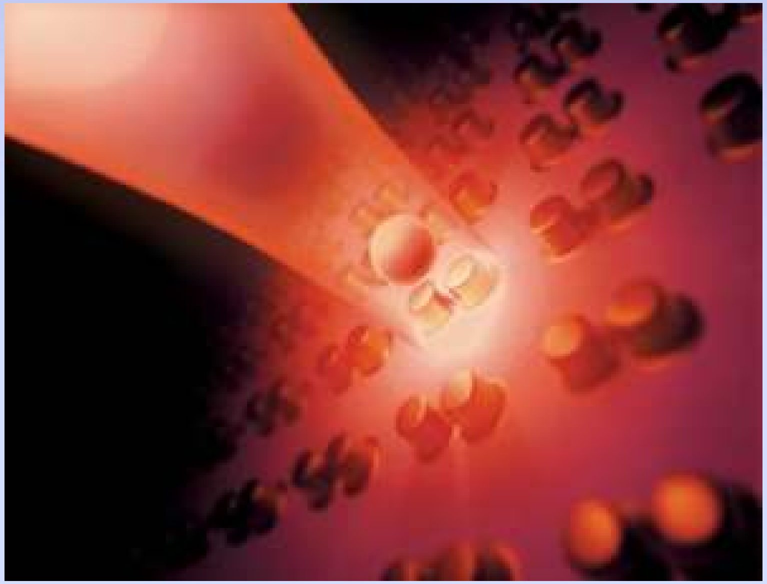
Fast Dot Project

COMPACT ULTRA**FAST** LASER SOURCES BASED ON NOVEL QUANTUM **DOT** STRUCTURES



Coordination : Dr. Edik Rafailov
Univ. of Dundee

Presentation : C. Mesaritakis
National and Kapodestrian Univ. of Athens

The FASTDOT project has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement no 224338

Presentation Overview

- **Project Overview**
  - Consortium
  - Main goal of the Fast-Dot project
  - Quantum Dot material (QD)
  - Expected impact of Fast-Dot
  - Fast-Dot Project Structure
- **First Year Highlights**
  - Edge emitting QD based lasers and SOAs
  - QD optically pumped vertical external cavity emitting lasers (OP-VECSELs)
  - Quantum well OP-VECSELs
  - ALL-QD based mode locked VECSELs
  - QW and QD SESAMs
- **Application in non-linear microscopy**

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Project Overview

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Academic and industrial Partners

Duration: June 2008 – 2012
Funding: **13.7**Million Euros (EU contribution **10.1M**)
Partners: 18

Academic Partners ⟷ Industrial Partners

1. University of Dundee (Coordinator)
2. University of Sheffield
3. ETH Zurich
4. Tampere University of Technology
5. KTH - Royal Institute of Technology, Stockholm
6. ICFO - Institut de Ciències Fotòniques, FUND. PRIV.
7. FORTH - The Foundation for Research and Technology Hellas
8. Vilnius University
9. Politecnico di Torino
10. University of Athens
11. Technical University of Darmstadt
12. Philips
13. Alcatel Thales III-V Lab
14. Innolume GmbH (SME)
15. M Squared Lasers Limited (SME)
16. TOPTICA Photonics AG (SME)
17. Time-Bandwidth Products AG (SME)
18. Molecular Machines and Industries GmbH (SME)

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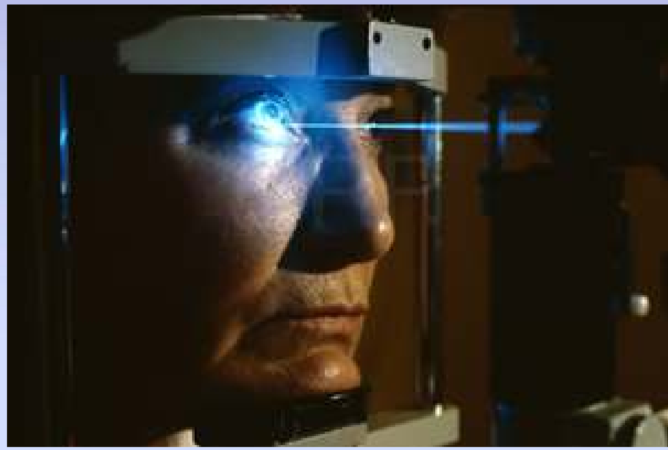
Main Goal of Fast Dot

- Revolutionize the use of lasers in the biomedical field providing both practitioners and researchers with:
  - *pocket sized lasers*
  - *ultra high performance lasers*
  - *at a substantially lower cost making their widespread use affordable*



- Applications focus on:
  - *Non-linear microscopy*
  - *Nanosurgery*
  - *Optical Coherent Tomography*
  - *Endoscopes*

By fabrication of ultra compact high efficient low cost lasers based on the unique properties of quantum dot materials

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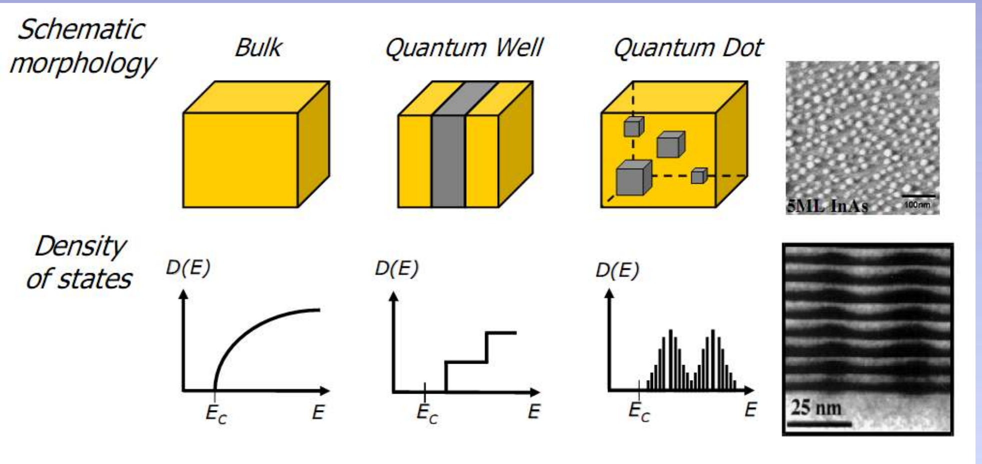
Advantages of Quantum Dots



Bulk, quantum well, and quantum dot schematic with the corresponding Energy density states

- Discrete energy states
- Temperature insensitivity
- Low threshold
- Ultra high optical bandwidth (inhomogeneous broadening)
- Ultra fast recovery times under both gain or absorption conditions

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Expected impact of FAST-DOT

- Enable widespread application and further development of laser based photonics
- Demonstrate new applications of lasers in biotechnology and medical fields
- Develop new industrially integrated design rules for the production of specific QD materials
- Unlock the potential of QD materials in bio-photonics
- Accelerate the implementation of QD lasers through European SMEs and companies
- Train a new generation of researchers in the range of new technological areas for QD devices

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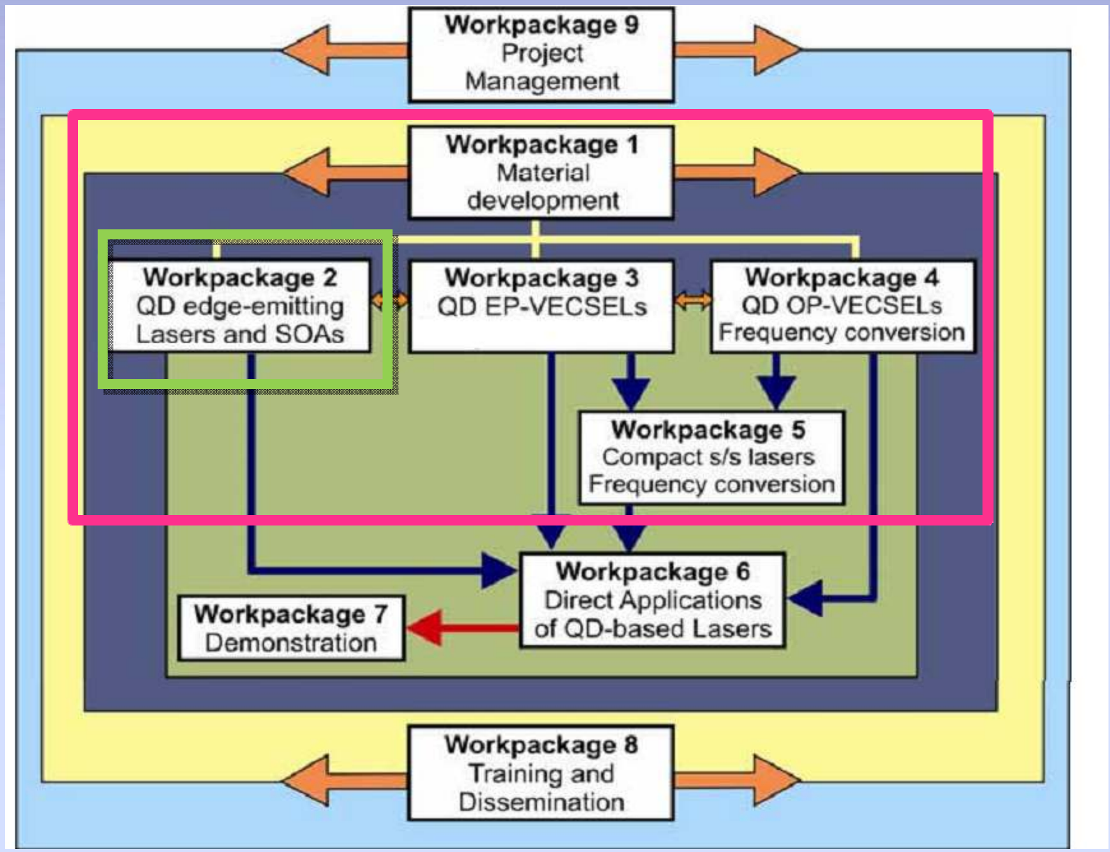
FAST-DOT Project structure



Fast-Dot project structure

➢Development of different QD materials and structures:

- *Edge emitting mode locked lasers and SOAs*
- *Electrically pumped mode locked VECSELs and SESAMs based on QD materials*
- *Ultra compact high power QD based optically pumped VECSELs*

➢Benchmark and test of QD lasers in biomedical applications

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First Year Highlights

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Major Achievements

- Detail theoretical/numerical models for the simulation of QD mode locked lasers
- Fabrication and evaluation of different QD materials and structures
- Identification of novel operating regimes for mode locked QD lasers
- Realization and evaluation of electrically pumped QD VECSELs
- Realization of highly efficient optically pumped QD VECSELs ($P_{average}$ > 4.3W)
- Realization of highly efficient optically pumped QD VECSELs ($P_{average}$ > 20W)
- First realization of QD mode locked VECSEL
- Non linear imaging of starch granules

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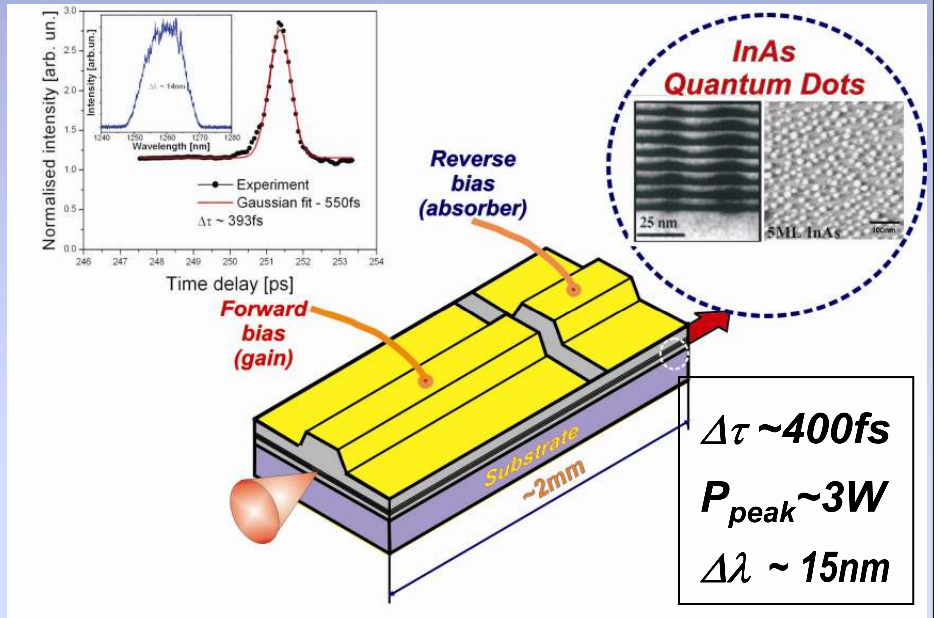
Ultrafast Edge emitting QD based lasers

ADVANTAGES:

- Broad gain bandwidth
- Ultrafast carrier dynamics
- Lower absorption saturation fluence
- Low threshold current
- Low temperature sensitivity
- Suppressed carrier diffusion



Typical schematic of a two section QD edge emitting mode locked laser with corresponding optical spectrum and autocorrelation trace

E. U. Rafailov, M. A. Cataluna *et al.,* Appl. Phys. Lett. 87, 081107 (2005)

E. U. Rafailov, M. A. Cataluna, *et al.*, Nature Photonics, v.1, p.395-401, 2007

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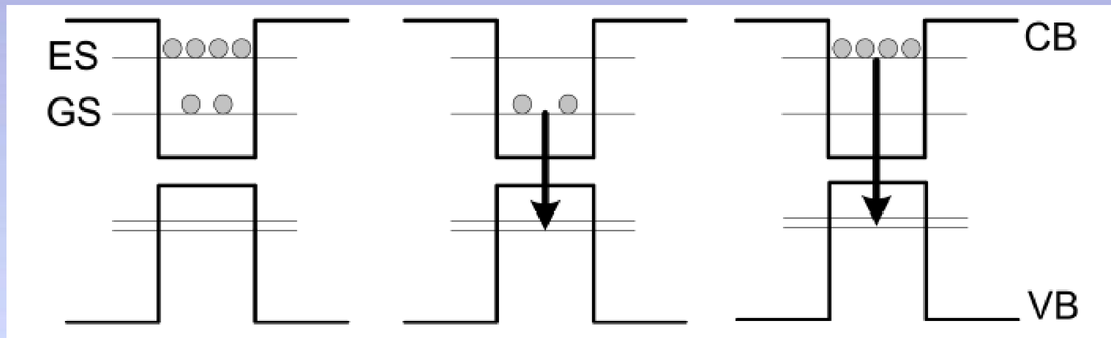
A new approach: using the excited state

Laser emission can occur via ground-state (GS) or excited-state (ES) transitions



Multi-wavelength ultrafast source – applications:

- non linear frequency conversion
- dual-wavelength microscopy modalities (e.g. CARS, STED)
- time-domain spectroscopy
- wavelength-division multiplexing
- ultrafast optical processing

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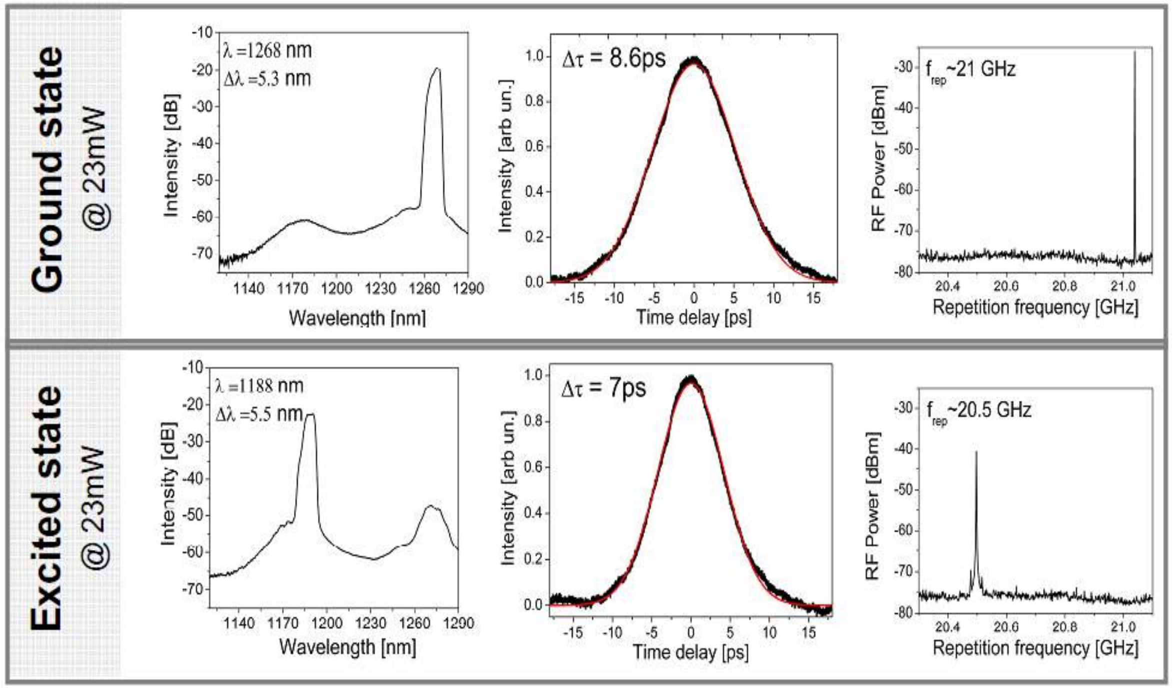
Mode Locking from GS or ES

- Similar output power (23mW) for GS and ES mode locking
- Different repetition rate due to different effective refractive index of GS and ES.
- Narrower pulses from the ES



M. A. Cataluna *et al.*, *Appl. Phys. Lett.* 89, 081124 (2006)

Optical spectrum, autocorrelation trace, and RF spectrum for GS and ES mode locking

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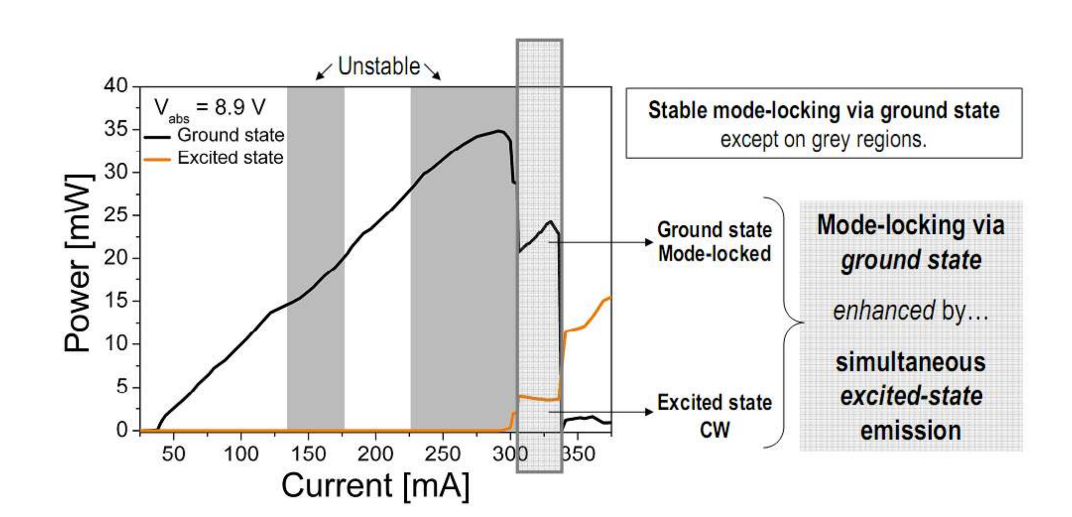
Mode locking in the GS under CW emission from ES

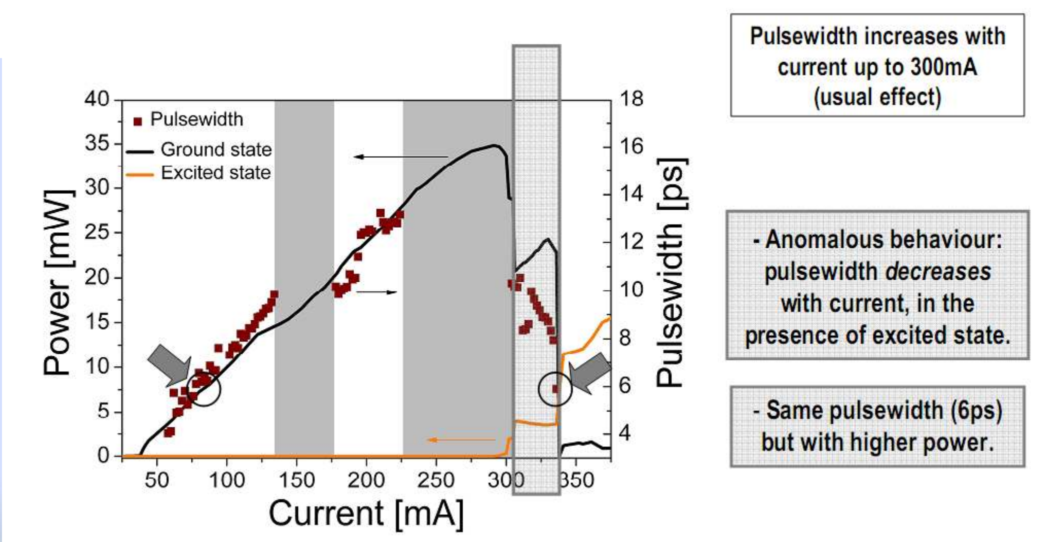


Emitted power versus gain current for GS and ES wavelength

The existence of ES CW affects GS mode locking

- Reduced pulse width with current
- Same pulse width with increased optical power

Emitted power and pulse width versus gain current for GS and ES wavelength



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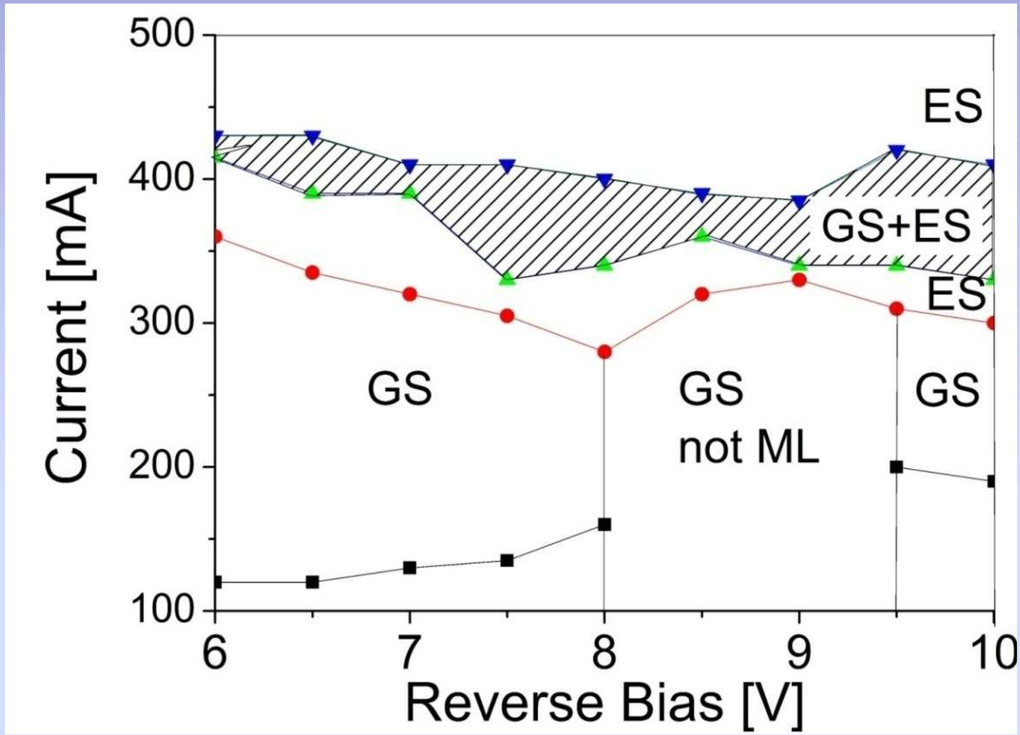
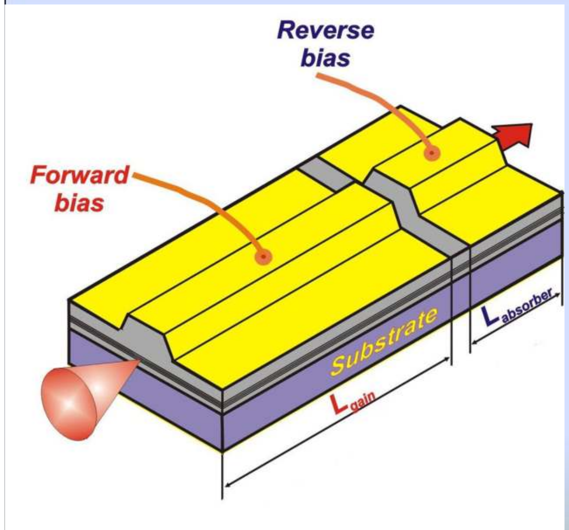
Dual-wavelength mode-locking

Two-section QD laser

- 2mm length, 300μm absorber
- 5 layers InAs QDs
- T=20ºC
- Facets AR/HR coated



Mapping of mode locking regions for different current and voltage bias



M.A. Cataluna, D. Nikitichev, I. Krestnikov, D.A. Livshits, A.R. Kovsh, E. U. Rafailov, "Dual wavelength mode-locked GaAs-based quantum-dot laser", *CLEO Europe 2009*, CB4.6.

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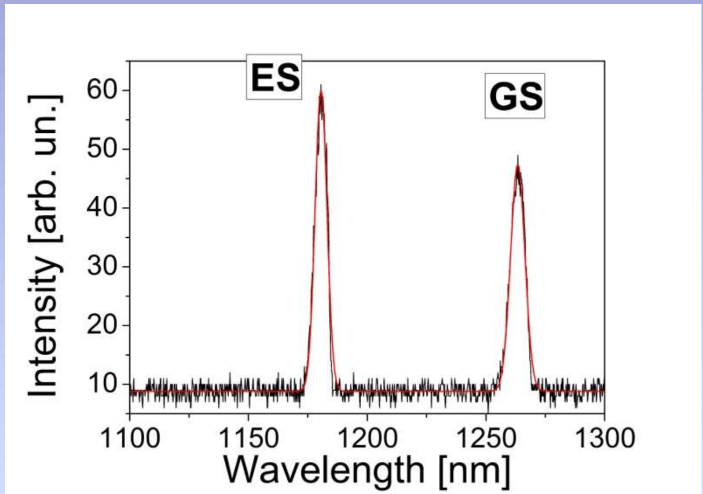
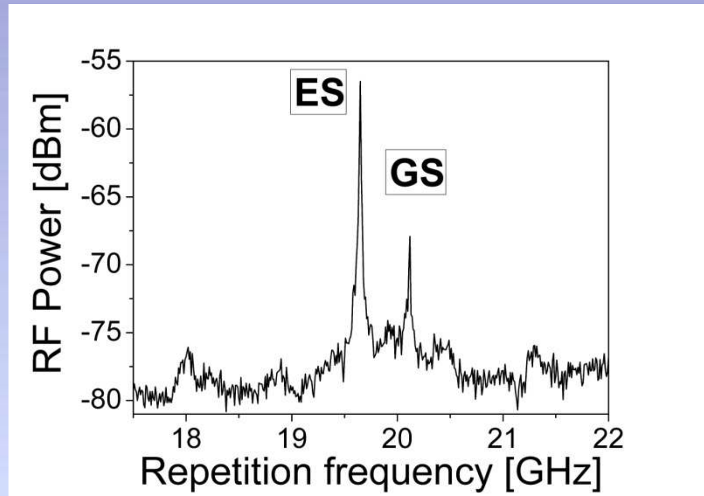
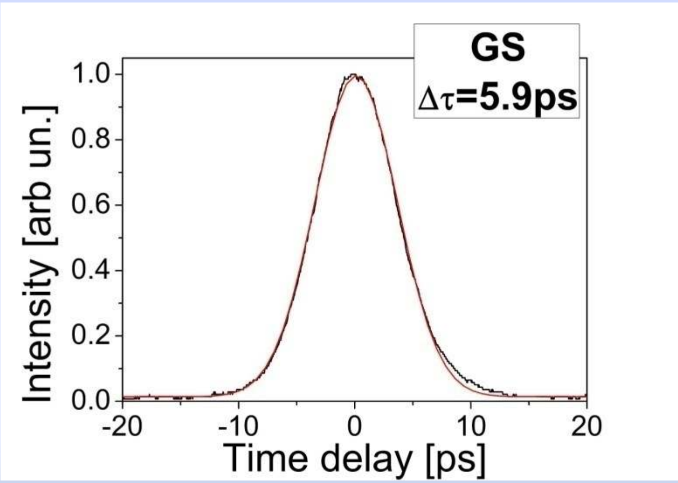
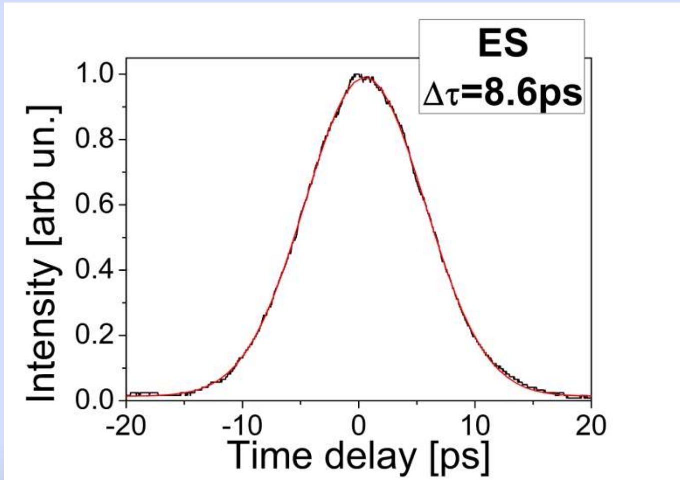
Characteristics of the new regime









M.A. Cataluna *et al, CLEO Europe 2009*, CB4.6.

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Advantages of dual wavelength mode locking operation

Added level of functionality, accessing new mode locking regimes

- Switchable mode locking ES–GS by changing the electrical bias of the laser
- Dual wavelength mode locking
- Improved mode locking in the GS by using the ES emission

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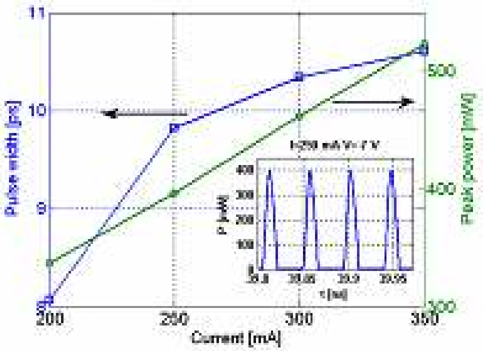
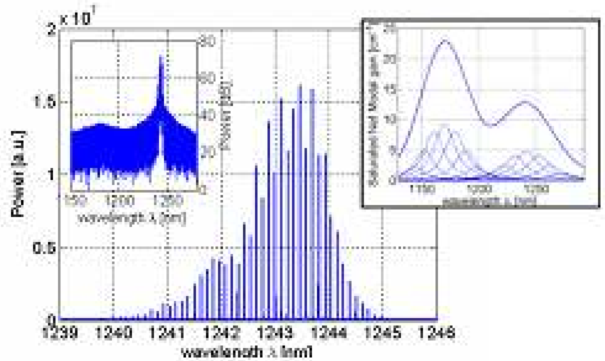
Ultra fast QD laser simulation

Finite-difference travelling-wave model

Simulations of mode-locking regime, evidencing the strong asymmetry in pulse and spectral shapes.

Mode-locking involving GS and ES has also been simulated.

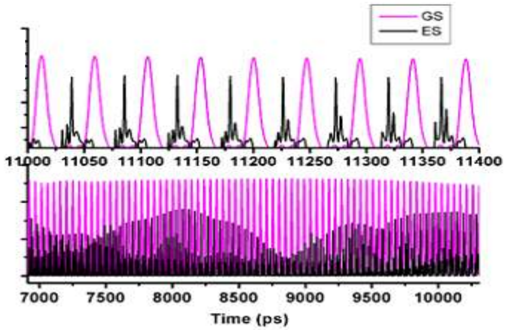


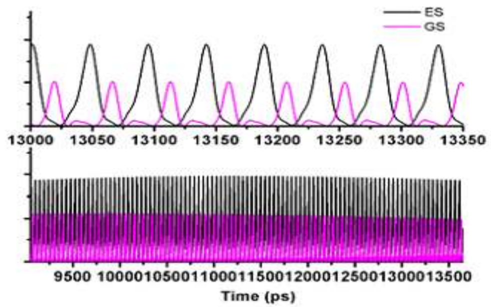


M. Rossetti *et al.*, *CLEO Europe 2009*

Multimode delay differential equations

Simulations of different operation regimes, showing the transition from mode-locking to multi-pulse unstable regimes (observed experimentally).





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QD based SOAs

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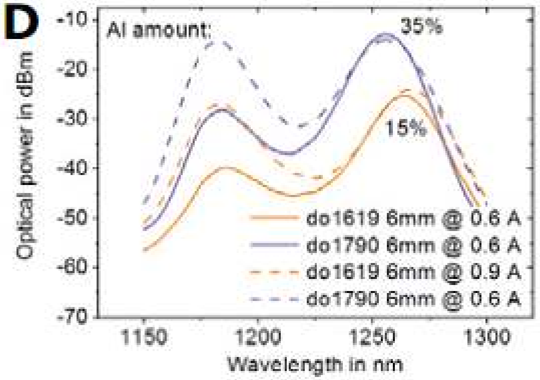
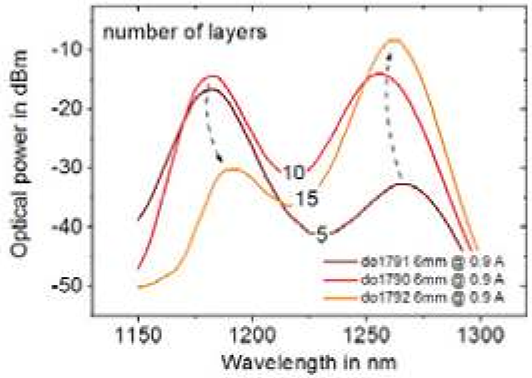
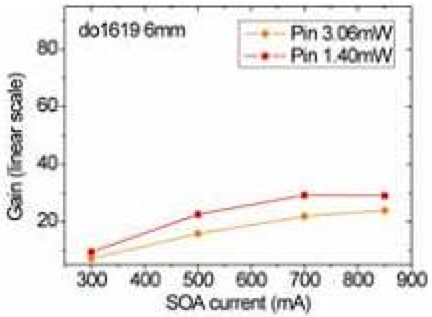
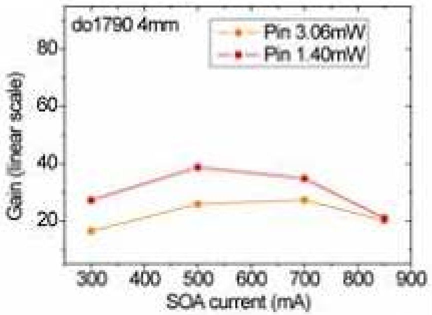
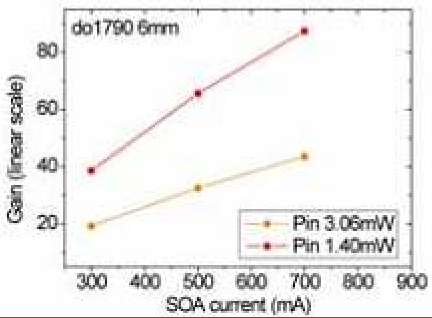
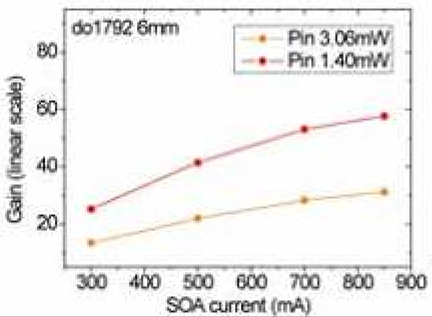




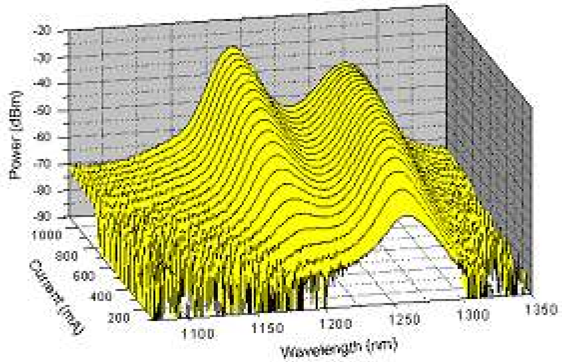








NKUA



- Variation with temperature and current was investigated

Results from this task:

- Assist design rules of QD MLLs and SOAs
- Parameter extraction for simulations
- Important feedback for WP1

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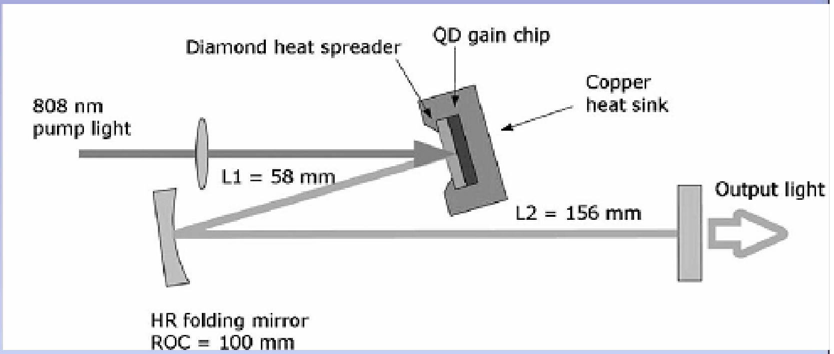
High Power QD semiconductor Disk Laser (VECSEL)

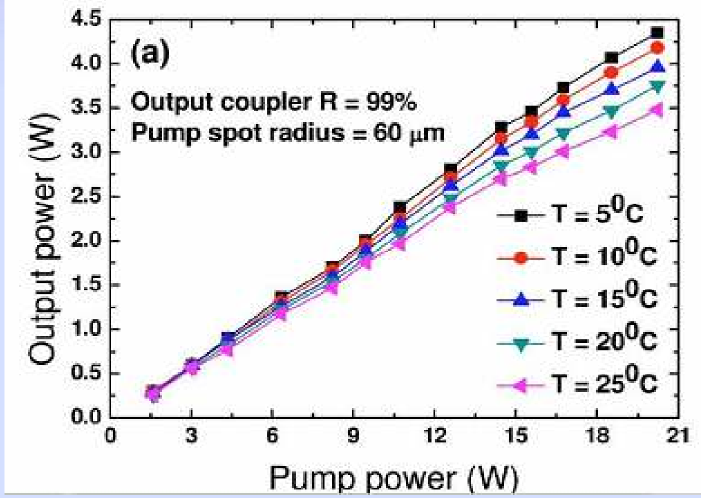
First All-QD VECSEL

- CW operation with power of 4.35W
- Slope efficiency of 22%
- Radical increase in emitted power in comparison with previous QD based devices (15 times)
- Radical increase of slope efficiency (10 times)



Basic schematic of the QD OP VECSEL

- FASTDOT achieved several world records for OP-VECSELs
- Power record for QD-VECSEL:
- 4.35 W continuous-wave operation with diamond heat spreader (UNIVDUN)



Output power emitted by the VECSEL versus the pump power

M. Butkus et al., Optics Letters, Vol. 34, Issue 11, pp. 1672, 1673, 2009

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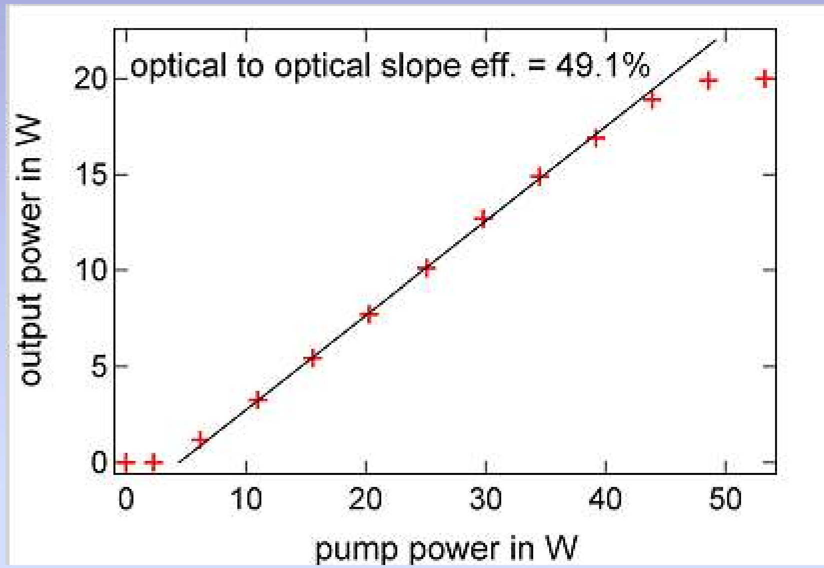
Optically Pumped QW - VECSELs

Development of Optically Pumped vertical external cavity surface emitting lasers (OP-VECSELs) for Multi Photon Imaging

- Average Power of 20W (CW) at central traversal mode (wavelength = 960nm)
- Slope efficiency of 49%
- Optical – to – Optical efficiency of 43%

Fast – Dot contribution
- Comparison OP-VECSELs with QW an QD gain
- Development of effective heat sink and mounting techniques
-Power record for TEM00 QW-VECSEL 20 W continuous-wave obtained (ETHZ)



Output power emitted by the VECSEL versus the pump power

B. Rudin et al., Optics Letters, Vol. 33, Issue 22, pp. 2719, 2721, 2008

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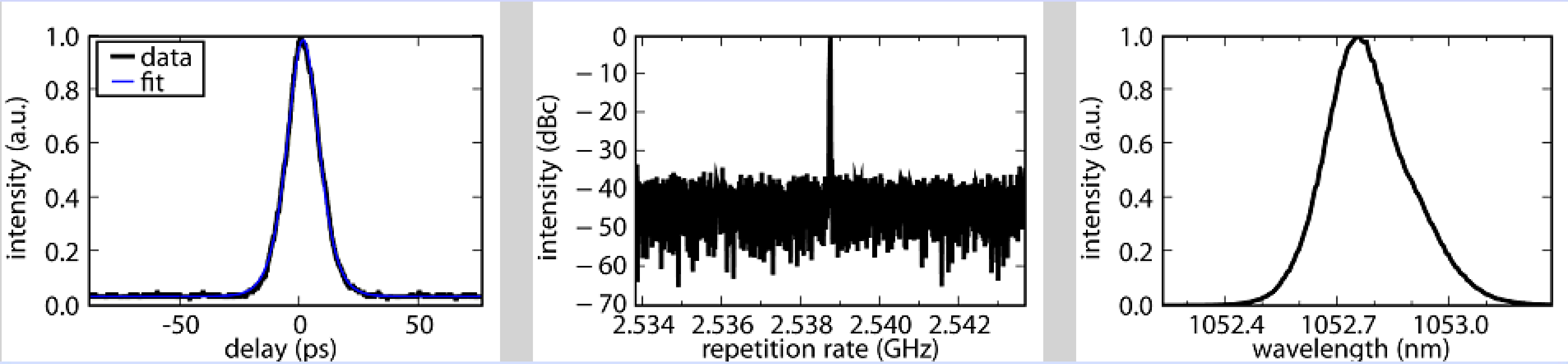
All-QD based mode locked VECSELs

FAST-DOT

Development of the first mode locked all QD VECSEL

- Pulse width of 10ps
- Average power of 22mW
- Central wavelength 1053nm
- Poor thermal properties limit the performance
- Substrate removal can enhance power in the near future
- Investigating and improving the recovery dynamics will enhance pulse width



Autocorrelation trace, RF spectrum and optical spectrum for the all-QD OP mode locked VECSEL

M. Hoffmann et al., Applied Physics B, Vol. 93, Issue 4, pp. 733-736, 2008

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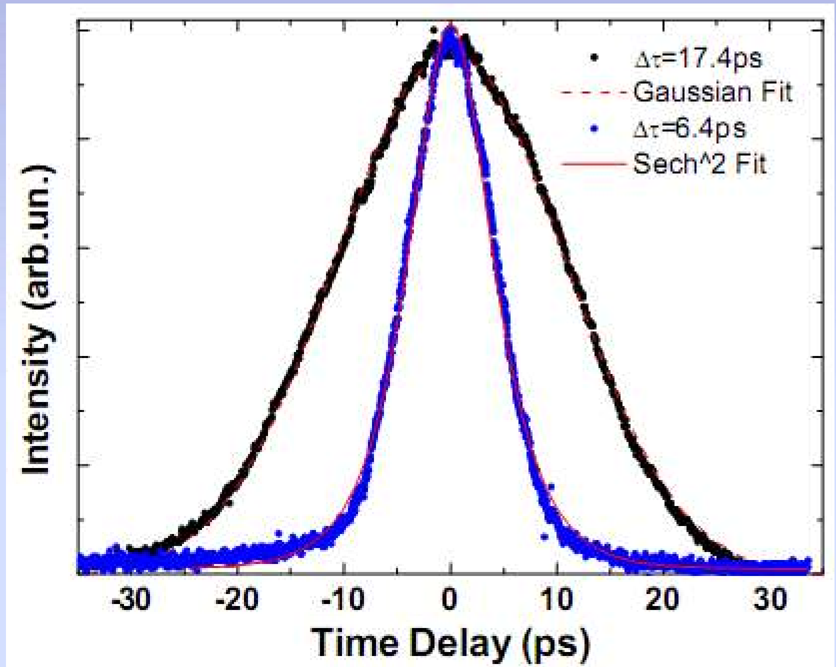
QD and QW based SESAMs

QD based saturable absorber mirrors (SESAMs)

- Both QW and QD SESAMs have been fabricated
- Extensive comparison in terms of pulse shaping and pulse narrowing have been performed between QD and QW SESAMs

FASTDOT achieved several world records for mode locked VECSELs
First mode locking of VECSEL with QD active section
- QW-SESAM (18 ps)
- QD-SESAM (10 ps)



Autocorrelation trace by using a QW SESAM (black) and a QD-SESAM (blue

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Nonlinear Microscopy

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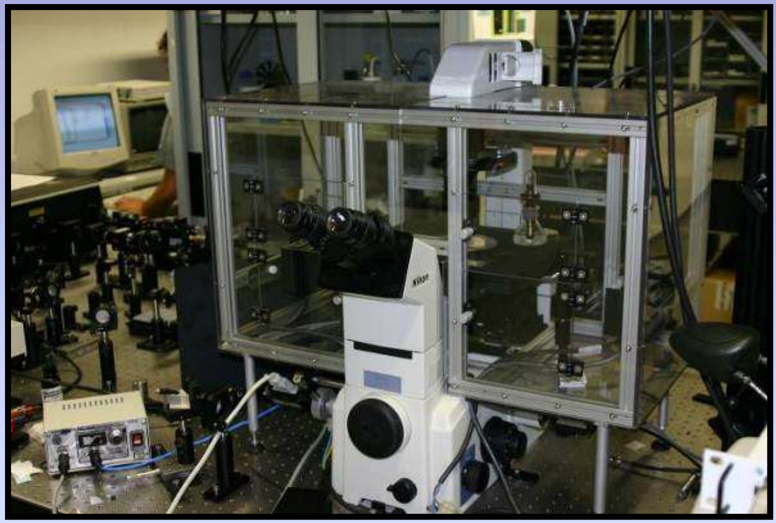
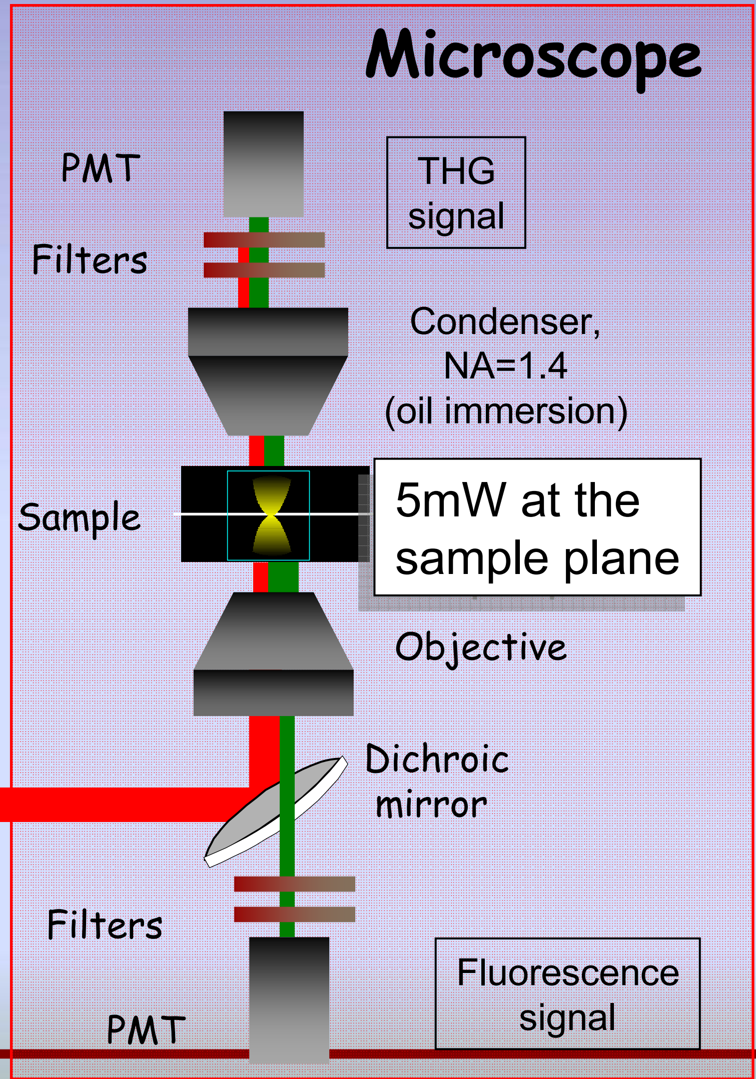
The basic setup



Amplified erbium fiber lasers (TOPTICA: FFS)

λ=1550nm
$\Delta\tau$=100fs
f=100MHz
P_{ave}=450mW



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Nonlinear microscopy & diagnostics

ICFO with Toptica system

1550 nm output at 400mW with 107MHz rep rate and 100fs duration **500W**

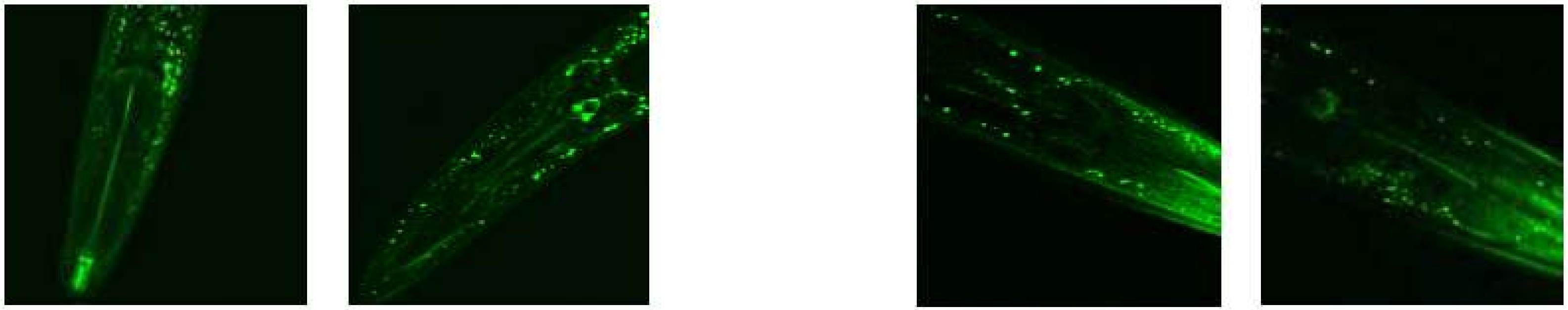
Microscope scanning system delivers 5mW at sample

Signal collected in forward direction

Sample composed of *C. elegans* worms

Signal centered at 513nm (Third harmonic image and nonlinear autofluorescence)

Minimum power ~5mW



Mouth

Pharynx

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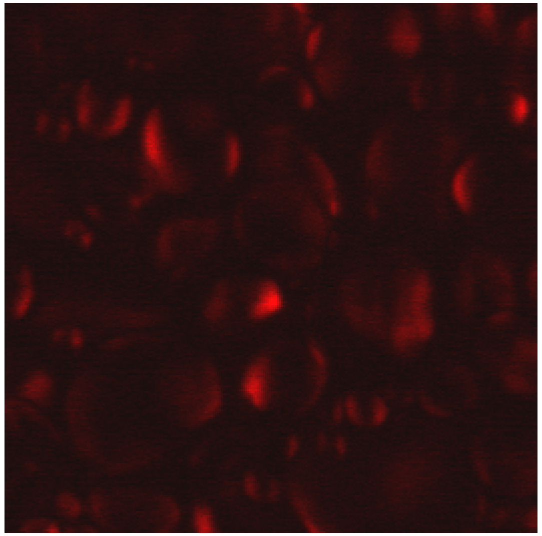
Nonlinear microscopy & diagnostics

ICFO with Toptica system

1550 nm output at 400mW with 107MHz rep rate and 100fs duration

Microscope scanning system delivers 5mW at sample

Signal collected in forward direction



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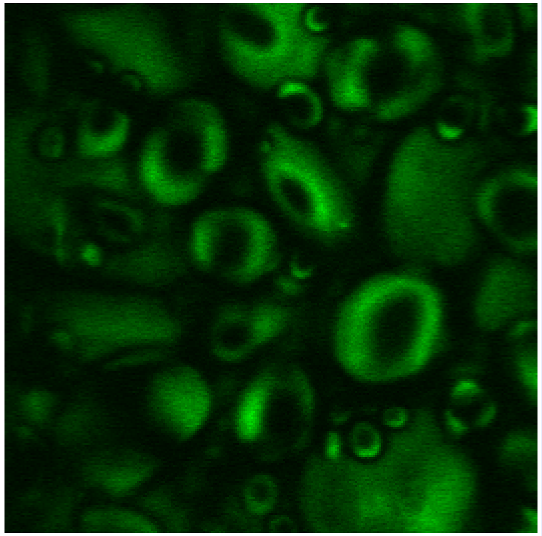

Sample composed of starch granules
Signal centered at 775nm (Second harmonic image)

Sample composed of starch granules
Signal centered at 513nm (Third harmonic image)
Minimum power ~2mW

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FAST-DOT

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