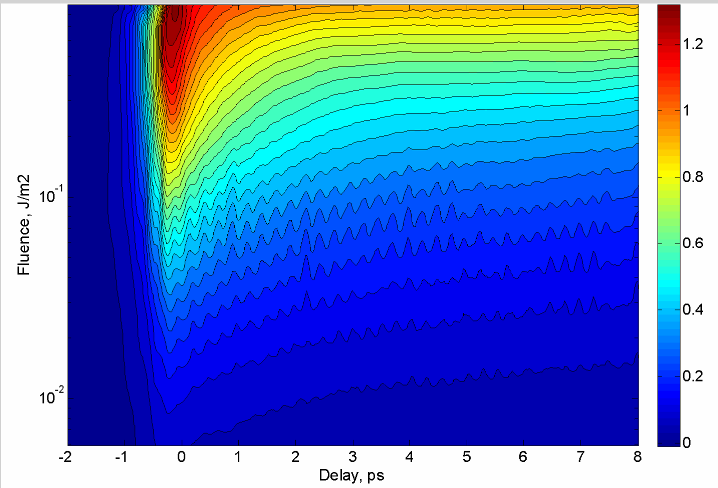


Left: Mapping of the different operational regimes versus the gain current at each section. The red dotted line corresponds to the threshold of ES lasing (A) corresponds to weak or no dynamics, (B) high frequency pulsations, (C) low frequency pulsations and (D) to broadband emission. Right: Contour plot mapping of correlation dimension of the laser's output vs. the current of the two gain section.

Mode-locked solid state and fiber lasers

Progress in quantum dot saturable absorption mirror (QDSAM) based fibre lasers

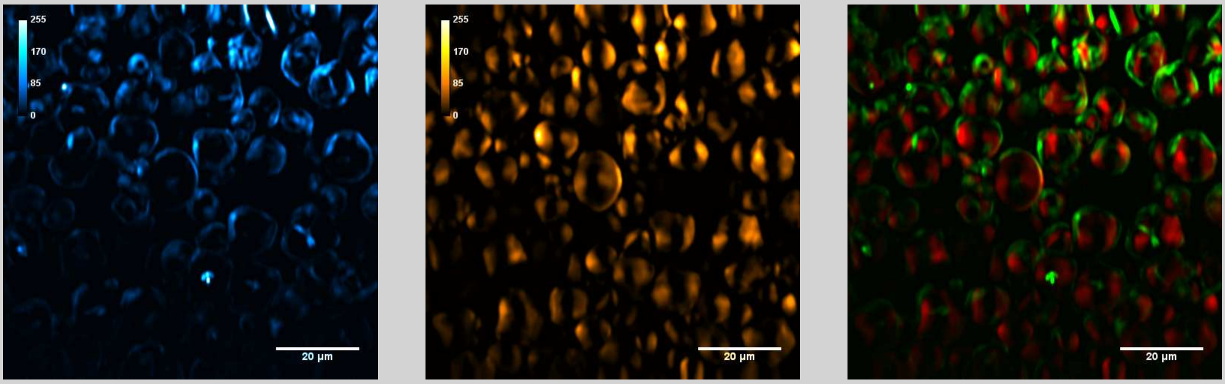
In parallel to the efforts on edge emitting devices, TOPTICA is working on quantum dot saturable absorption mirror (QDSAM) based fibre lasers. Ultrafast pump-probe measurements on various quantum dot based SAM structures have been performed characterizing nonlinear temporal response and saturation fluence. For an 80 layer InGaAs QD enhanced QDSAM structure, the graph displays the saturation of absorption at 1064 nm induced by a strong 200 fs long pump pulse at t = 0 and the subsequent relaxation and recombination of carriers on a ps-timescale.



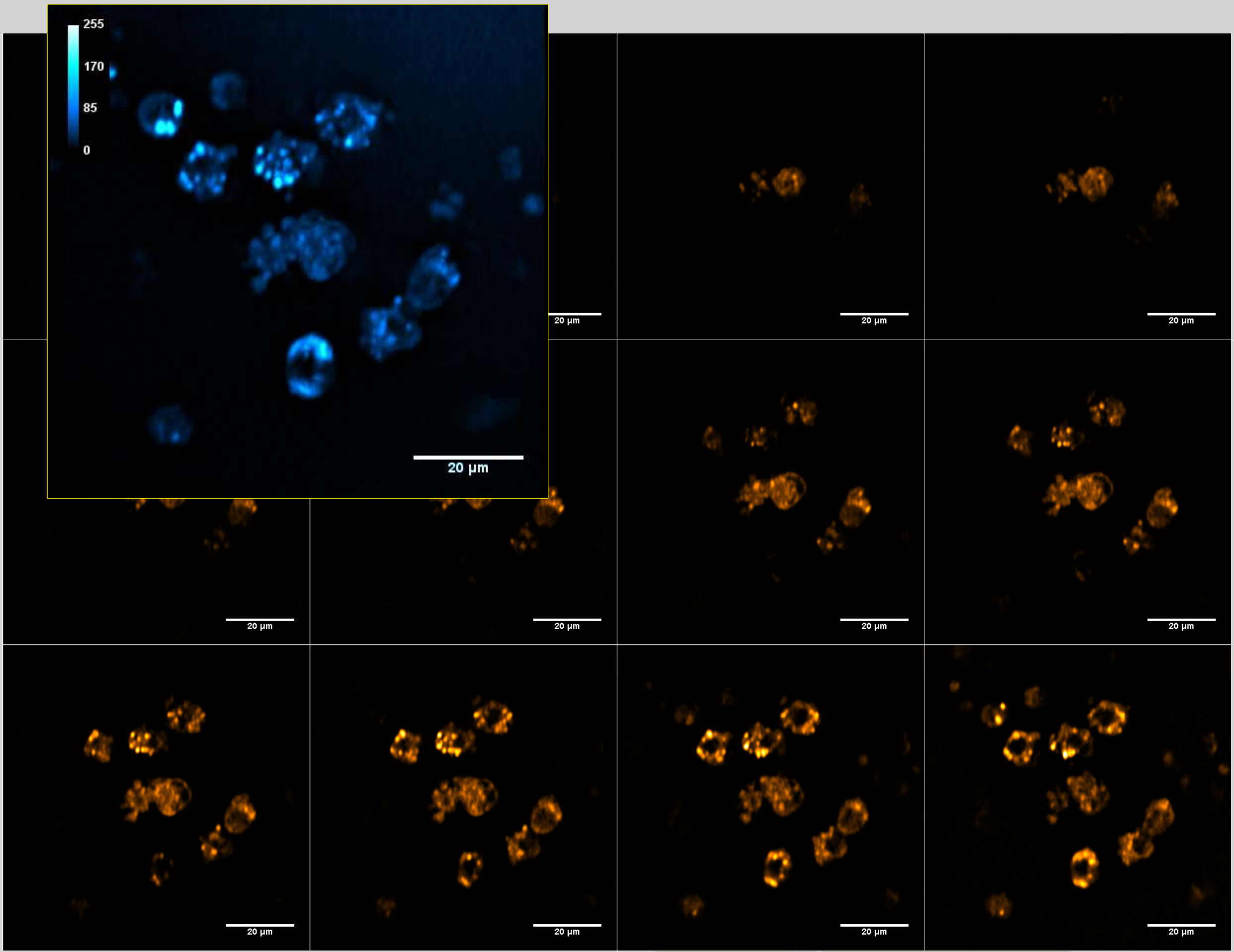
Right now, modulation depth is still too low to operate mode-locked fibre lasers with those devices.

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

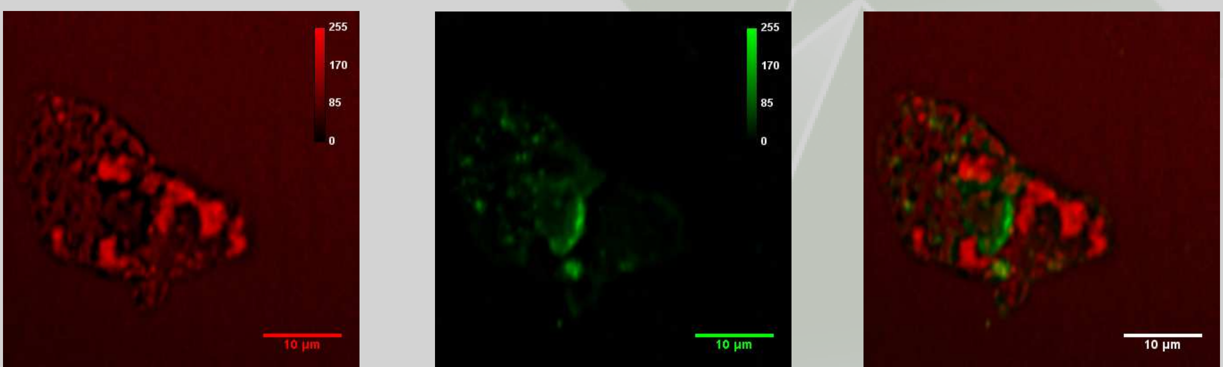
The FAST-DOT partner Time-Bandwidth Products has developed a laser for multiphoton imaging and cell surgery, both to be done with the same laser. The prototype Yb based solid state laser is built and tested with 83 MHz repetition rate, >2.5 W of average power and <200 fs pulse duration. The laser is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

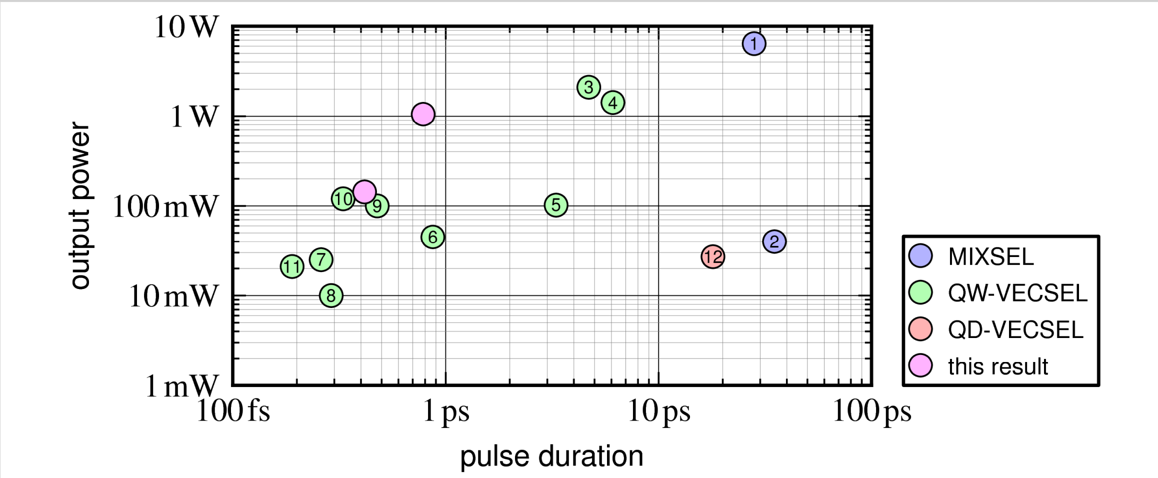


HeLa Cancer Cell (THG) – Gold Nanorods (TPL).
Left: THG, right: TPL, right: multimodal (Green: THG, Red: TLP)

Optically pumped VECSELs

1 W average power femtosecond VECSEL

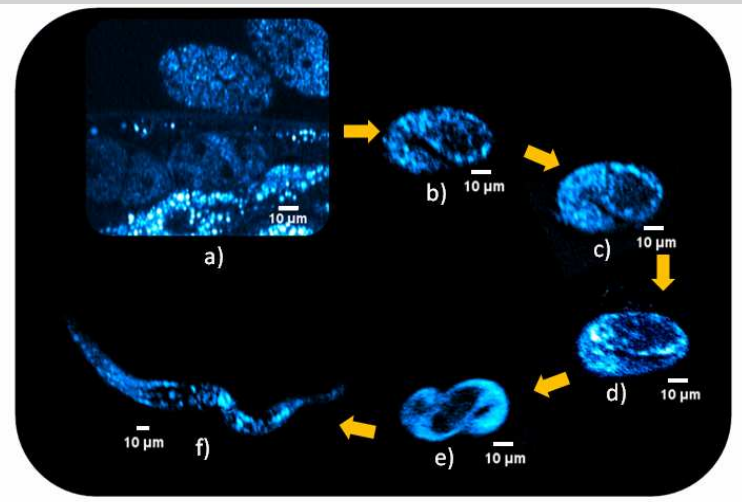
ETHZ demonstrated recently a femtosecond VECSELs with up to 1 W average output power (submitted to CLEO US). The new results are illustrated in the following graph. We achieved 1.05 W of average output power with pulses of 784 fs duration at a center wavelength of 970 nm. In another experiment we could also obtain 416 fs pulses at 143 mW of output power.



Overview of fundamentally SESAM modelocked optically pumped VECSELs.

Non-linear imaging applications

Third Harmonic Generation (THG) for the study of morphological evolution of living C. elegans embryos

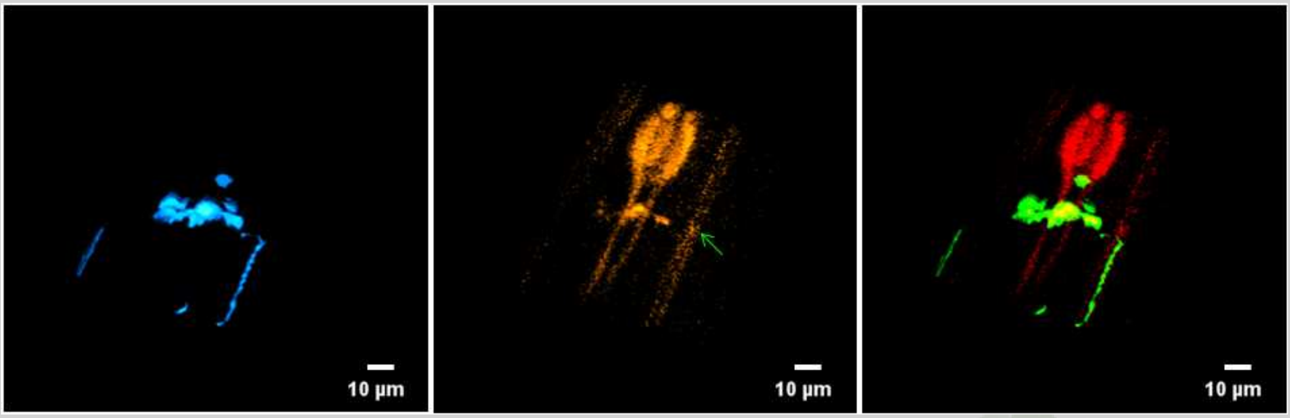


ICFO in collaboration with TOPTICA demonstrated Third Harmonic Generation (THG) for the study of morphological evolution of living C. elegans[7,8]. THG images of the C. elegans development cycle taken from several C. elegans embryos at different development stages are shown in the figure at the left. Case a, depicts in-utero and ex-utero embryos at cell division stage. Cases b-e depicts the coma, 1.5 fold, two fold and three fold stages of the imaged C. elegans embryos respectively. Case f depicts the L1 stage larva. The THG signal is depicted in blue.

[7] R. Aviles-Espinosa et al, Journal of Biomedical Optics, 15, 046020 (2010).
[8] R. Aviles-Espinosa et al, Proceedings in Biomedical Optics, paper. BTuD78 (2010).

The first Quantum Dot-based laser prototype was employed to obtain the first TPEF and SHG images from living samples at ICFO

The first Quantum Dot based system developed by M2 (in collaboration with ETHZ, Time-Bandwidth products) was tested at ICFO with the participation of M squared and FORTH, leading to the demonstration of the first Two-Photon Excited Fluorescence (TPEF) and Second Harmonic Generation (SHG) *in-vivo* C. *elegans* images. All results have been published in several conference papers and journals [9].



3D projections of TPEF signal from motoneurons expressing GFP (left panel blue signal) and signal of muscles in the pharyngeal region (central panel orange signal) of the C. elegans nematode. The right panel depicts the combined TPEF (Green) and SHG (red) images of both structures.

---

[9] R. Aviles-Espinosa et al, SPIE Photonics West Proceedings, San Francisco C.A (USA), Paper 7903-99 (2011)

Exploitation and dissemination activities

FAST-DOT partner wins prestigious fellowship

Dr. Bojan Resan from Time-Bandwidth Products is a recipient of the prestigious Marie Curie International Incoming Fellowship. The fellowship will support him to perform cutting-edge research and will enhance abilities of Time-Bandwidth Products to rapidly commercialize the newly developed technologies. He will continue to be involved in FAST-DOT project. As the Marie Curie project is well aligned with FAST-DOT interests, in Time-Bandwidth Products they are certain that the newly developed lasers and essentially the whole FAST-DOT consortium will also strongly benefit from this Fellowship.

FAST-DOT researcher awarded PhD

Benjamin Rudin graduated at ETHZ September 15th 2010, the title of his PhD thesis is "High-Power Optically Pumped VECSELs and MIXSELs".

FAST-DOT partners organized a new conference in SPIE Photonics West 2011

The FAST-DOT partner ETHZ organized the Conference LA116 on Vertical External Cavity Surface Emitting Lasers (VECSELs) at SPIE Photonics West. Professor Ursula Keller will be the conference chair. The final program is now online http://spie.org/LA116. Many Fast-Dot partners will participate. Details and the final program of Conference LA116 are given below:

Monday-Tuesday 24-25 January 2011
Proceedings of SPIE Vol. LA116
Vertical External Cavity Surface Emitting Lasers (VECSELs)
Conference Chair: Ursula Keller, ETH Zurich (Switzerland)
http://spie.org/LA116

FAST-DOT results in Light for Health event

The key results of THG FAST-DOT related work were presented to a broader public, during the lab tours at ICFO during the *Light for Health* event.