NEWSLETTER Y4a

"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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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 uses 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

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

The activities during the first-half of the fourth 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:

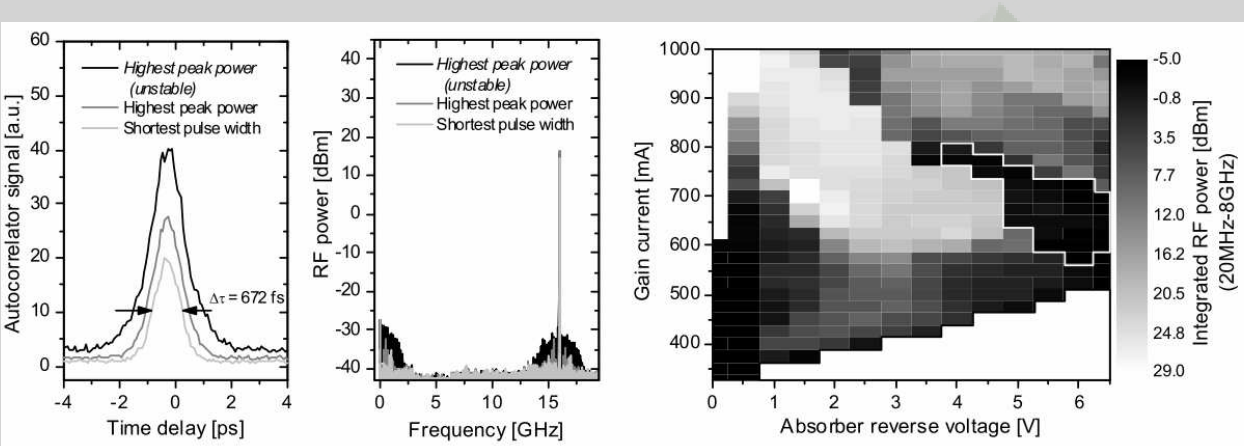
- ***Realization and measurements of monolithic two-section passively mode-locked gain-guided tapered quantum-dot lasers.***
- ***Dual-pulse generation from monolithic two-section passively mode-locked quantum-dot edge emitting lasers***
- ***Realization of electrically-pumped Vertical External Cavity Surface Emitting Lasers for passive mode-locking.***
- ***Realization of a femtosecond repetition-rate tunable optically-pumped VECSEL.***
- ***Full gain characterization of optically pumped VECSELs***
- ***Low timing jitter of a free-running SESAM mode-locked VECSEL***
- ***Demonstration of a high repetition rate Ti:Sapphire laser mode-locked by InP Quantum-Dot saturable absorber***
- ***10 GHz Pulse Repetition Rate ERGO Laser Modelocked by a 1550 nm InAs/GaAs Quantum-Dot SESAM***
- ***Study of the pre-implantation embryo patterning based on Third Harmonic Generation (THG) using a femtosecond t-pulse laser.***
- ***Near-infrared tunable 30-fs system with optional multi-spectral output for multi-photon microscopy***

In conclusion, the project is proceeding according to the original schedule and, in the fourth year, has produced a number of novel and interesting results which have been published in ***6 journal publications*** and ***7 international conference publications***.

Mode-locked QD edge-emitting lasers and amplifiers

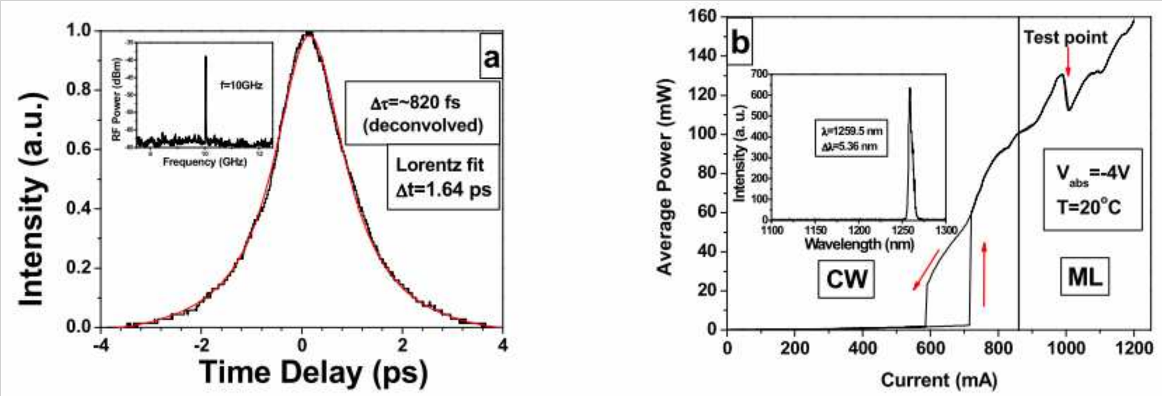
High power and sub-ps passively mode-locked monolithic two-section gain-guided tapered quantum-dot lasers

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. Recently they have demonstrated two major achievements [1, 2].
The partners have demonstrated sub-picosecond Fourier-limited pulse generation from a new gain guided tapered laser structure with a pulse width of 672 fs and a pulse peak power of 3.40 W [1]. The active region of the laser structure consists of 10 InGaAs QD layers separated by GaAs barriers integrated in a GaAs waveguide. Gain guiding is achieved by ion implantation. The tapered section is 2.1 mm long, has a taper angle of 2°, the straight absorber section is 0.4 mm long and the absorber-to-gain length ratio amounts to 0.19. The laser emits at a wavelength of 1260 nm and is operated by driving the gain section with a current source and the absorber section with a voltage source. In another operating condition, the partners measured the highest peak power of 4.65 W with a pulse width of 785 fs, and a time-bandwidth-product of 0.45 and an average power of 66 mW in stable mode-locked operation [1].



Autocorrelator signal for three specified key operation conditions (left), RF signal for three specified key operation conditions (middle) and integrated RF power (20MHz – 8GHz) in dependence of gain current and absorber voltage, the white frame indicates the stable mode-locking regime (right) .

The second major achievement is the demonstration of the highest peak power of 15 W directly from a monolithic quantum-dot tapered laser, with sub-picosecond pulse width [2]. 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^{o}), 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, thus corresponding to a repetition rate of 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 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 [2].



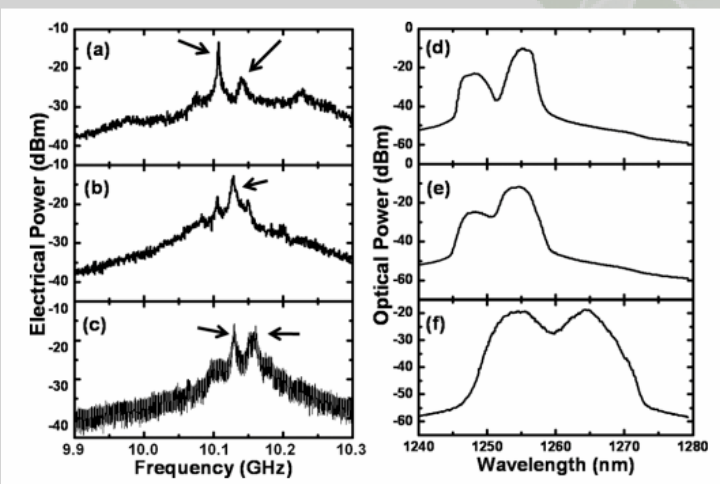
a) Autocorrelation for an injection current of 1A and reverse bias -4V for sub-ps regime; inset: Corresponding RF spectrum b) Light-current characteristic at 20 °C for reverse bias of -4V inset: Optical spectrum for I=1A and V=-4V.

[1] L. Drzewietzki, M. Ruiz, S. Breuer, M. Tran, Y. Robert, M. Rossetti, T. Xu, P. Bardella, W. Elsäßer, M. Krakowski, I. Montrosset, I. Krestnikov, "Passively mode-locked monolithic two-section gain-guided tapered quantum-dot lasers: I. Ultrashort and stable pulse generation", CLEO EUROPE/EQEC 2011.

[2] D. I. Nikitichev, M. Ruiz, Y. Ding, M. Tran, Y. Robert, M. Krakowski, M. Rossetti, P. Bardella, I. Montrosset, I. Krestnikov, D. Livshits, M. A. Cataluna and E. U. Rafailov, "Passively mode-locked monolithic two-section gain-guided tapered quantum-dot lasers: II. Record 15 Watt peak power generation", CLEO EUROPE/EQEC 2011.

Dual pulse generation from passively monolithic two-section mode-locked quantum-dot lasers

FAST-DOT partners NKUA and INNOLUME have demonstrated the generation of dual pulses from two independent ground state (GS) sub-bands in a multi section InAs/InGaAs passively mode-locked quantum dot laser. The emission of these sub-bands is related to gain suppression at the center of the ground state emission, whereas their wavelength separation is tunable with injection current. The two independent pulses were obtained, with typical pulse width of ~17 ps. The two GS sub-bands exhibited wavelength tunability in the range of 2-14 nm variation of the bias conditions. The tunability and the dual pulse generation can be combined in order to create through photo-mixing a cost-effective pulsed terahertz source with frequency ranging from 350 GHz to 2.6 THz. [3].

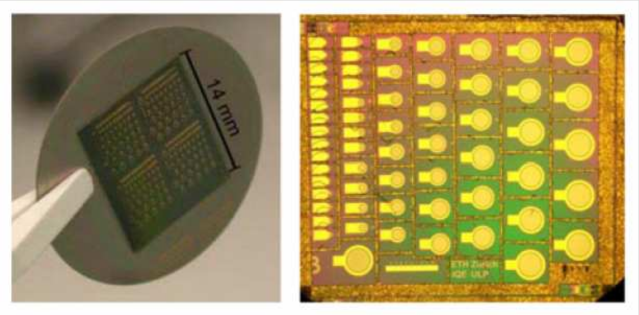


(a)-(c) Electrical spectra for (a): V_{abs} = -1 V and I = 225 mA, (b): V_{abs} = -2 V and I = 225 mA, and (c): V_{abs} = -3.5 V and I = 281 mA. (d)-(f) The corresponding optical spectra.

[3] Charis Mesaritakis, Christos Simos, Hercules Simos, Igor Krestnikov and Dimitris Syvridis, "Dual ground-state pulse generation from a passively mode-locked InAs/InGaAs quantum dot laser", Applied Physics Letters, vol. 99, 141109, 2011.

Electrically pumped VECSELs

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

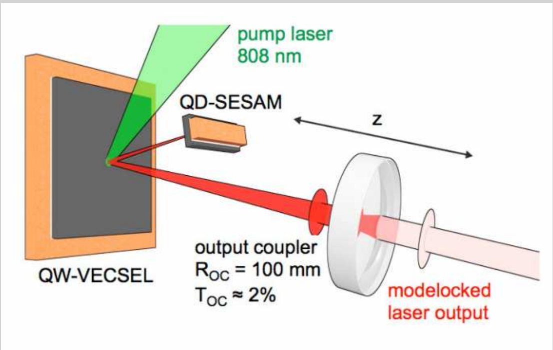


Modelocked optically pumped vertical external cavity surface emitting lasers (VECSELs) have generated up to 6.4-W average power, which is higher than for any other semiconductor lasers. Electrical pumping of mode-locked VECSELs is the next step toward a higher level of integration. With continuous wave (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 [4]. 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.

[4] Yohan Barbarin, Martin Hoffmann, Wolfgang P. Pallmann, Imad Dahhan, Philipp Kreuter, Michael Miller, Johannes Baier, Holger Moench, Matthias Golling, Thomas Sudmeyer, Bernd Witzigmann, and Ursula Keller, "Electrically Pumped Vertical External Cavity Surface Emitting Lasers Suitable for Passive Modelocking", IEEE Journal of Selected Topics in Quantum Electronics, vol. 17 (6), pp. 1997-1786 (2011)

Optically pumped VECSELs

Femtosecond VECSEL with tunable multi-gigahertz repetition rate

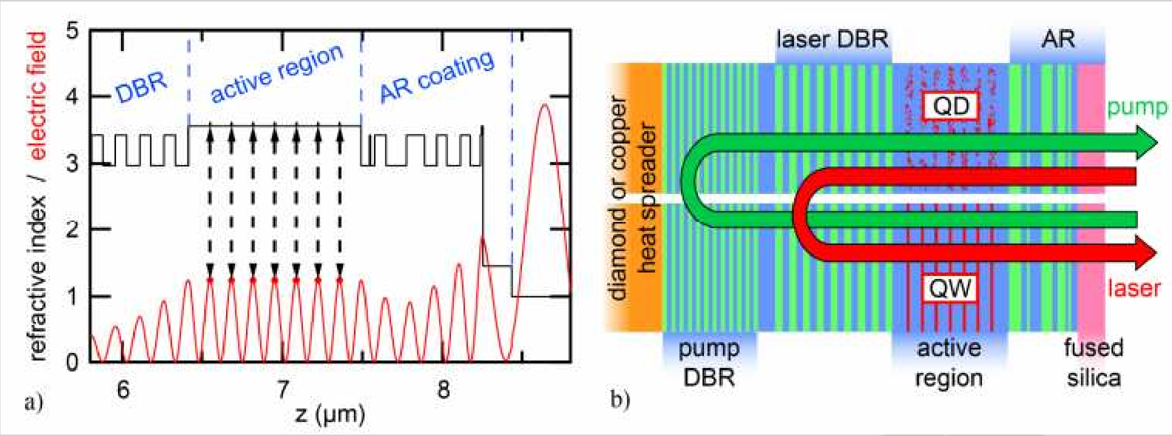


FAST-DOT partner ETH demonstrated a femtosecond vertical external cavity surface emitting laser (VECSEL) that is continuously tunable in repetition rate from 6.5 GHz up to 11.3 GHz [5]. The use of a low-saturation fluence semiconductor saturable absorber mirror (SESAM) enables stable cw modelocking with a simple cavity design, for which the laser mode area on SESAM and VECSEL are similar and do not significantly change for a variation in cavity length. Without any realignment of the cavity for the full tuning range, the pulse duration remained nearly constant around 625 fs with less than 3.5% standard deviation. The center wavelength only changed ±0.2 nm around 963.8 nm, while the output power was 169 mW with less than 6% standard deviation. Such a tunable repetition rate is interesting for various metrology applications such as optical sampling by laser cavity tuning (OSCAT).

[5] Oliver D. Sieber, Valentin J. Wittwer, Mario Mangold, Martin Hoffmann, Matthias Golling, Thomas Südmeyer, and Ursula Keller, "Femtosecond VECSEL with tunable multi-gigahertz repetition rate", Optics Express, vol. 19 (23), pp. 23538-23543 (2011).

VECSEL gain characterization

FAST-DOT partner ETH reported the first full gain characterization of two vertical external cavity surface emitting laser (VECSEL) gain chips with similar designs operating in the 960-nm wavelength regime[6]. The structures are optically pumped with continuous-wave (cw) 808-nm radiation and the nonlinear reflectivity for 130-fs and 1.4-ps probe pulses are measured as function of probe pulse fluence, pump power, and heat sink temperature. With this technique the saturation behavior for VECSEL gain chips are measured for the first time. The characterization



with 1.4-ps pulses resulted in saturation fluences of 40-80 µJ/cm^2, while probing with 130-fs pulses yields reduced saturation fluences of 30-50 µJ/cm^2 for both structures. For both pulse durations this is lower than previously assumed. A small-signal gain of up to 5% is obtained with this technique. Furthermore, in a second measurement setup, the spectral dependence of the gain is characterized using a tunable cw probe beam. A gain bandwidth of over 26 nm for both structures is measured.

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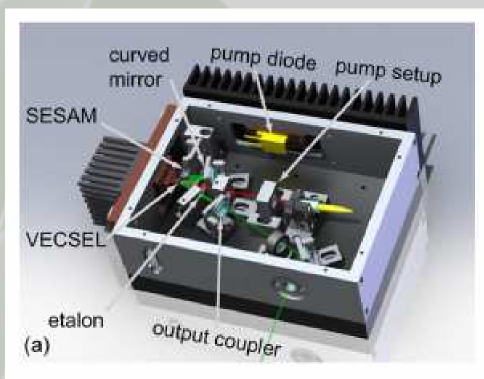
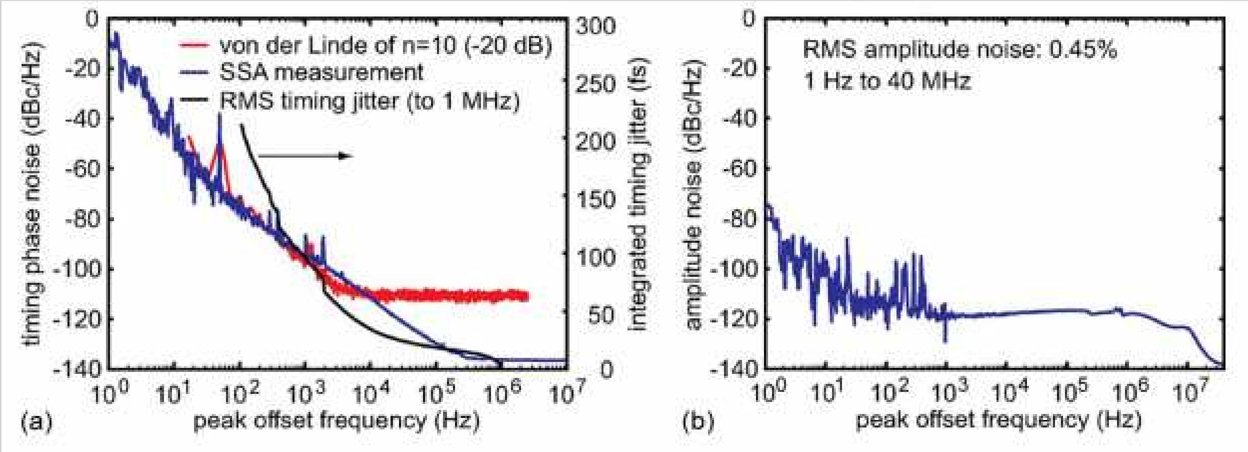
[6] Mario Mangold, Valentin J. Wittwer, Oliver D. Sieber, Martin Hoffmann, Igor L. Krestnikov, Daniil A. Livshits, Matthias Golling, Thomas Südmeyer, and Ursula Keller, "VECSEL gain characterization", Optics Express, vol. 20 (4), pp. 4136-4148 (2012).

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

FAST-DOT partner ETH 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 [7]. 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.





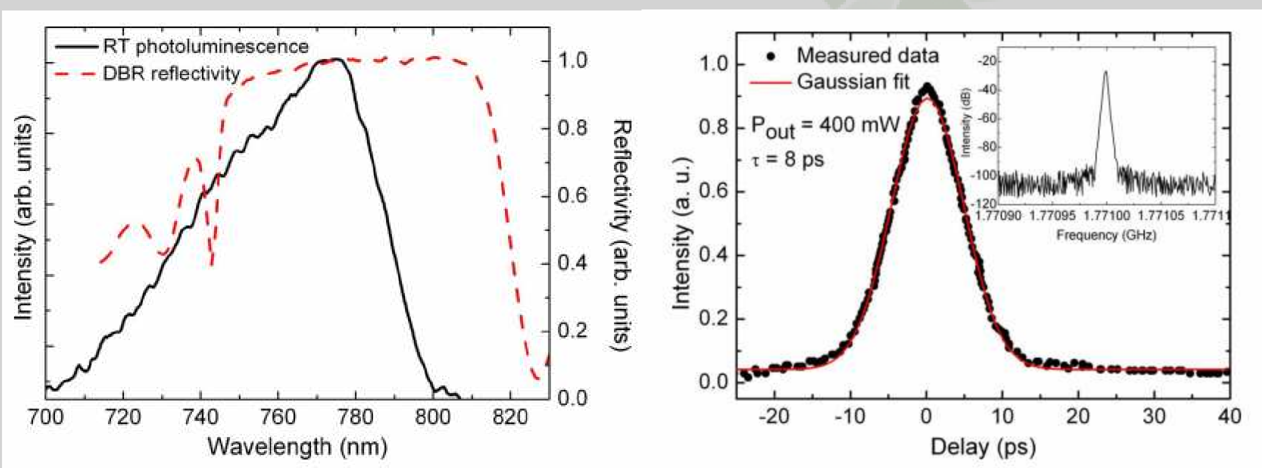
Noise characterization. (a) Two-sided power density of the phase noise (dBc/Hz) and integrated timing jitter (fs) integrated from f_{low} to f_{high} = 1 MHz as a function of f_{low} and (b) amplitude noise with an integrated RMS amplitude noise of 0.45% in [1 Hz, 40 MHz].

[7] V. J. Wittwer, C. A. Zaugg, W. P. Pallmann, A. E. H. Oehler, B. Rudin, M. Hoffmann, M. Golling, Y. Barbarin, T. Sudmeyer, and U. Keller, "Timing Jitter Characterization of a Free-Running SESAM Mode-locked VECSEL", IEEE Photonics Journal, vol. 3 (4), pp. 658-664 (2011).

Ti:Sapphire mode-locked laser

Demonstration of a high repetition rate Ti:Sapphire laser mode-locked by InP Quantum-Dot saturable absorber

FAST-DOT partners UNIVDUN, M2, USFD reported the first demonstration of a Ti:sapphire laser mode-locked with a quantum-dot mode-locker (QDM) at repetition rates up to 1.77 GHz with 8-ps pulse duration and 400-mW average output power [8]. So far, with quantum-well-based mode-lockers, a repetition rate of only up to 300 MHz has been achievable in our experiments. The QDM can support mode-locking in a wide range of repetition rates from 100 MHz to 1.8 GHz.



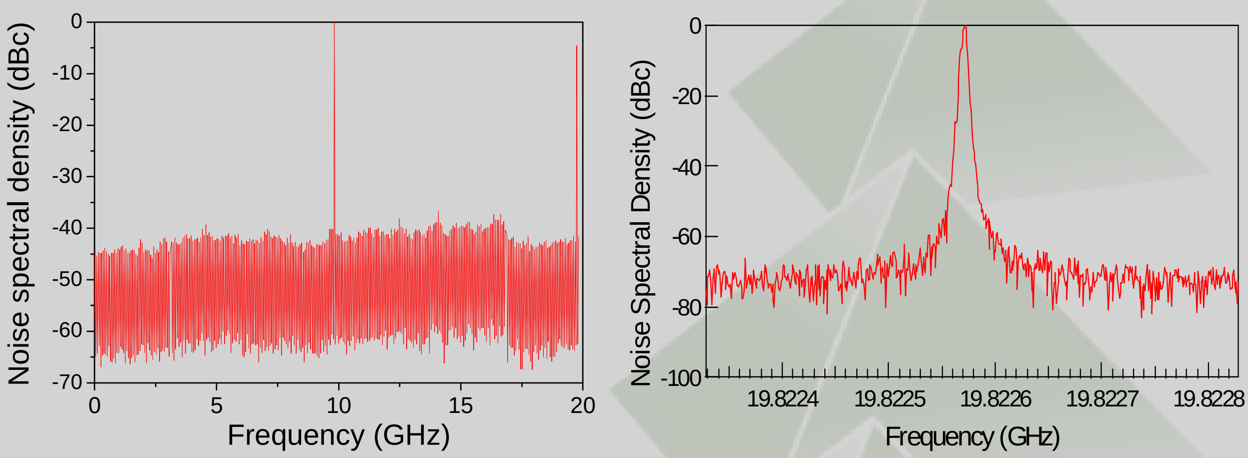
Left: RT photoluminescence spectrum of the active part of QDMs and measured reflectivity spectrum of DBR. Right: Autocorrelation signal of the mode-locked laser at X fold cavity configuration. Inset shows RF Spectrum of the mode-locked laser at Z-shape cavity configuration.

[8] Mantas Butkus, Gordon Robertson, Gareth Maker, Graeme Malcolm, Craig Hamilton, A. B. Krysa, B. J. Stevens, Richard A. Hogg, Yang Qiu, Thomas Walther, and Edik U. Rafailov, "High Repetition Rate Ti:Sapphire Laser Mode-Locked by InP Quantum-Dot Saturable Absorber", IEEE Photonics Technology Letters, vol. 23 (21), pp. 1603-1605 (2011)

High repetition laser for 1550 nm

10 GHz Pulse Repetition Rate ERGO Laser Modelocked by a 1550 nm InAs/GaAs Quantum-Dot SESAM

Solid-state lasers, fundamentally modelocked using semiconductor saturable absorber mirrors (SESAMs), typically exhibit low timing jitter, high pulse-to-pulse phase coherence, high pulse quality, and high individual optical spectral-mode signal to noise ratio (SNR). These features are particularly important, but very difficult to achieve at high repetition rates (10 GHz or more), which are necessary for ultrahigh speed transmission systems, optical clocking, multiwavelength sources, continuum generation and frequency metrology, to name a few. The ERGO (erbium-doped glass oscillator) laser systems have been field demonstrated to be an enabling technology for coherent optical communication systems with bandwidths of 10's of Tbit/s. In high pulse repetition rate lasers, QD technology promises to offer lower material saturation fluence combined with more design freedom than a QW based SESAMs.
FAST-DOT partners TBP, USFD and ETH demonstrated the first 10-GHz high repetition rate QD SESAM modelocked laser operating at 1550 nm [9]. The lower 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 higher repetition rate (e.g.>25 GHz) fundamentally modelocked lasers, highly desired in telecom and other applications.



RF spectrum of the output pulses from QD SESAM modelocked 10 GHz ERGO laser. Total span is 20 GHz (left) and 500 kHz (right). The laser is not locked to a reference signal.

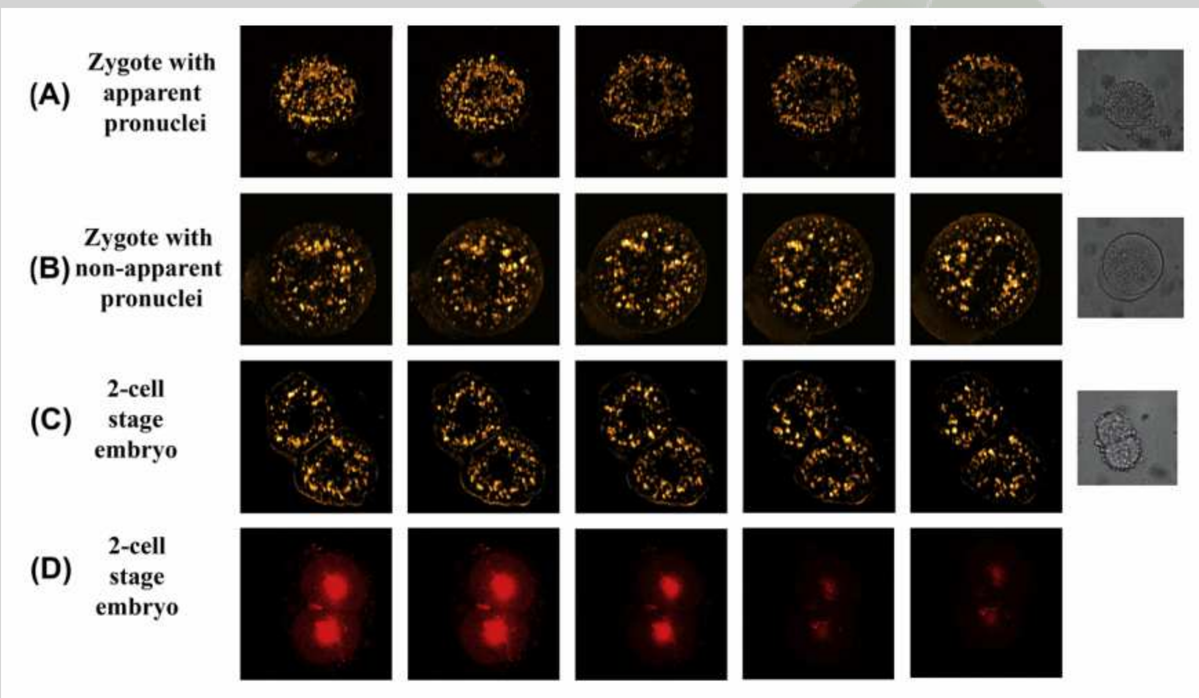
[9] Bojan Resan, Felix Brunner, Andreas Rohrbacher, Hubert Ammann, and Kurt J. Weingarten, "Low cost laser system generating 26 fs pulse duration, 30 kW peak power, and tunability from 800 to 1200 nm for multiphoton microscopy", Procceding of SPIE, Vol. 8226, 82262Y (2012).

Biomedical imaging

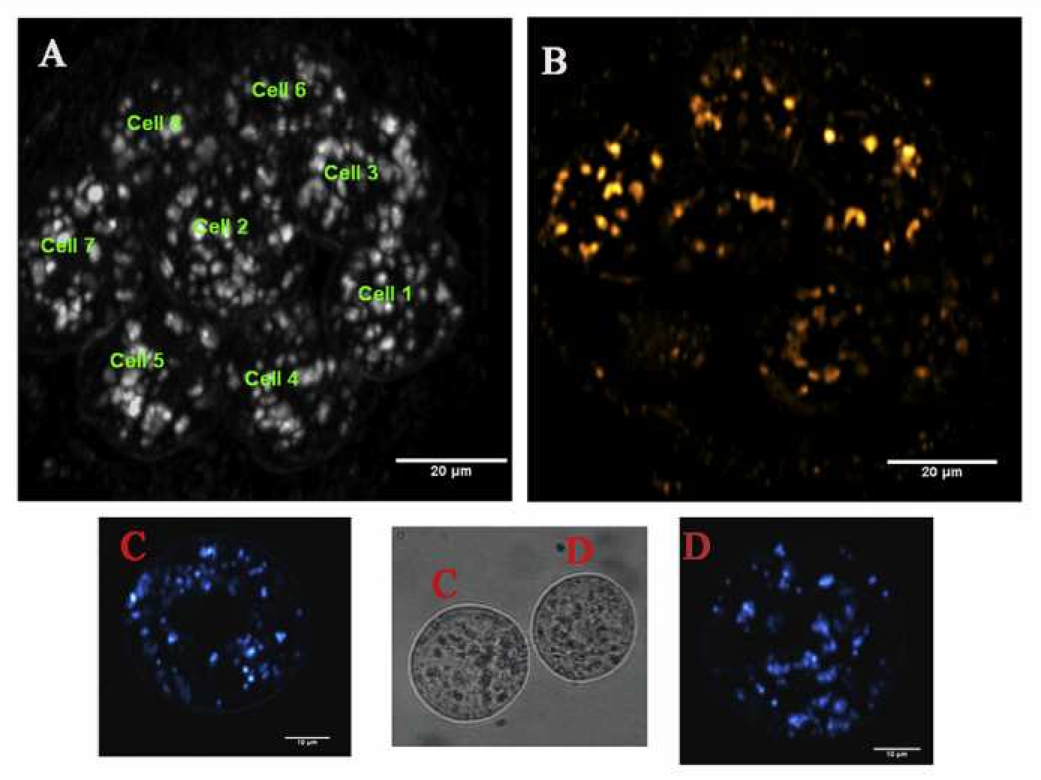
Study of the pre-implantation embryo patterning based on Third Harmonic Generation (THG) using a femtosecond t-pulse laser.

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 partners describe new methodologies to evaluate pre-implantation mouse embryo patterning [10]. 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.

[10] Christiana Kyvelidou, George J. Tserevelakis, George Filippidis, Anthi Ranella, Anastasia Kleovoulou, Costas Fotakis, Irene Athanassakis, "Following the course of pre-implantation embryo patterning by non-linear microscopy", Journal of Structural Biology, 176, pp. 379-386 (2011).



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.

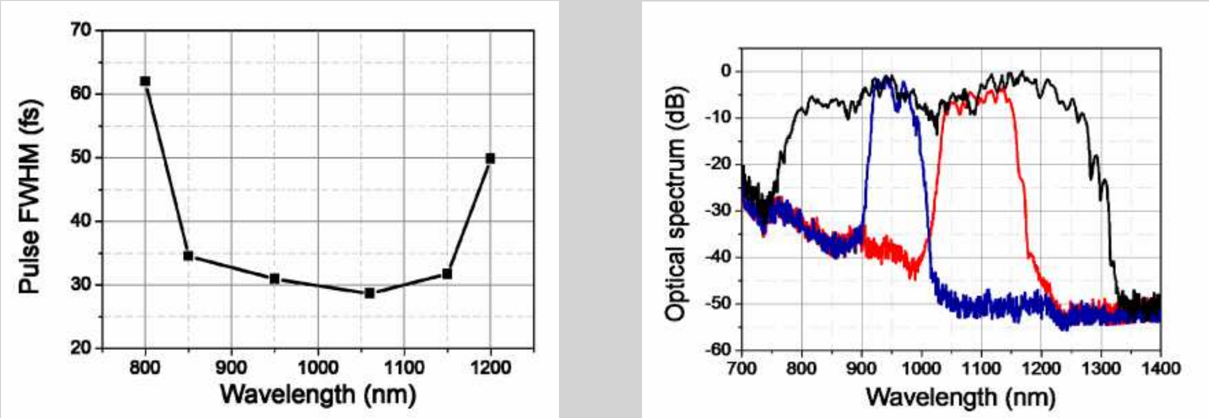


THG signal of blastomeres in 8-cell stage embryos with their zona pellucida (A: 3D reconstruction, B: central slice image) and in isolated blastomeres from 4-cell stage embryos (C and D). Signal quantification in blastomeres C and D (calculated as described in Section 3) reveals a 16% difference.

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 [11]. 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 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.

[11] Bojan Resan, Felix Brunner, Andreas Rohrbacher, Hubert Ammann, and Kurt J. Weingarten, "Low cost laser system generating 26 fs pulse duration, 30 kW peak power, and tunability from 800 to 1200 nm for multiphoton microscopy", Procceding of SPIE, Vol. 8226, 82262Y (2012).



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).

Exploitation and dissemination activities

Successful implementation of the 2nd FAST-DOT summer school

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