# Multi-level transitions in ultrafast QD lasers

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*University of Dundee*

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

# People involved in this work

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# **FAST-DOT:** Compact Ultra**FAST** Laser Sources based on Novel Quantum-**DOT** Structures

**Integrated Project, FP7 European Programme, ICT**
**Coordinator:** Dr Edik Rafailov, University of Dundee
**Duration:** June 2008 – 2012
**Funding:** 10.1 Million Euros **Partners:** 18

## Academic Partners

- University of Dundee
- University of Sheffield
- ETH Zurich
- Tampere University of Technology
- KTH - Royal Institute of Technology, Stockholm
- ICFO - Institut de Ciències Fotòniques, FUND. PRIV.
- FORTH - The Foundation for Research and Technology Hellas
- Vilnius University
- Politecnico di Torino
- University of Athens
- Technical University of Darmstadt

## Industrial Partners

- Philips
- Alcatel Thales III-V Lab
- Innolume GmbH (SME)
- M Squared Lasers Limited (SME)
- TOPTICA Photonics AG (SME)
- Time-Bandwidth Products AG (SME)
- Molecular Machines and Industries GmbH (SME)

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# Overview of the Project

- Main targets of FAST-DOT:
  - Enable widespread bio-photonic applications
    - Nanosurgery
    - Nonlinear microscopy
    - Optical Coherent Tomography
    - Endoscopy
  - By development of
    - Compact Ultrashort pulsed lasers
    - High efficiency and low cost lasers
  - Based on unique properties of novel nanostructures - Quantum Dots

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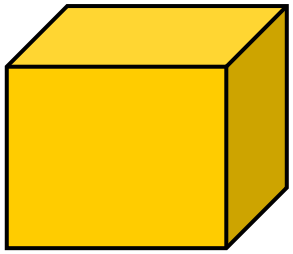
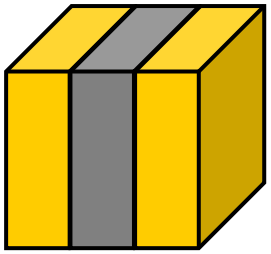
# Quantum-Dot structures

*Schematic morphology*

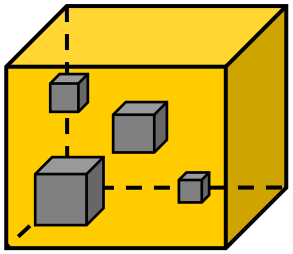
*Bulk*

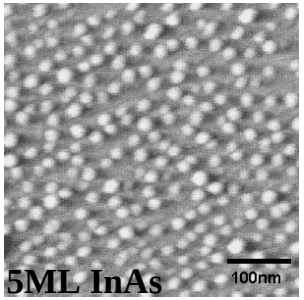


*Quantum Well*

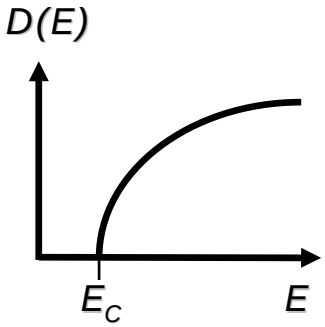


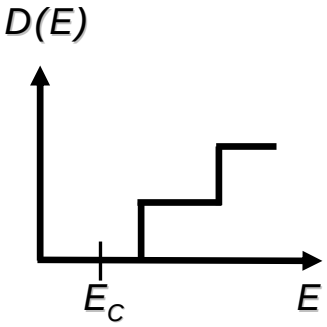
*Quantum Dot*

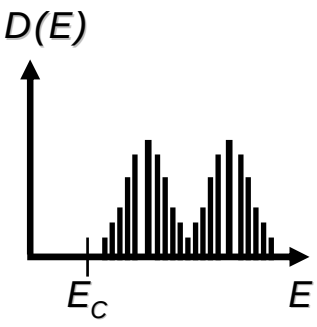


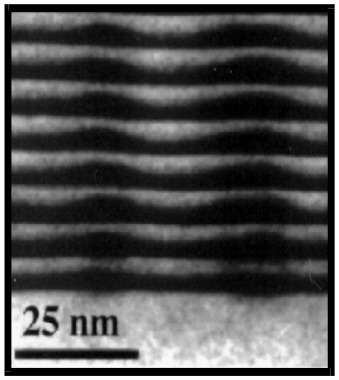



*Density of states*

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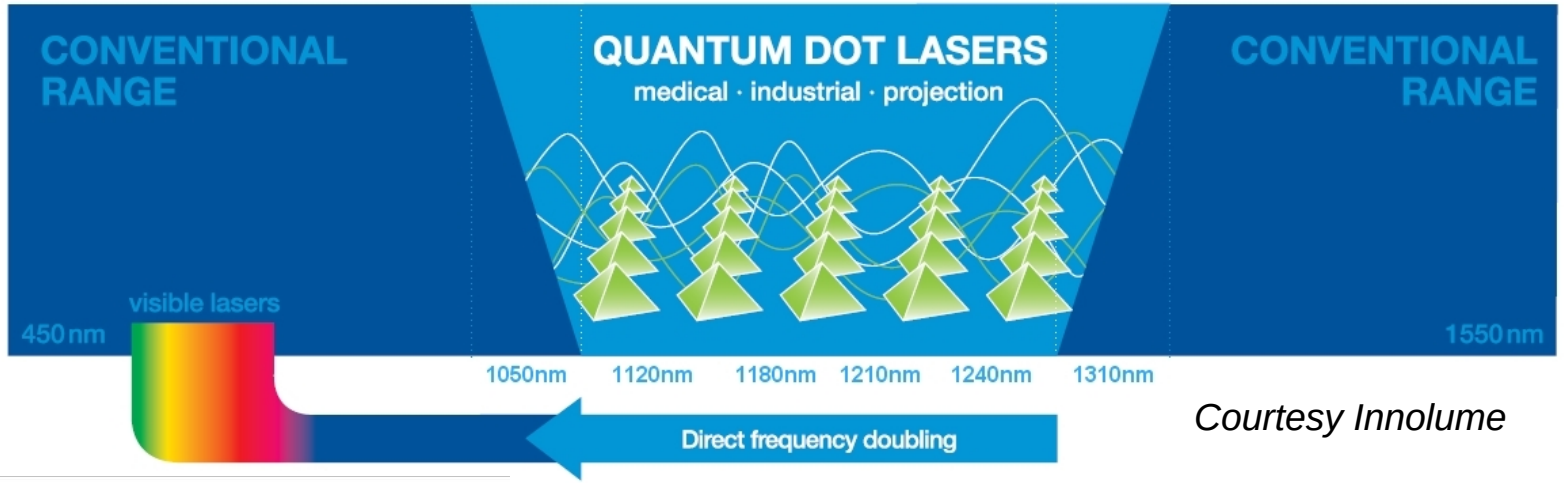
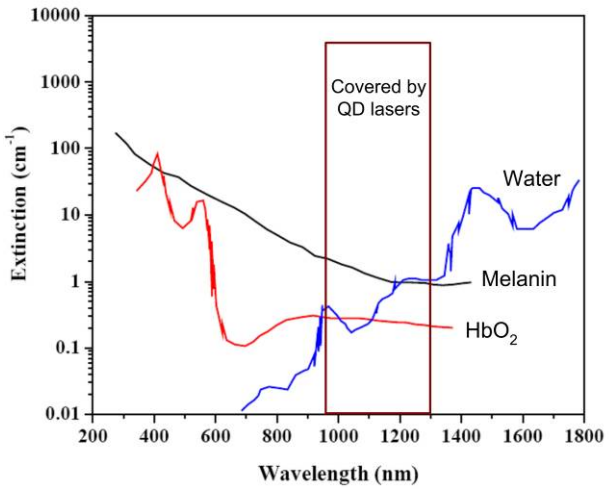
# QD-based lasers




*Courtesy Innolume*




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

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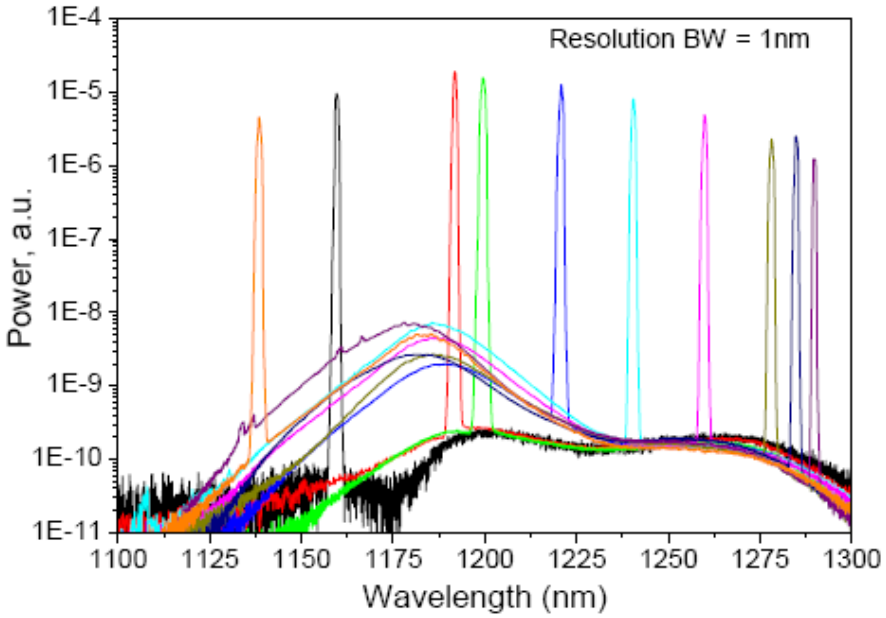
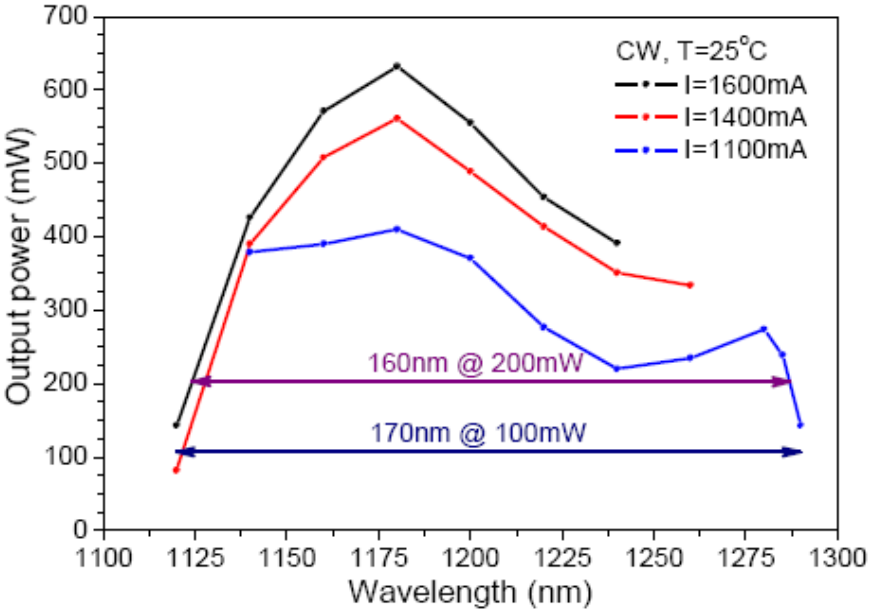
# Tunability

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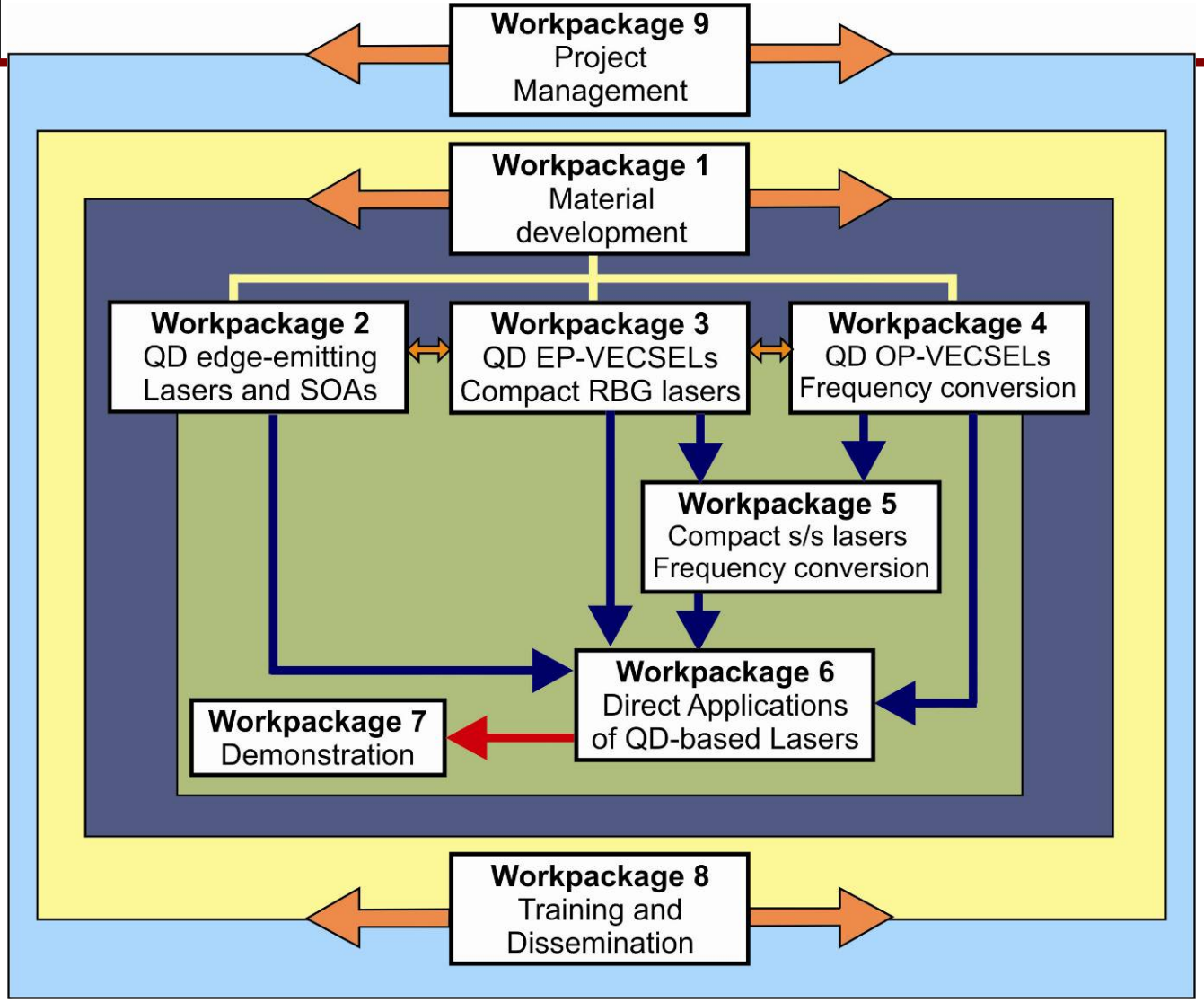
# FAST-DOT Project Structure

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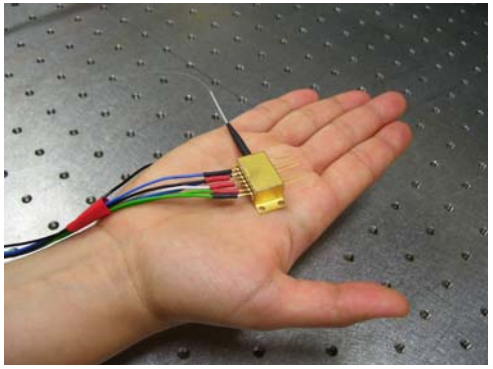
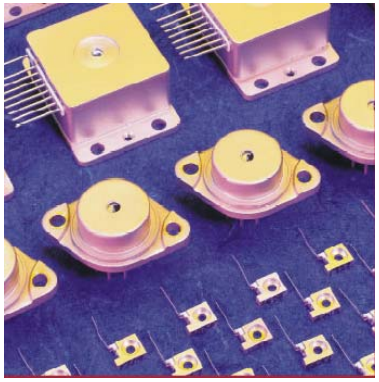
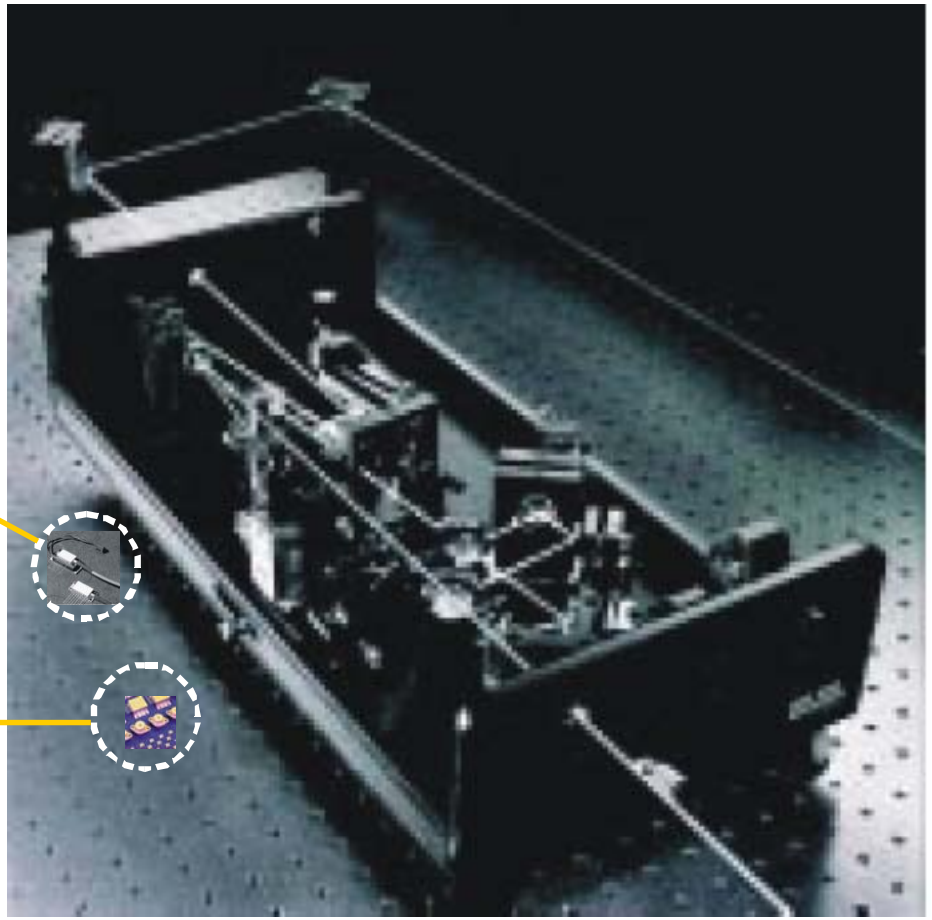
FAST-DOT

*"**Diode lasers** are very efficient and reliable, and **will probably lead to a silent revolution in medical applications**."*

*Peng et al, Lasers in Medicine, Rep. Prog. Phys. **71** (2008) 056701*







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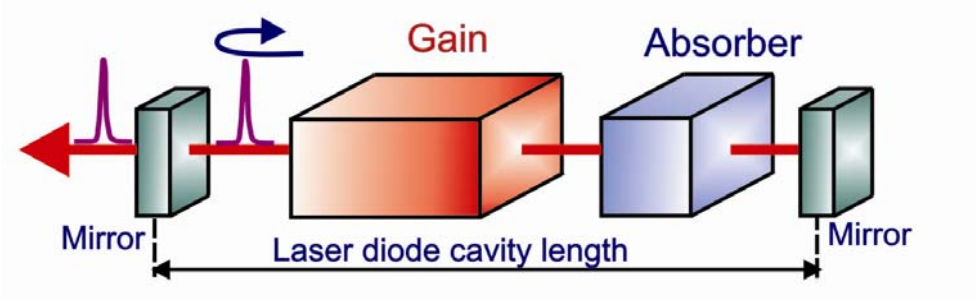
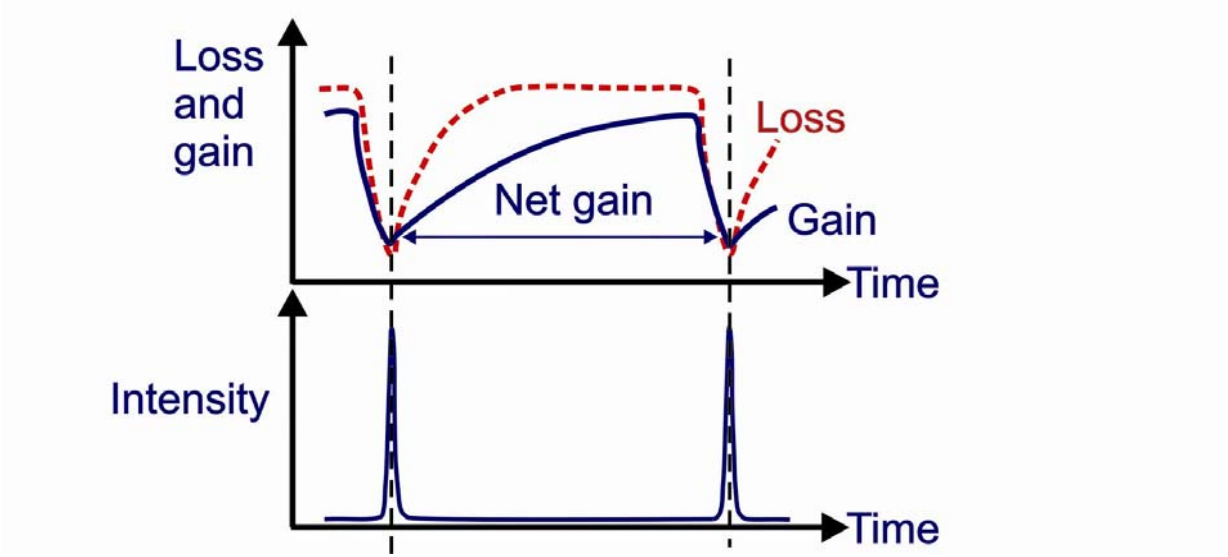
# Pulse generation via mode-locking

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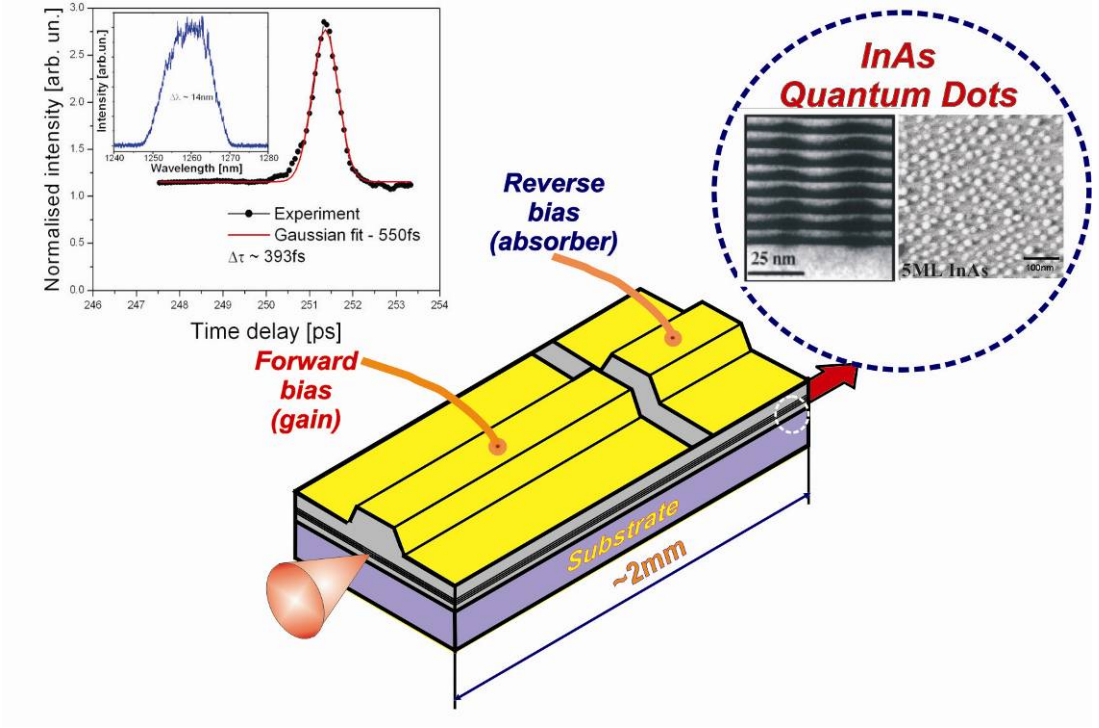
# QD mode-locked laser

***Short pulse duration*** $\Delta\tau$ ***~400fs***

***Highest peak power*** $P_{peak}$***~3W***

***Wavelength bandwidth*** $\Delta\lambda$ *~ 15nm*





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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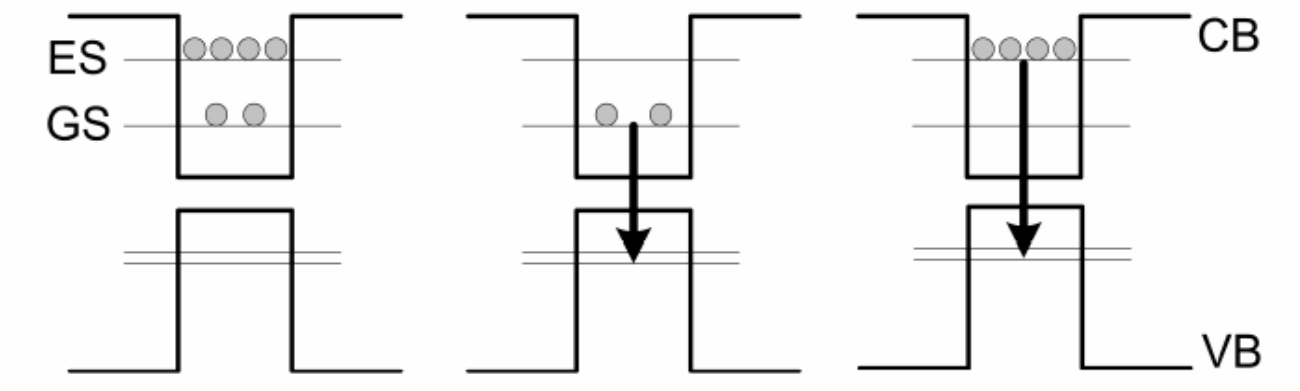
# A new approach: using the excited state too




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

*- Is it possible to achieve mode locking via the excited-state transitions? And how different is excited-state mode locking from ground-state mode locking?*

*- Does the excited state plays any influence in the mode locking via ground state?*

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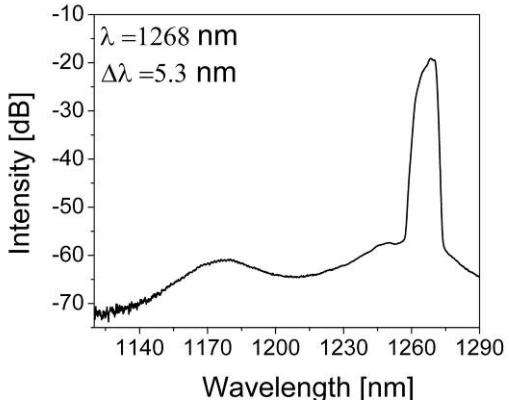
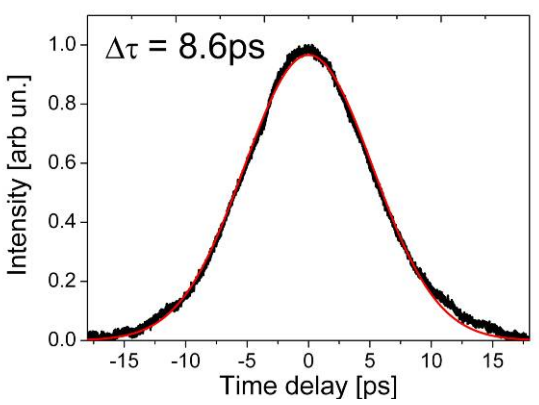
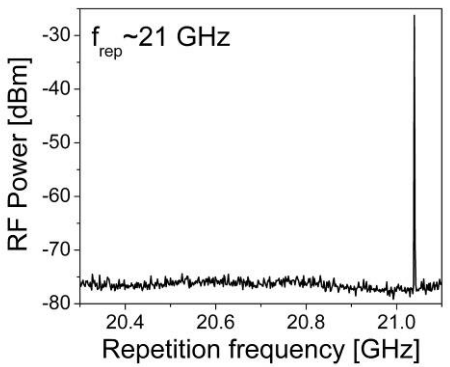
# Mode locking via ground or excited states

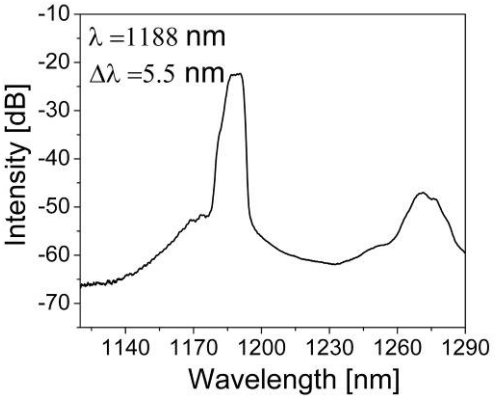
Ground state @ 23mW

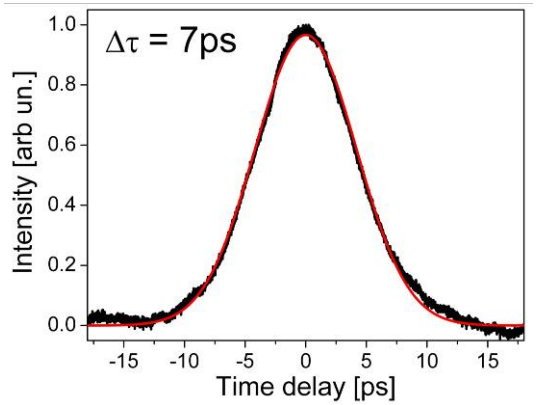


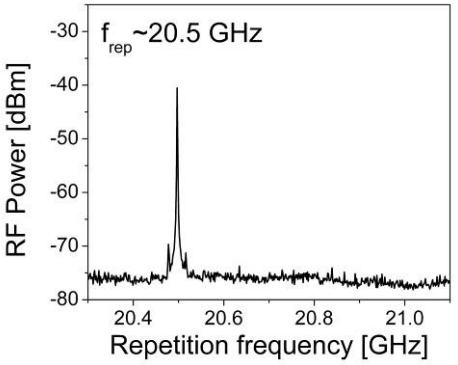




Excited state @ 23mW




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

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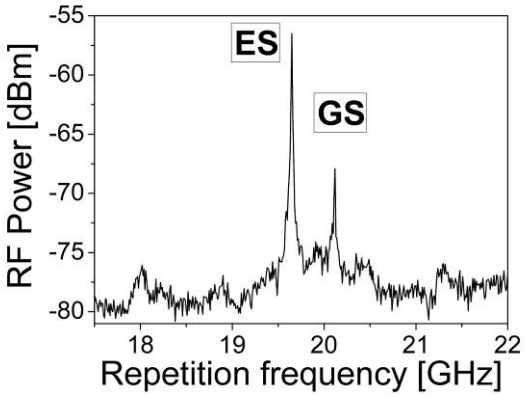
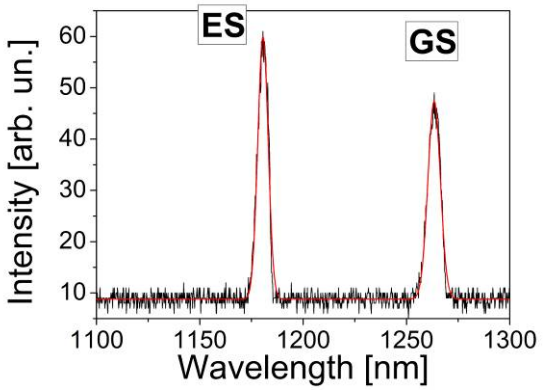
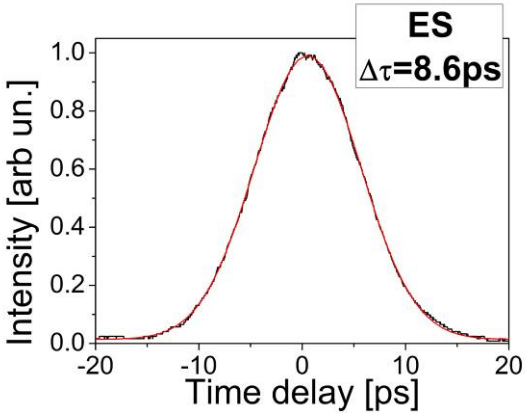
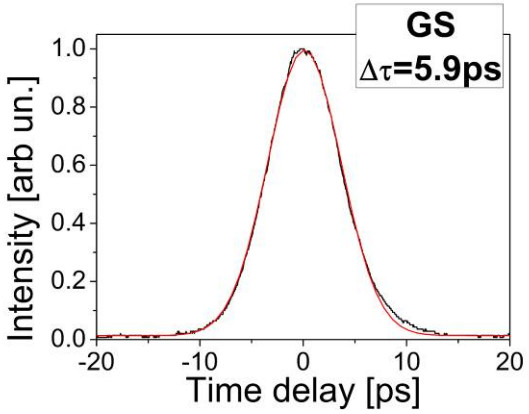
# Dual-wavelength mode-locking




**Two-section QD laser**

- 2mm length, 300μm absorb.
- 5 layers InAs QDs
- T=20°C

**Modelling activity under way**

(Politecnico di Torino)

M. A. Cataluna, *et al.*, submitted to CLEO-Europe, 2009.

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FAST-DOT

## *Our aim* - to use QD lasers for generating pulses that have:

| Shorter pulsewidth | Lower noise | Higher power |
|---|---|---|

➡ 1st choice: operating the laser close to threshold

| Shorter pulsewidth | Lower noise | ~~Higher power~~ |
|---|---|---|

➡ 2nd choice: operating the laser at high currents

| ~~Shorter pulsewidth~~ | ~~Lower noise~~ | Higher power |
|---|---|---|

➡ 3rd choice: using simultaneous excited-state emission

| Shorter pulsewidth | Lower noise | Higher power |
|---|---|---|

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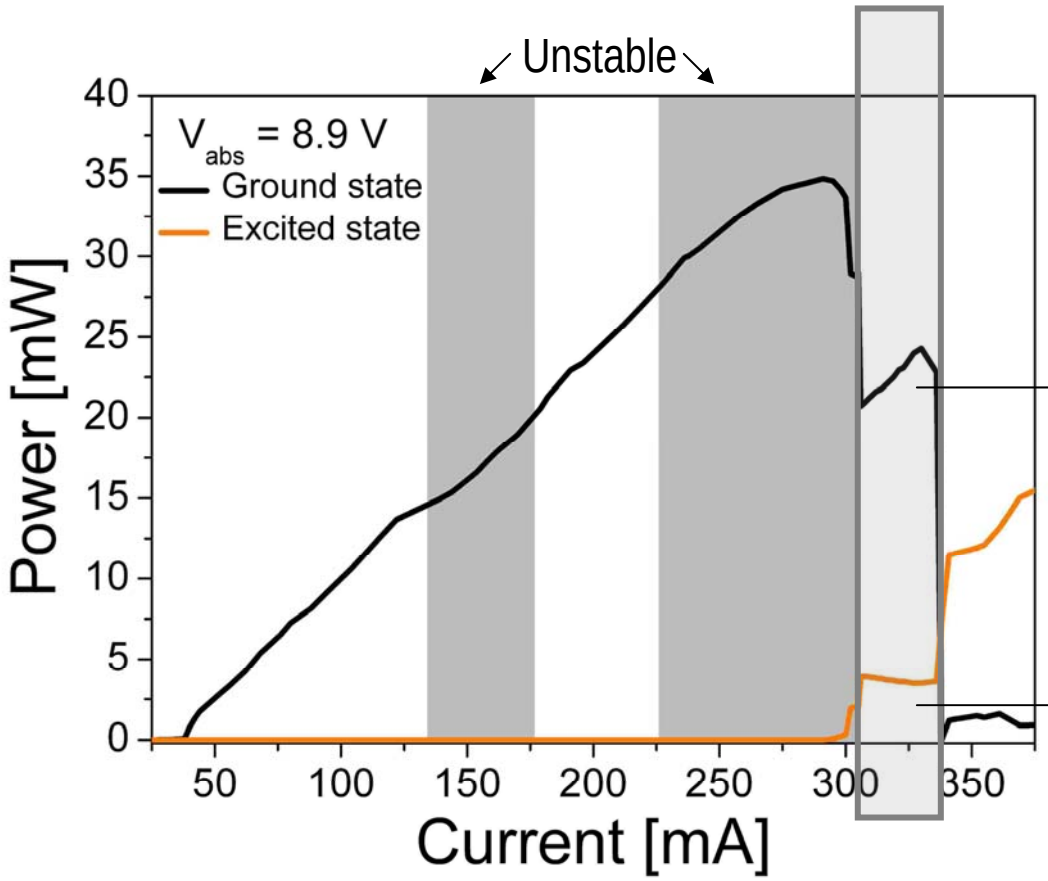
# LI curve: ground and excited states




Stable mode-locking via ground state except on grey regions.

Ground state Mode-locked

Excited state CW

Mode-locking via *ground state*

*enhanced* by…

simultaneous *excited-state* emission

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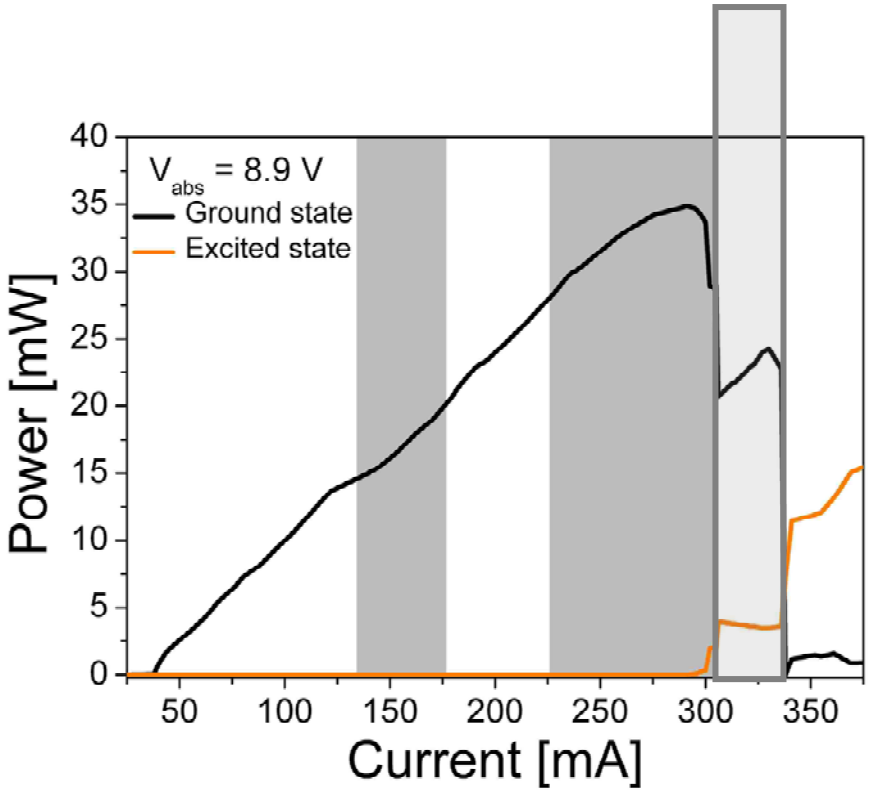
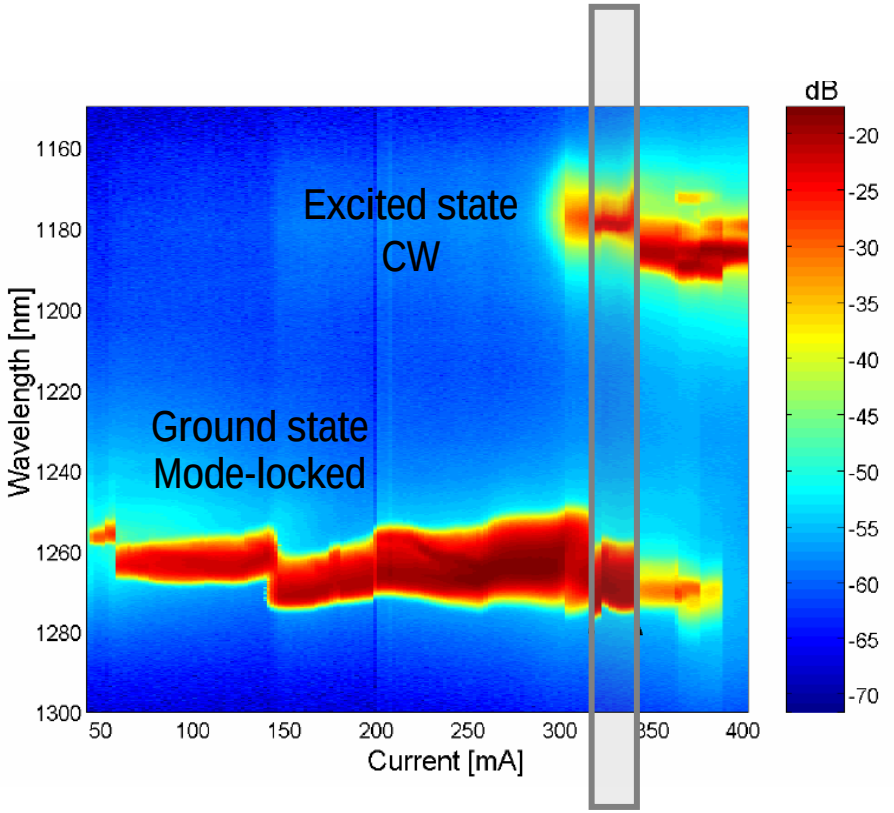
# Evolution of optical spectrum

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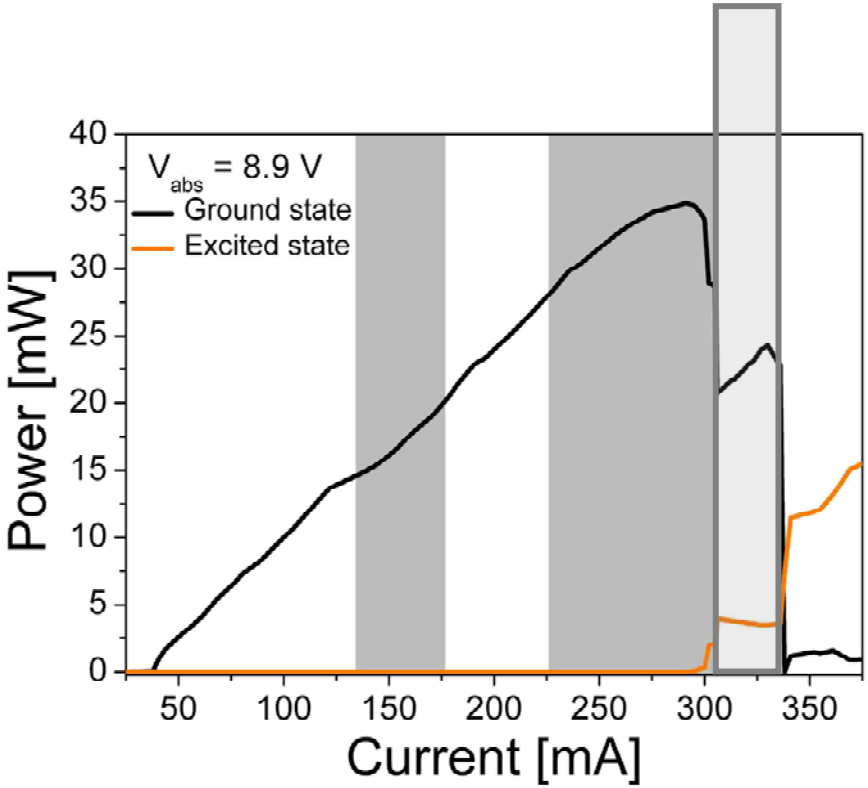
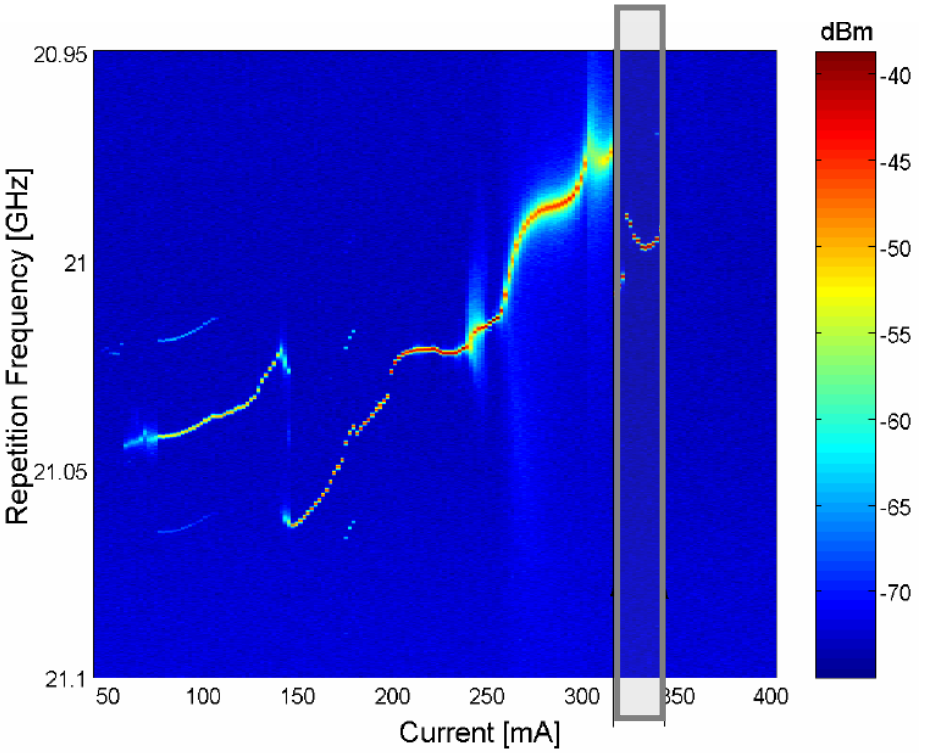
# Evolution of RF spectrum




Ground state
Mode-locked @ 21 GHz

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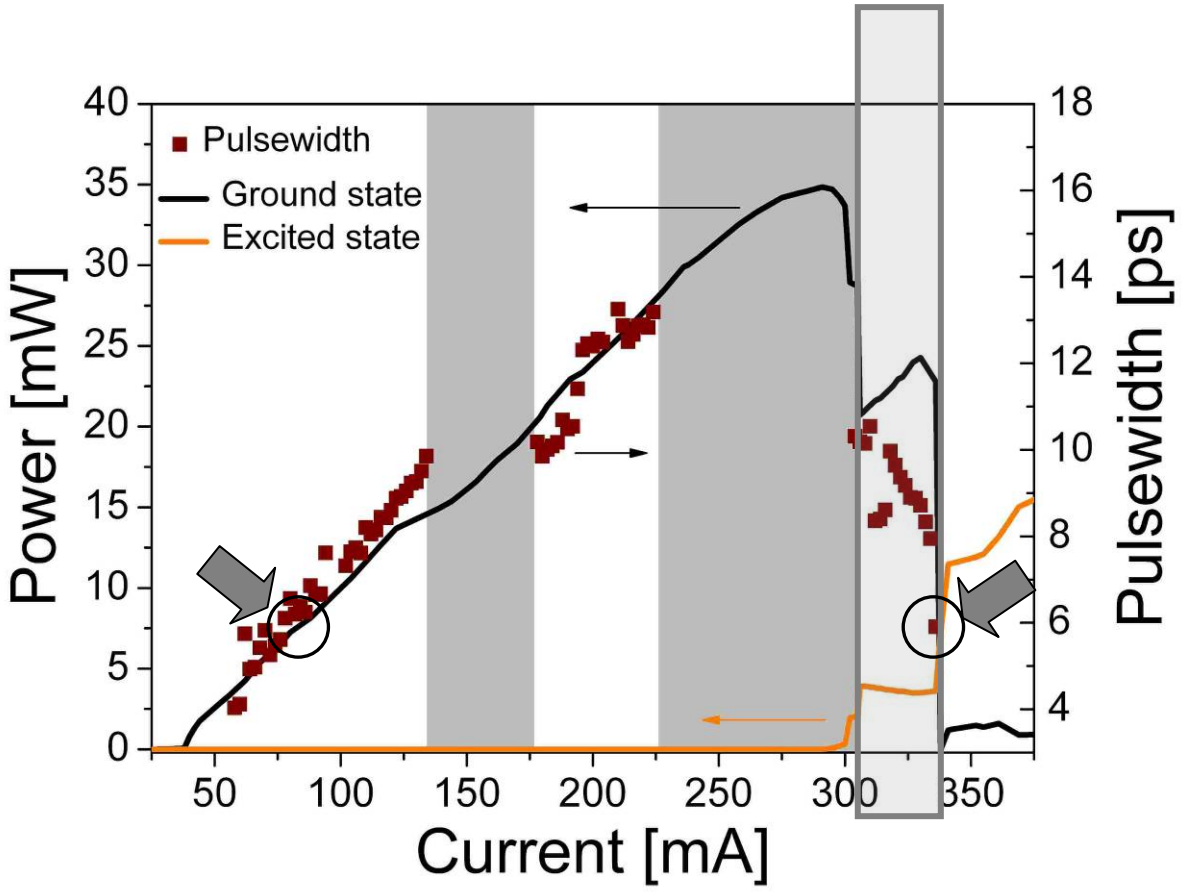
# Impact of excited state on pulsewidth




Pulsewidth increases with current up to 300mA (usual effect)

- Anomalous behaviour: pulsewidth *decreases* with current, in the presence of excited state.

- Same pulsewidth (6ps) but with higher power.

M. A. Cataluna et al., CLEO 2006, CThH3, USA (2006).

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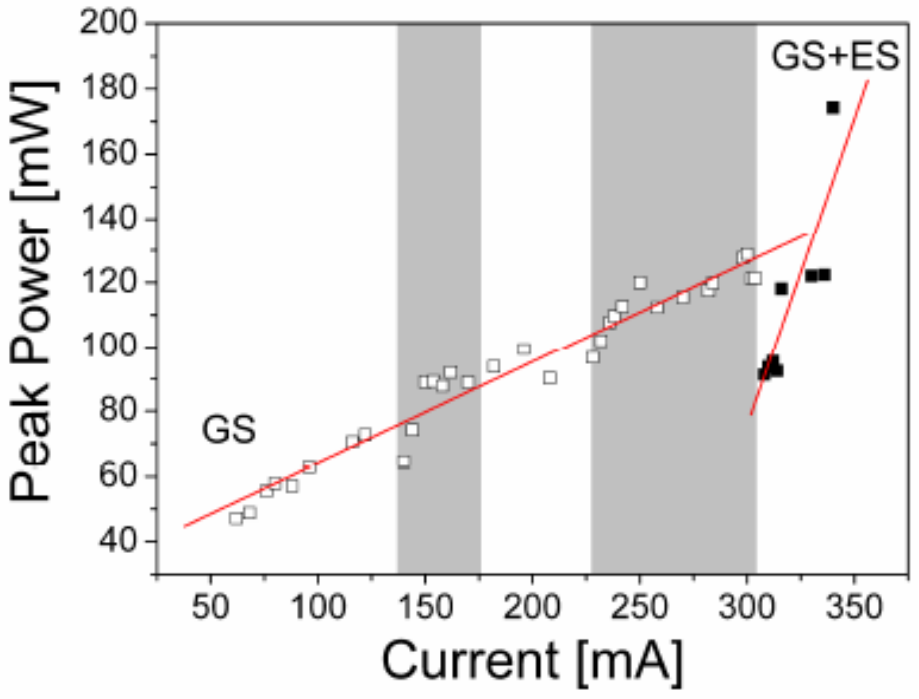
# Increase in peak power

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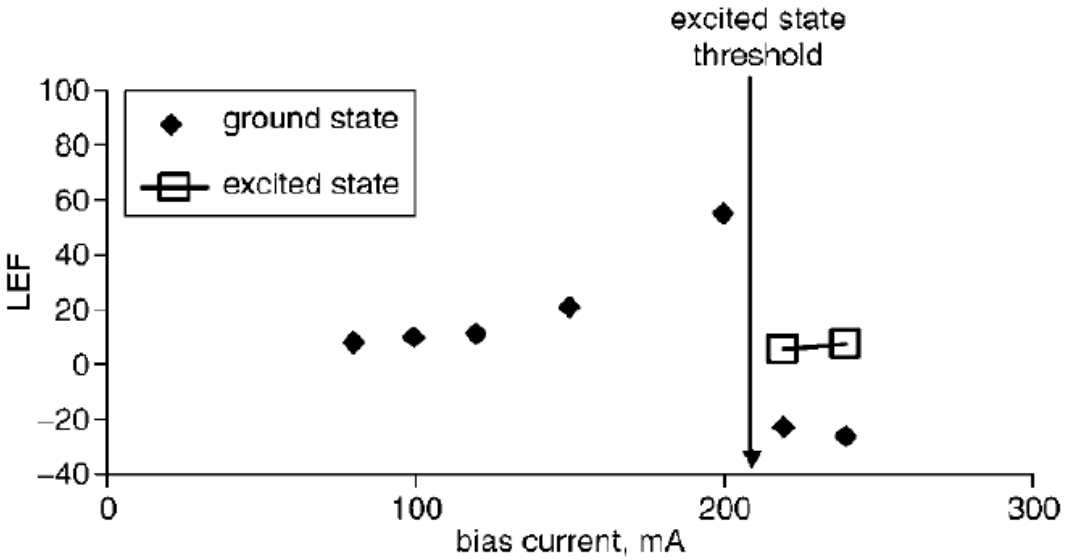
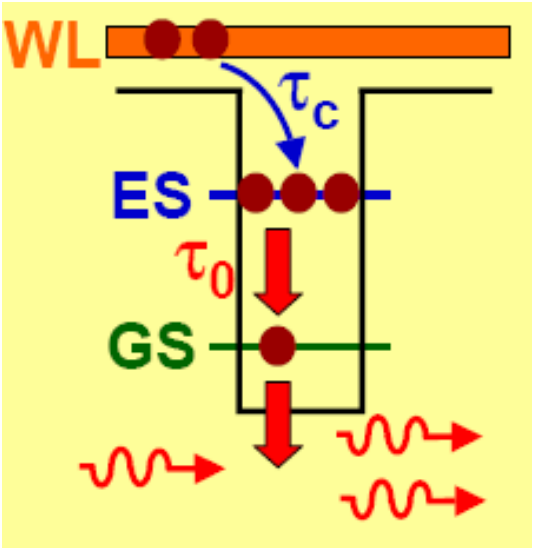
# Hypothesis




B. Dagens *et al.*, *Electron. Lett.*, vol. 41, pp. 323-324, 2005.

**Modelling activity under way**
(Politecnico di Torino)

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# Conclusions

**Excited state as a additional degree of freedom for ultrashort pulse generation in QD lasers.**

Added level of functionality, accessing new mode-locking regimes

- Switchable mode-locking: GS or ES.
- Dual-wavelength mode-locking: GS and ES.
- Improved GS mode locking, by using ES emission.

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# The FAST-DOT Team

www.fast-dot.eu

**Open for collaborations!**

e-mail: fastdot@dundee.ac.uk

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NanoPhotonics Concertation Meeting
12-13 February