Compact Quantum Dot based CW and ultrafast lasers for Biophotonics application

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Outline

- Quantum Dot materials
- InAs/GaAs Quantum Dot edge-emitting lasers
  - Continuous wave regime
  - Mode-locked regime
- Second-harmonic generation of QD edge-emitting lasers
- VECSELs
- Second-harmonic generation of VECSELs
- Biophotonics applications
- Conclusions

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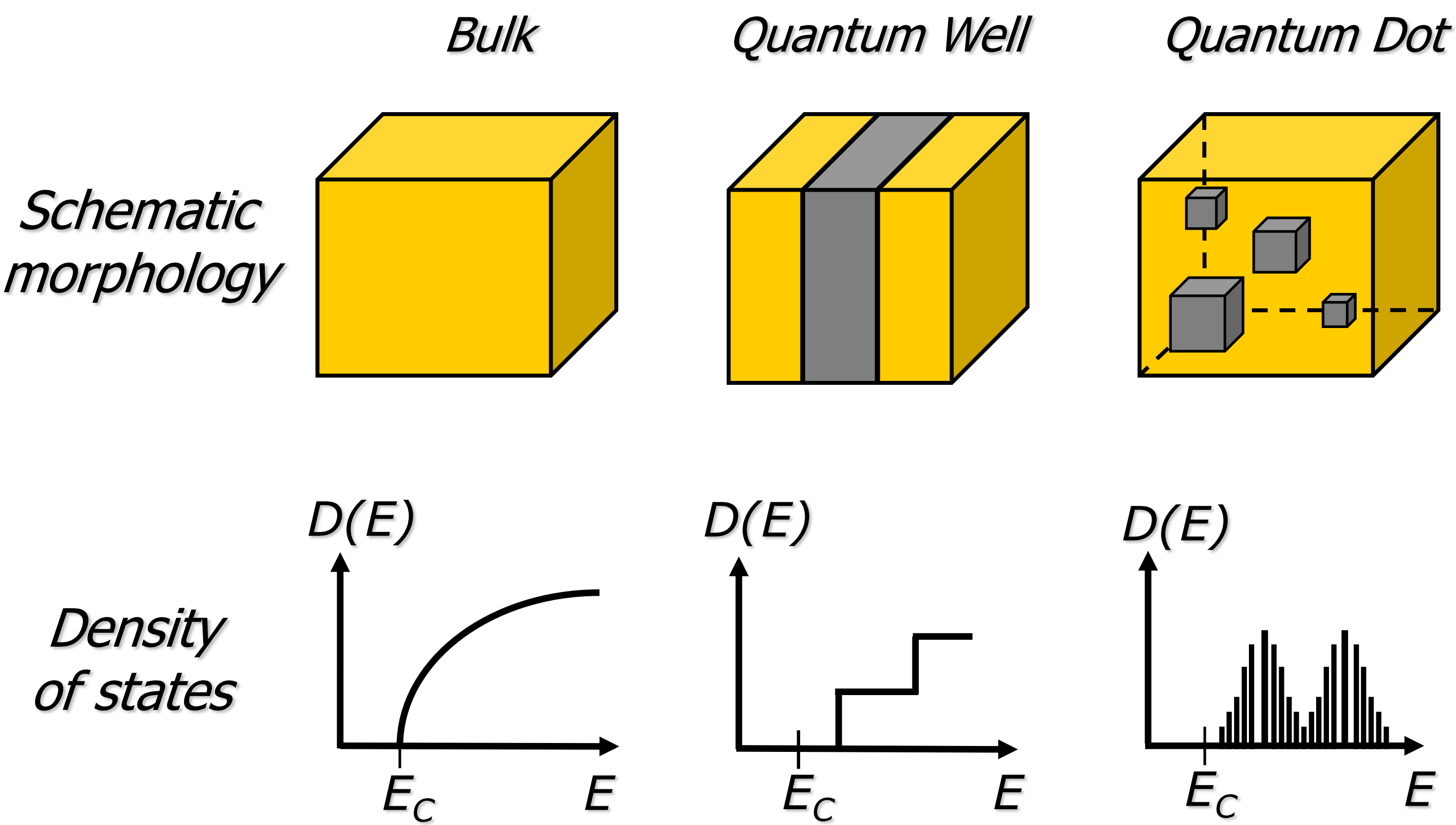
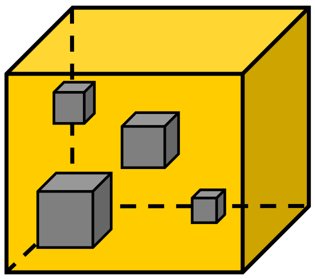
Quantum-dots structures

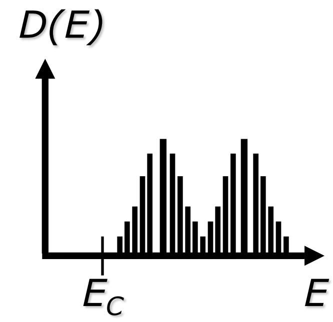


Quantum-dots for ultrafast devices

- Broad gain bandwidth
- Ultrafast carrier dynamics
- Low threshold current
- Low temperature sensitivity
- Lower absorption saturation fluence
- QD-SESAMs
- Great potential in THz radiation

Quantum Dot





InAs/GaAs Quantum Dot lasers

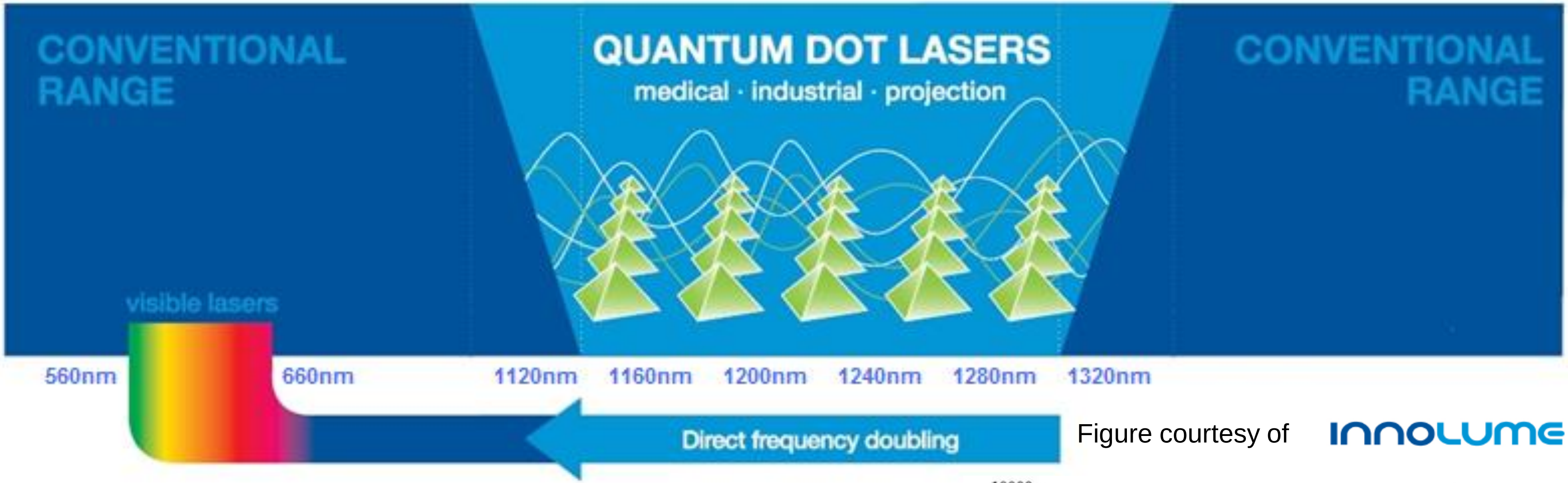
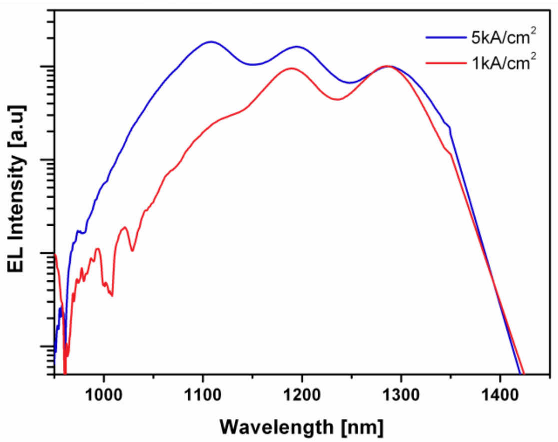
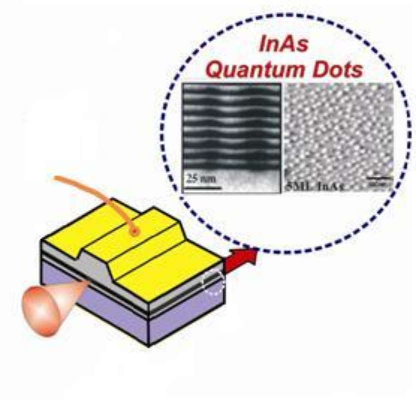
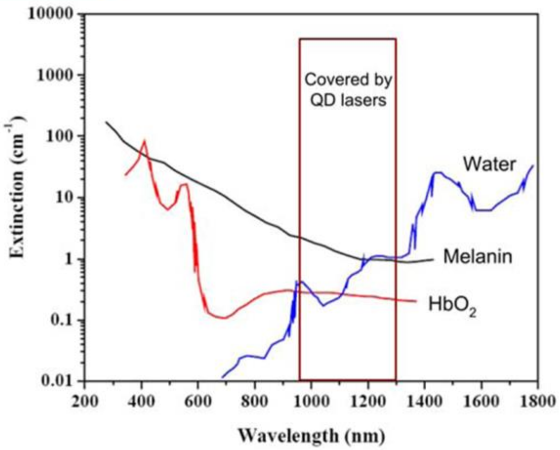


Figure courtesy of INNOLUME







Ultra-broad electroluminescence spectra of a specially designed QD device

Low light absorption and minimal scattering in human tissue in 1 – 1.3 μm range

E.U. Rafailov et al., Nature Photonics, 1, p. 395, 2007

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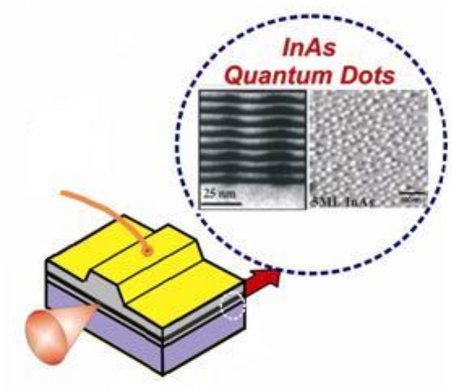
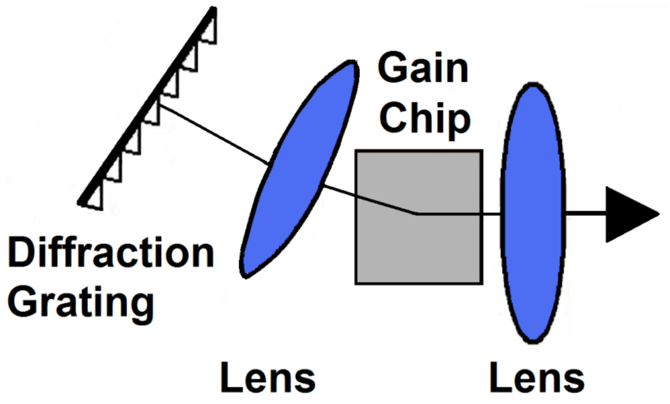
InAs/GaAs QD tunable laser

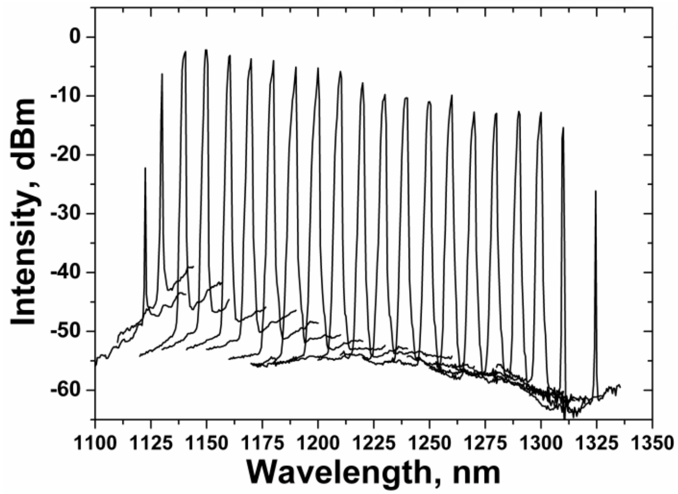
High-power CW external cavity InAs/GaAs quantum-dot diode laser with a tuning range of 202 nm (between 1122 nm and 1324 nm)

- **4 mm length, 5 μm wide waveguide**
- **10 layers InAs QDs, grown on GaAs substrate**
- **waveguide angled at 5^o**
- **facets AR coated: $R_{angled} < 10^{-5}$**

  $R_{front} \sim 2 \cdot 10^{-3}$

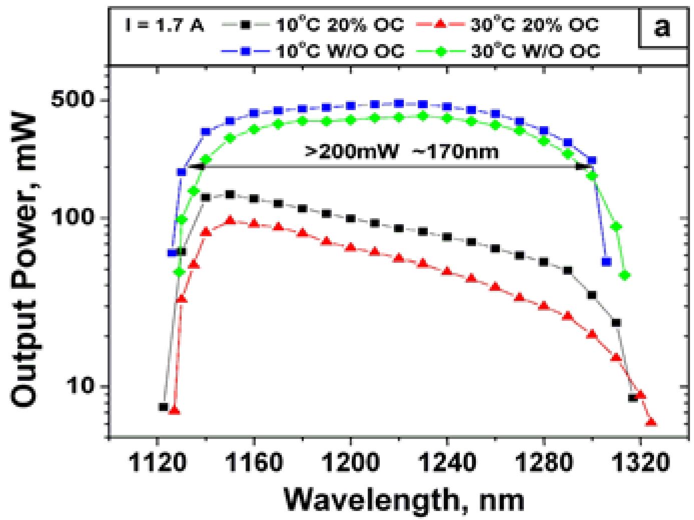


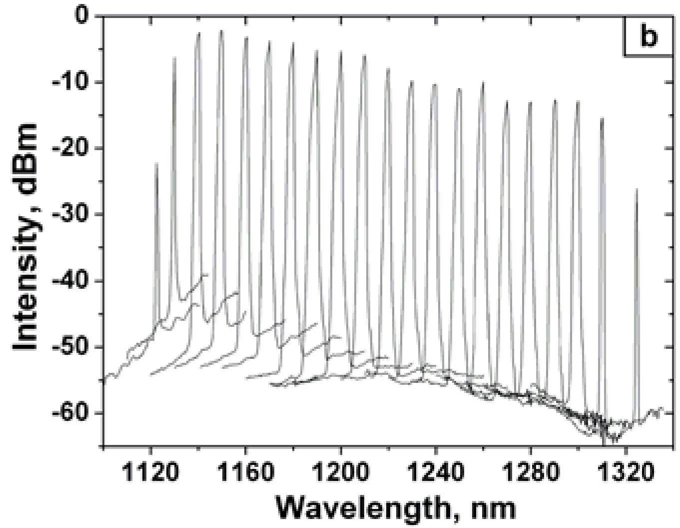




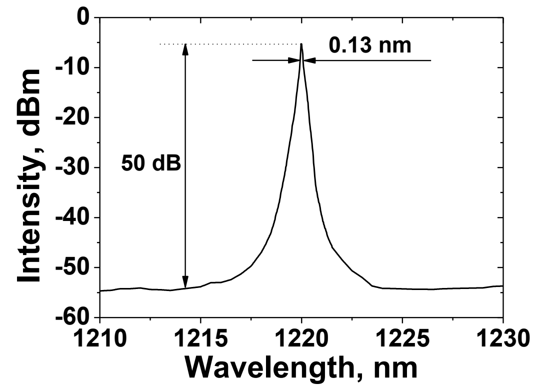
K.A. Fedorova et al., Opt. Express, 18(18), p. 19438, 2010

Spectral characteristics





A tuning range of **202nm** was achieved with the QD laser.

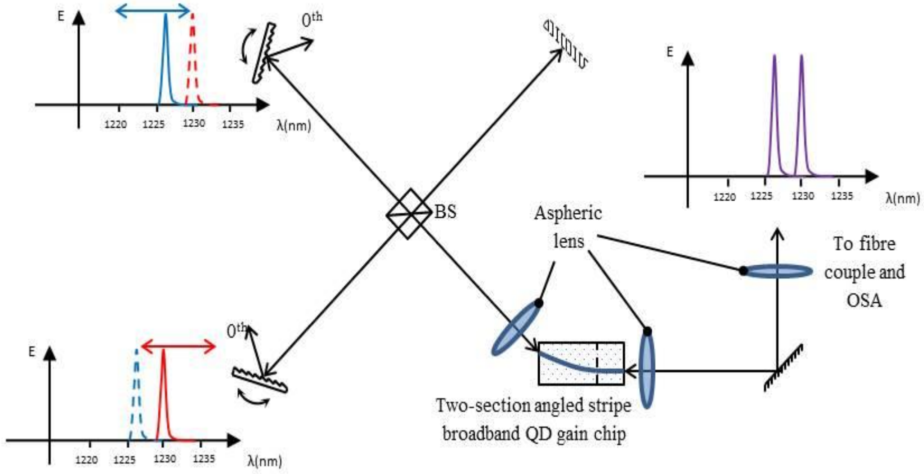


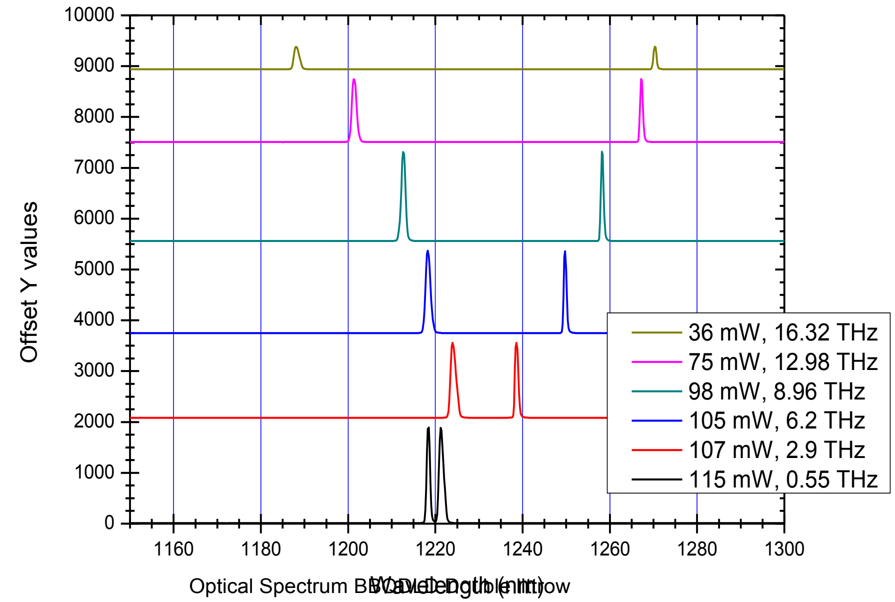
Max Output Power @10ºC, 1700mA:		
W/O OC	**500 mW**	**(λ=1220nm)**
20%OC	**140 mW**	**(λ=1150nm)**

The results obtained show that the tuning range is mostly enhanced on the blue side of the spectrum for lower temperatures and higher pump currents, whereas reducing the cavity losses assists in the enhancement of the tuning range on the red side of the spectrum.

K.A. Fedorova et al., Opt. Express, 18(18), p. 19438, 2010

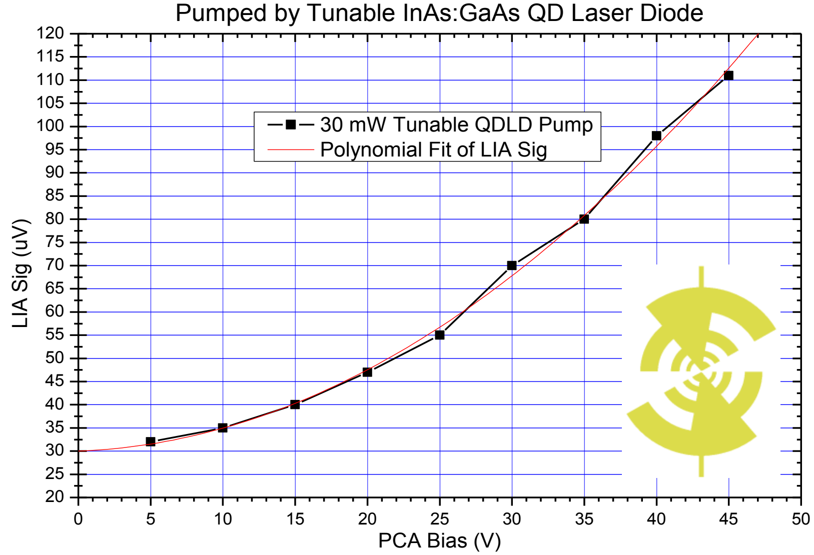
Spectral characteristics

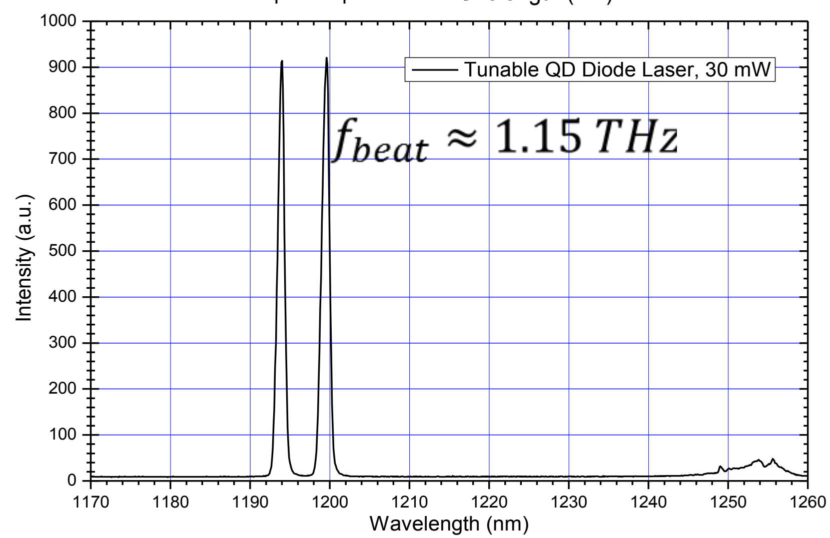




Broadly tunable CW LD

THz Output Trend, 25-layer QD Structure with 5um Gap Antenna
Pumped by Tunable InAs:GaAs QD Laser Diode

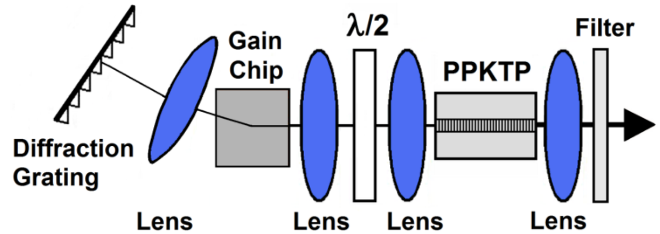




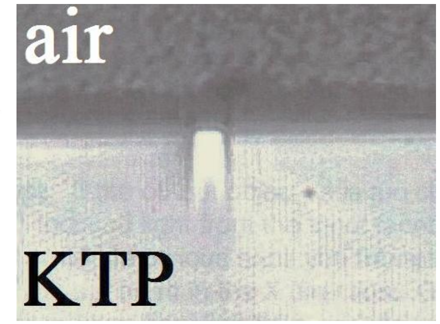
SHG in a periodically poled KTP waveguide

<u>PPKTP crystal used in this work</u>

- 16 mm length
- facets not AR coated
- waveguide with cross-sectional area of ~4×4 μm^2
- periodically poled for SHG at ~1183 nm
  (poling period ~12.47 μm)
- refractive index step Δn≈0.01

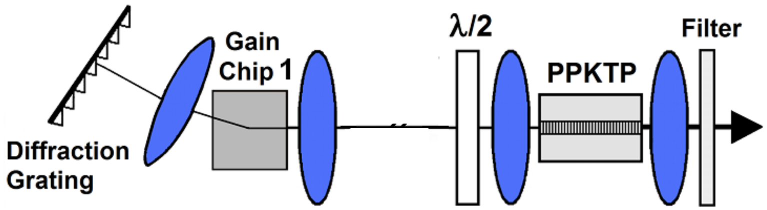


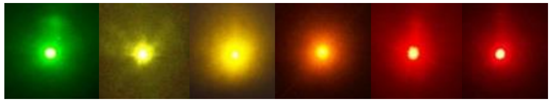
Both the pump laser and the crystal were operating at room temperature

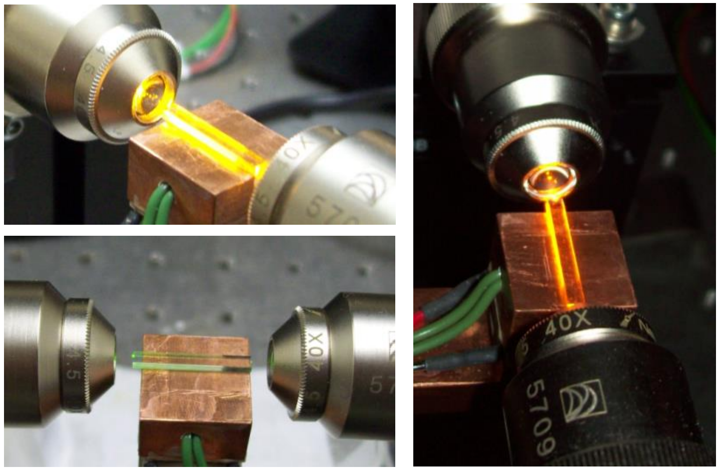


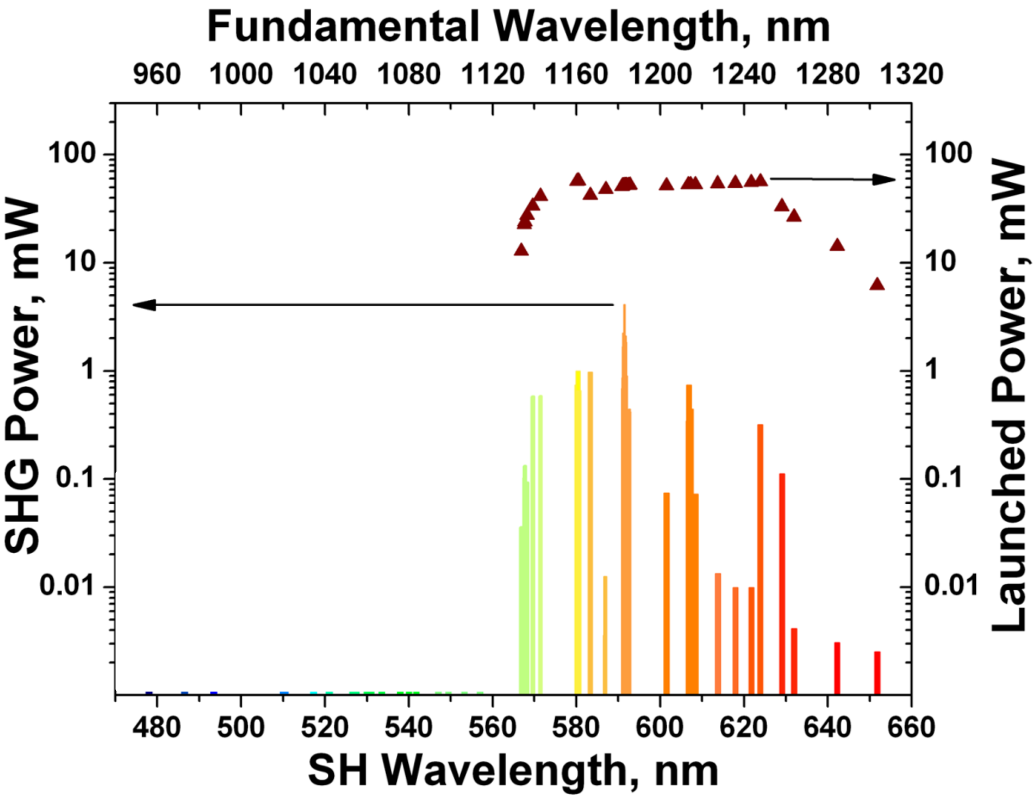
K.A. Fedorova et al., Laser Physics Letters, 9(11), p. 790, 2012

Blue-to-Red tunable SHG





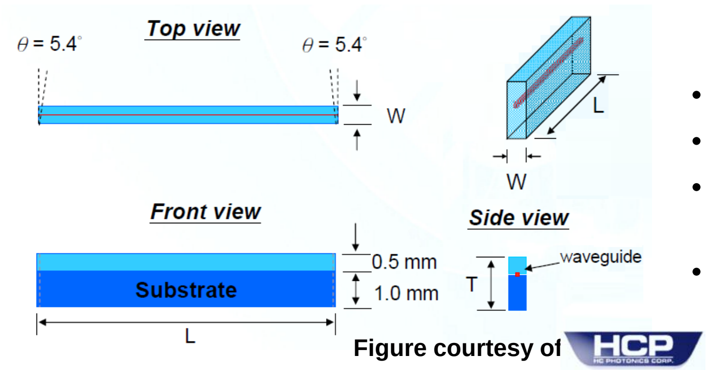




Dependence of SHG and launched pump power on wavelength over **567 nm – 652 nm** wavelength range

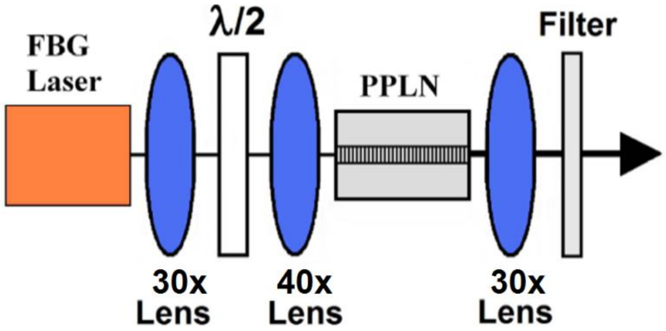
K.A. Fedorova et al., Laser Physics Letters, 9(11), p. 790, 2012

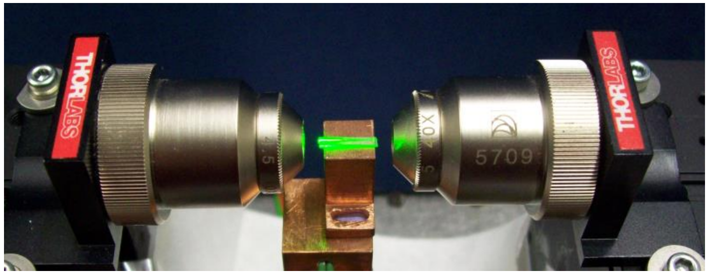
SHG at 561 nm from a PPLN waveguide

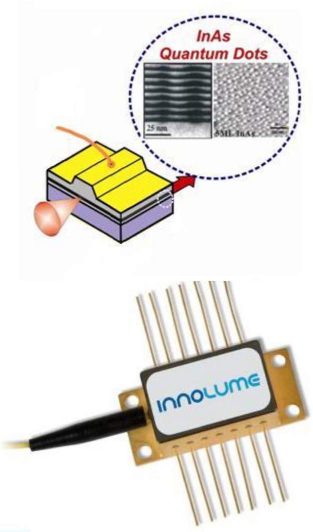


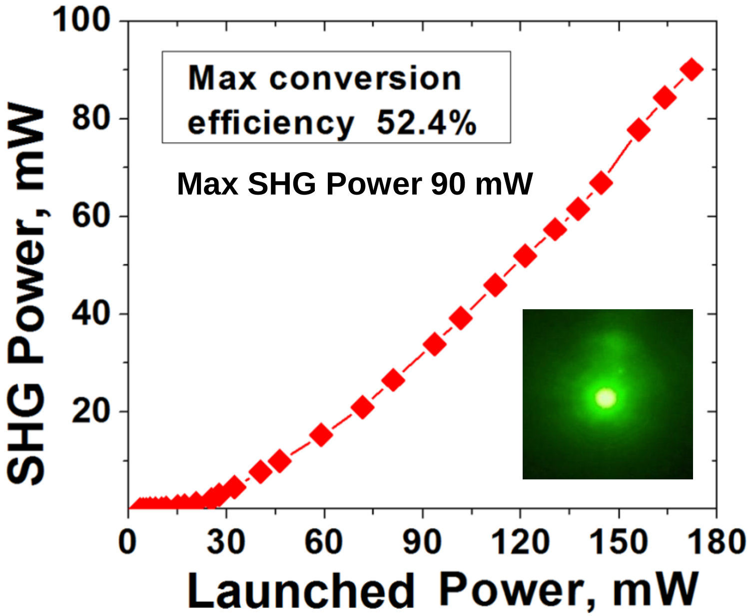
5% MgO-doped Y-cut congruent lithium niobate

- Dimensions: 10 mm (L) x 0.5 mm (W) x 1.5 mm (T)
- Facets optically polished at ~5.4^{o}
- AR coating at 1122 nm (R<0.5%) & at 561 nm (R<1%) on both input/output facets
- Cross-sectional area of the waveguide is ~ 4 x 5 μm^2



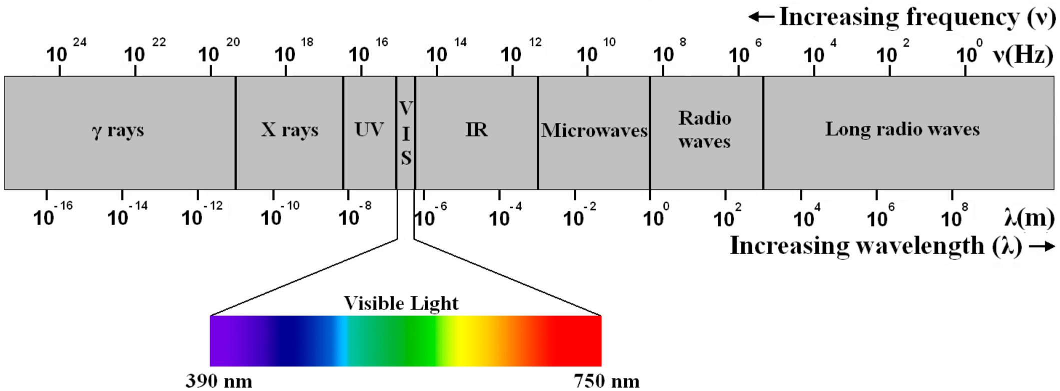






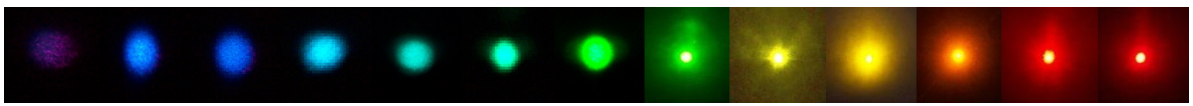
K.A. Fedorova et al., CLEO/Europe-EQEC, CD-P.21, 2013

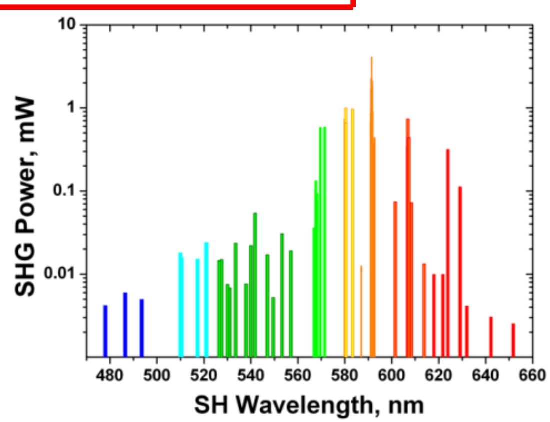
Compact visible laser sources



477nm

652nm

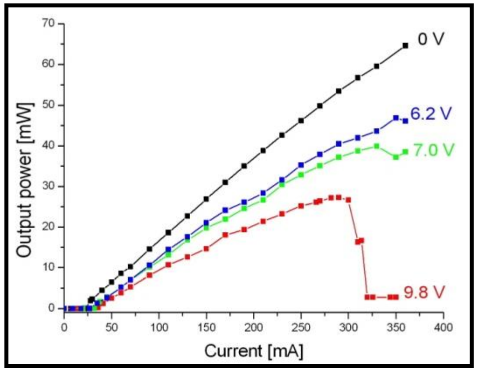


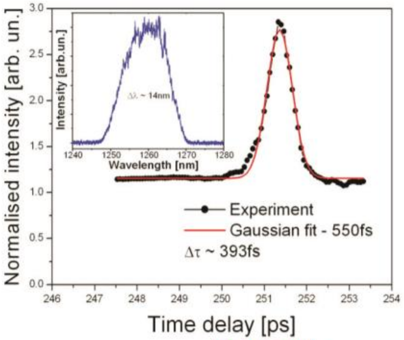


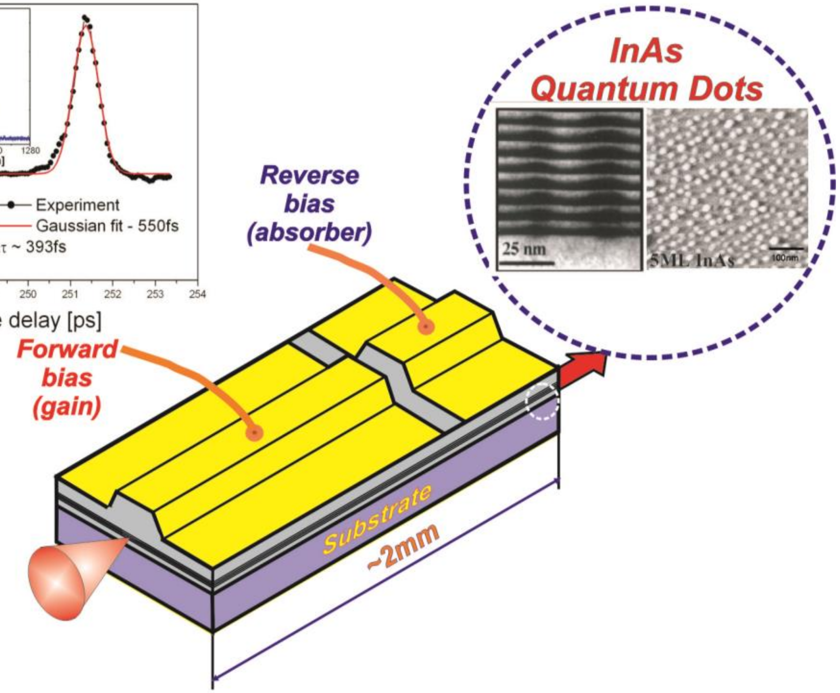
Applications

- Fluorescence microscopy
- Spectroscopy
- Medical Biotechnology
- Cell-surgery
- Dermatology (e.g. photodynamic therapy of cancer)
- Cosmetic treatments (tattoo removal, hair removal)
- Ophthalmology
- Flow cytometry
- Dentistry

Mode-locked QD laser





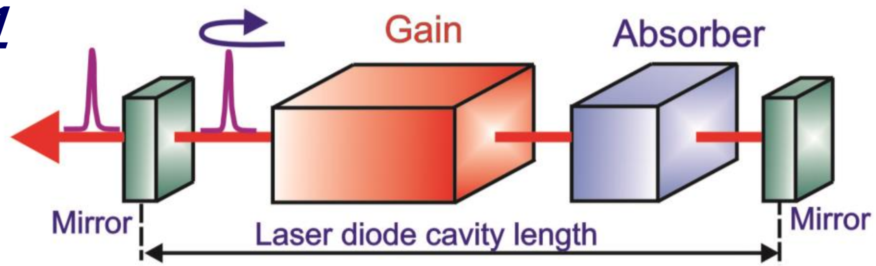


Shortest pulse duration $\Delta\tau$ **<400fs**

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

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

Time bandwidth product $\Delta\tau\,\Delta\nu \sim 1$



E.U. Rafailov et al., Appl. Phys. Lett. 87, p. 081107, 2005

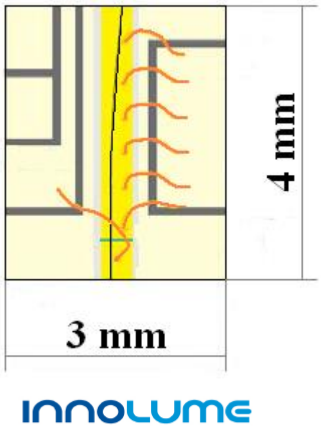
E.U. Rafailov et al., Nature Photonics, 1, p. 395, 2007

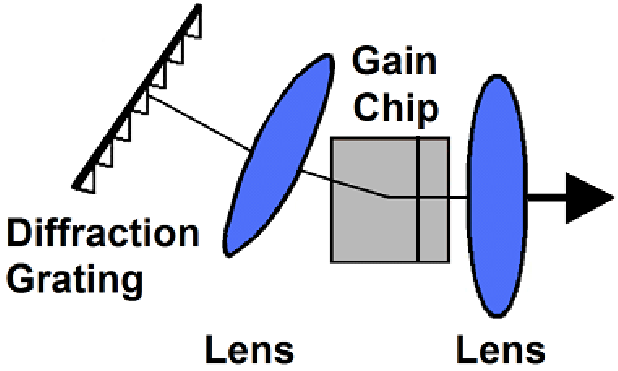
InAs/GaAs QD mode-locked tunable laser

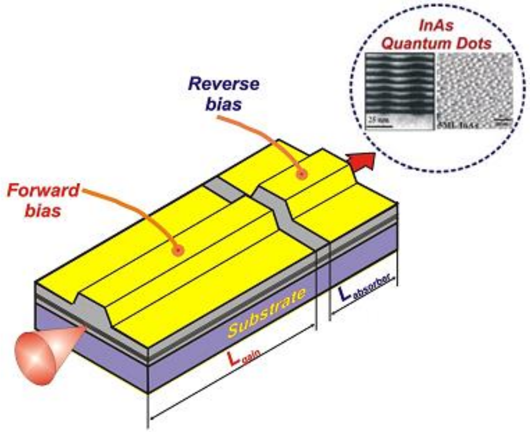
- 10 non-identical InAs QD layers, grown on GaAs substrate
- 4 mm length, 800 µm saturable absorber
- 6 µm wide waveguide
- waveguide angled at 7°
- facets AR coated: $R_{angled} < 10^{-5}$

  $R_{front} \sim 10^{-2}$

Gain Chip







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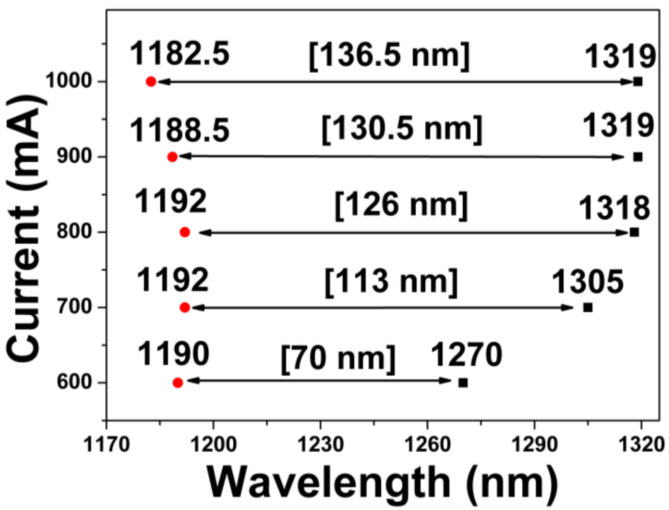
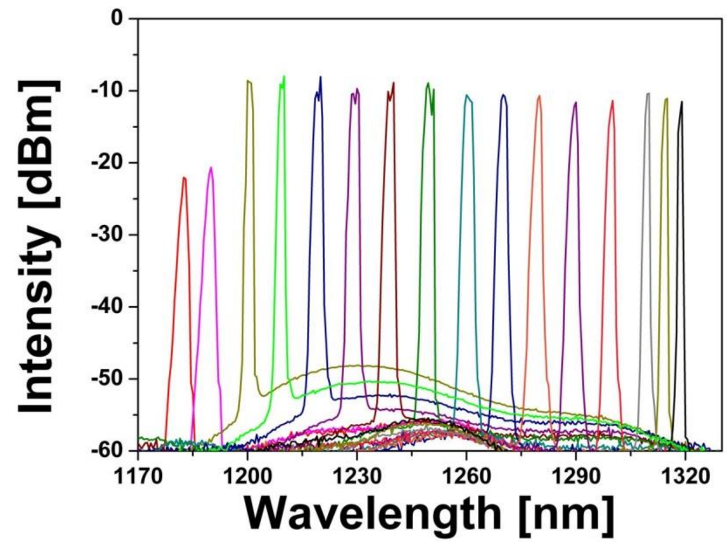
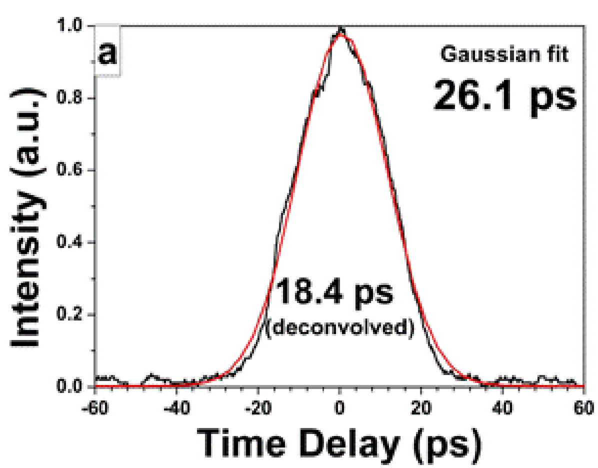
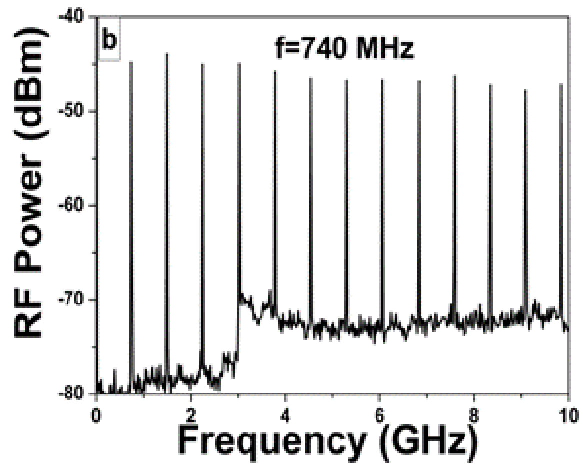
InAs/GaAs QD mode-locked tunable laser









Operating current: 1A
Reverse bias: 4V
Ppeak = 870 mW
Δt = 18.4 ps
λ = 1226 nm
$\Delta\lambda$ = 1.2nm
TBWP = 4.4

A broadly tunable high-power external cavity InAs/GaAs quantum-dot mode-locked laser with a tuning range of 137 nm (1182 nm – 1319 nm) is demonstrated

Appl. Phys. Lett. 101(12), p. 121107, 2012

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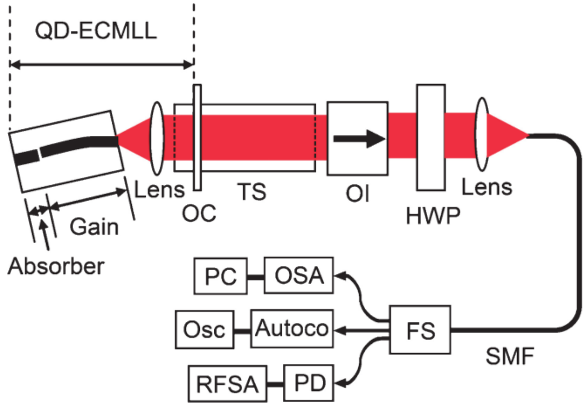
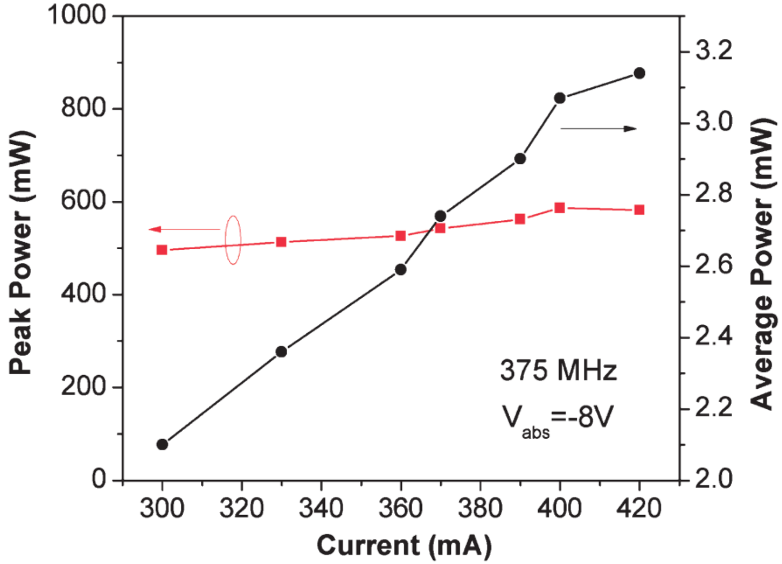
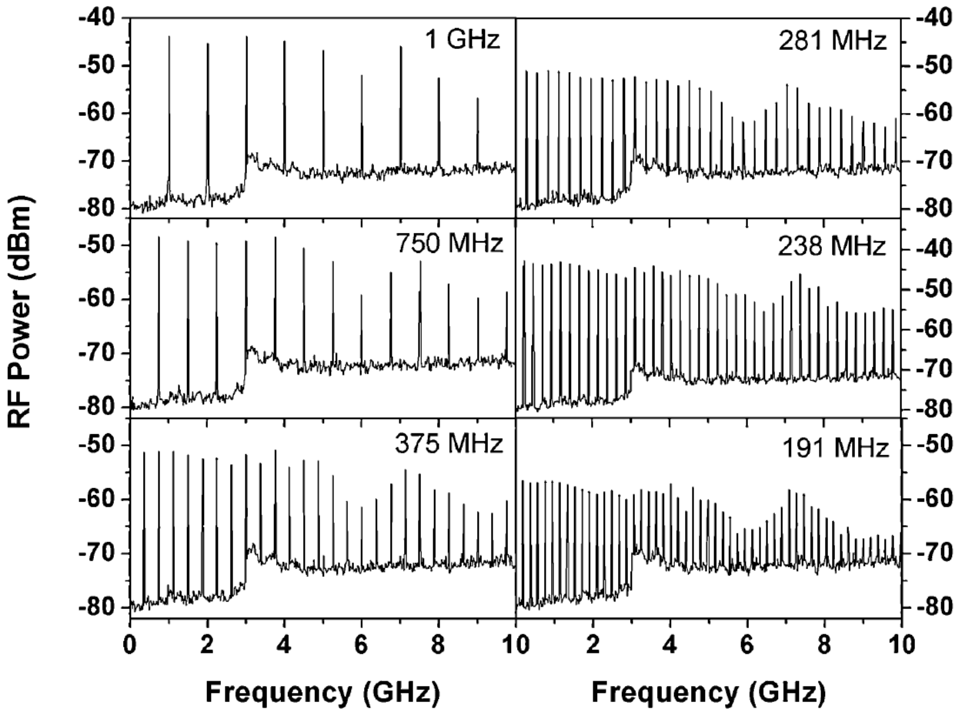
Broad Repetition-Rate Tunable QD-ECMLL





The peak power remains nearly constant under certain operation conditions (especially at a low gain current and a high reverse bias), with different pulse repetition rates



Broad repetition-rate tunable QD-ECMLL demonstrated frequency tuning range from **1 GHz** to a record-low value of **191 MHz** (The corresponding total optical cavity length varied from 15 to 78.5 cm)

Appl. Phys. Express, 4, p. 062703, 2011

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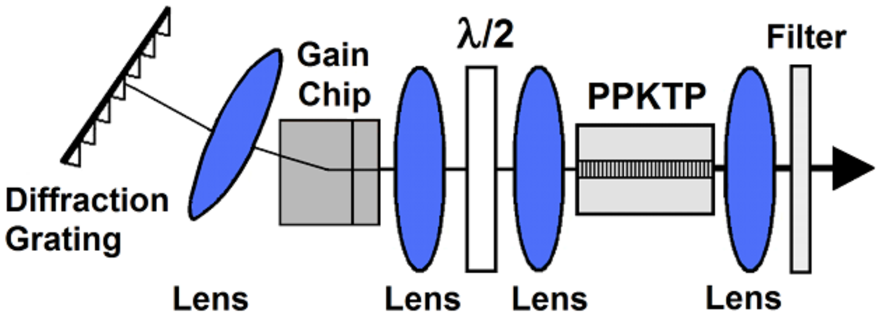
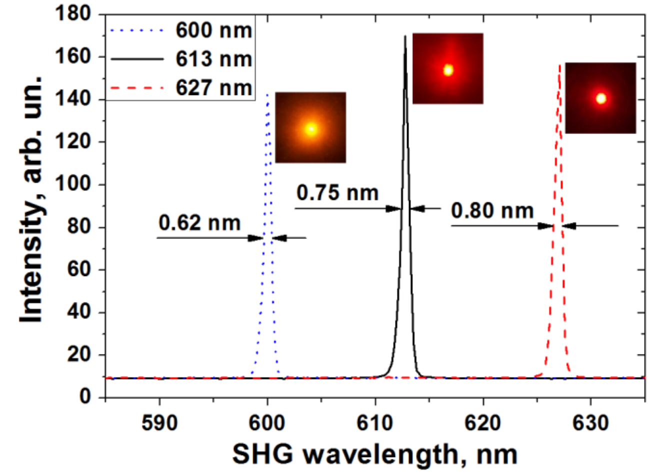
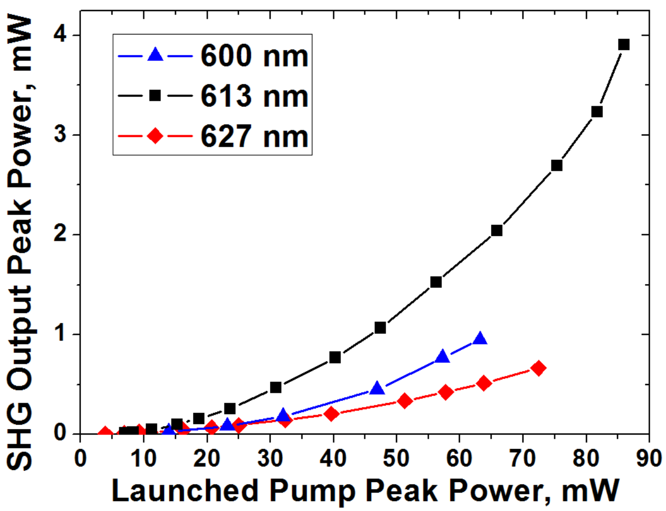
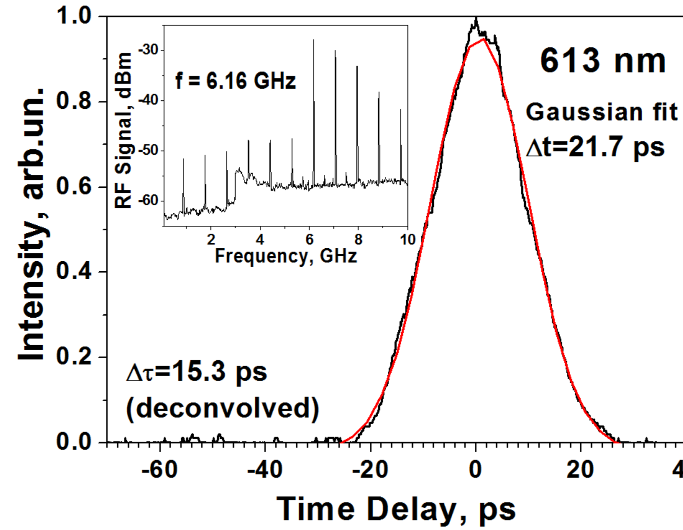
Orange-to-Red tunable picosecond SHG









K.A. Fedorova et al., Optics Letters, 38(15), p. 2835, 2013

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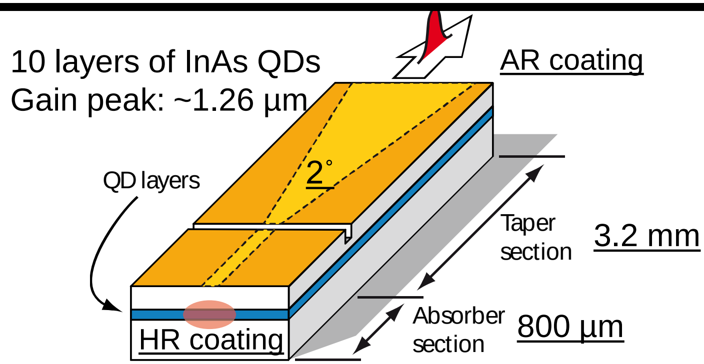
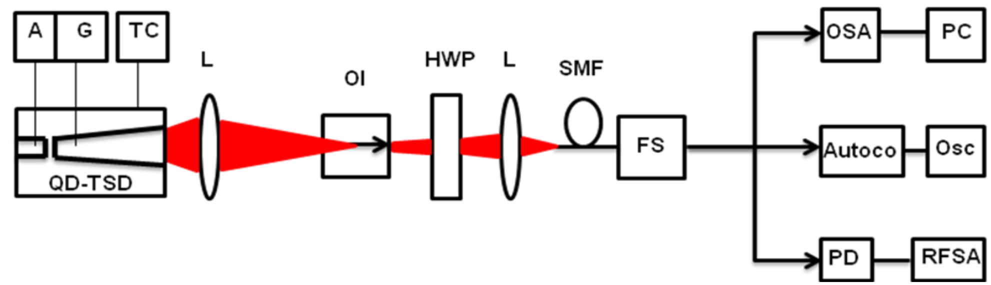
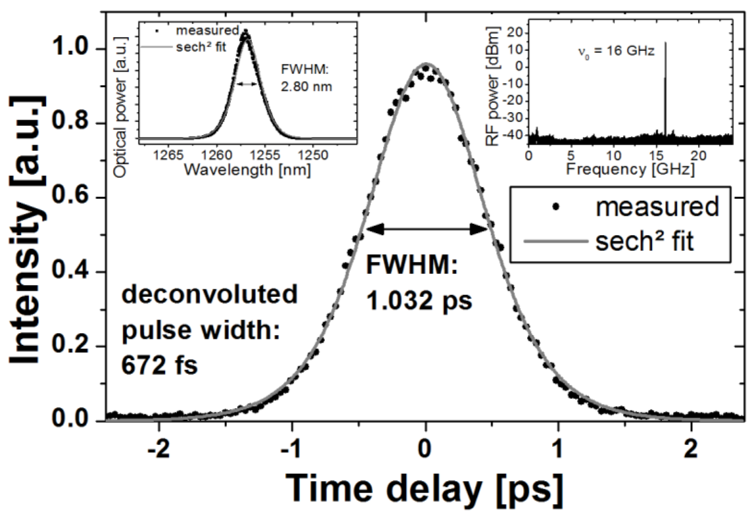
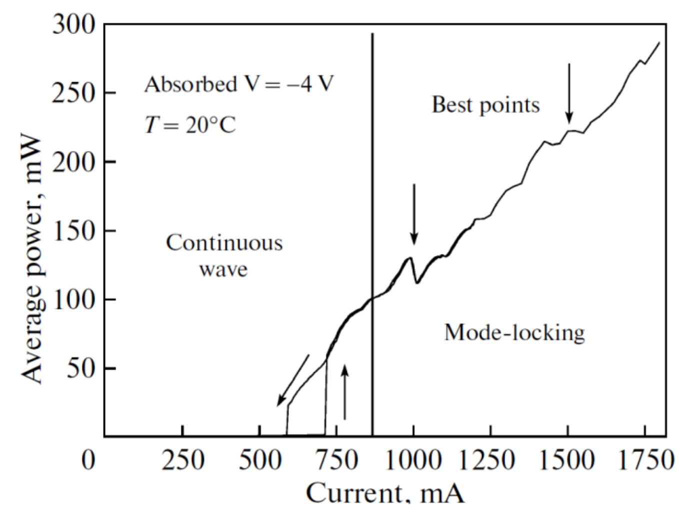
QD Tapered Lasers









P_{aver} = 288 mW; P_{peak} = 17.7 W; λ ~ 1260 nm;
Δt ~ 672 fs; Δλ = 2.8 nm; f ~ 16 GHz

Laser Physics, 22(4), p. 715, 2012

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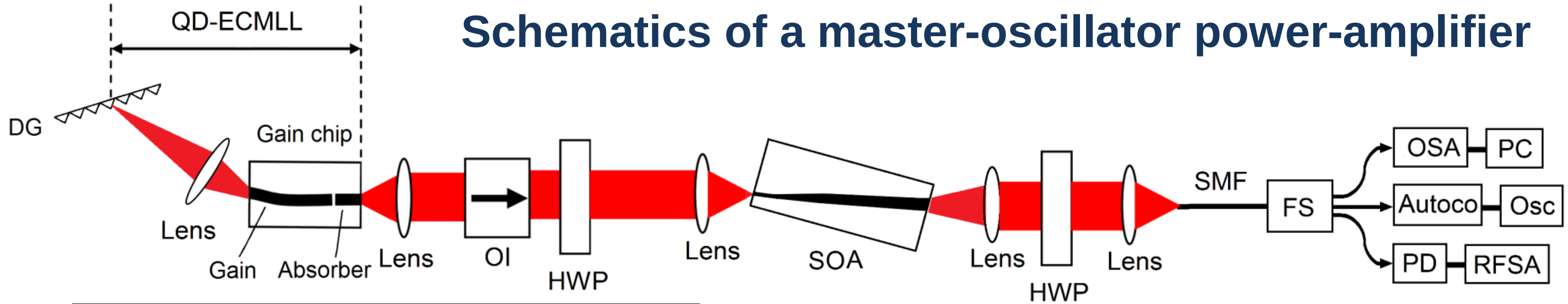
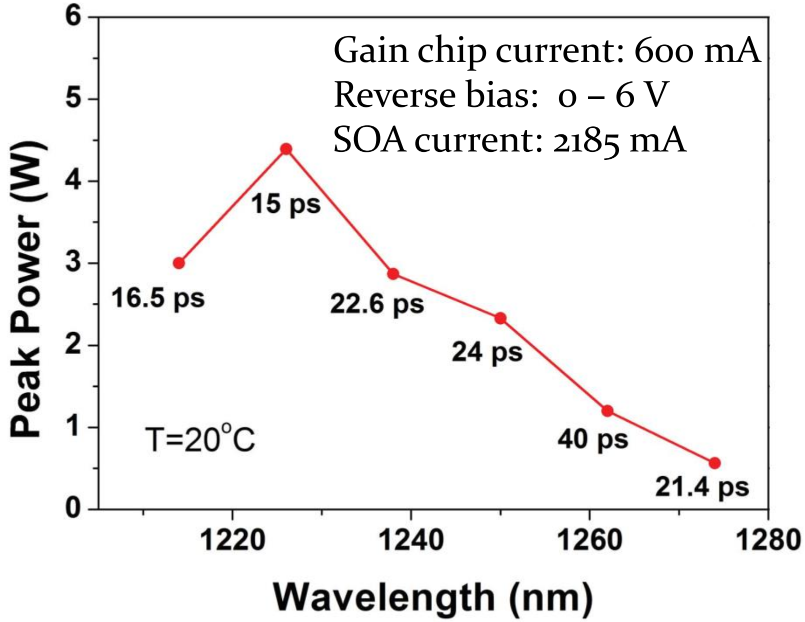
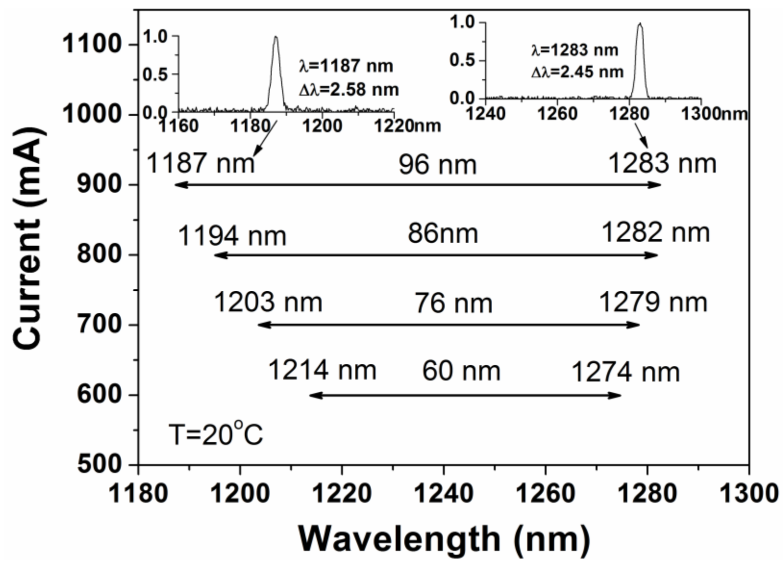
Broadly tunable QD-based MOPA

Schematics of a master-oscillator power-amplifier



IEEE Phot. Tech. Lett. 24(20), p.1841, 2012





Demonstration of a **96-nm** tunable (between **1187 nm** and **1283 nm**) MOPA picosecond optical pulse system formed by an QD-ECMLL and a tapered SOA with **4.39-W** peak power under fundamental mode-locked operation

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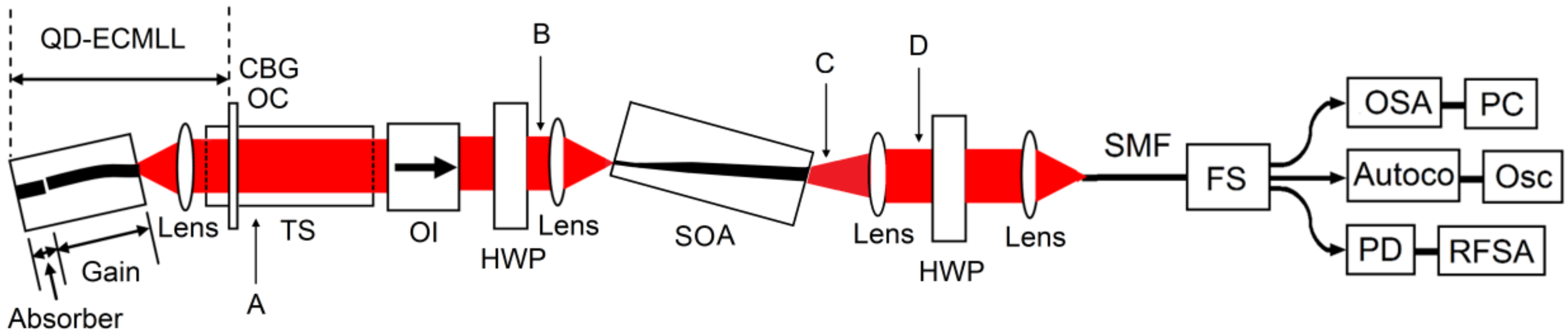
High-power QD-based MOPA



Gain Chip

- 10 layers InAs QDs, grown on GaAs substrate
- 4 mm length, 800 μm saturable absorber
- 6 μm wide waveguide
- waveguide angled at 7°
- front facet AR coated: R angled < 10^{-5}
- back facet HR coated: R ~ 95%

SOA

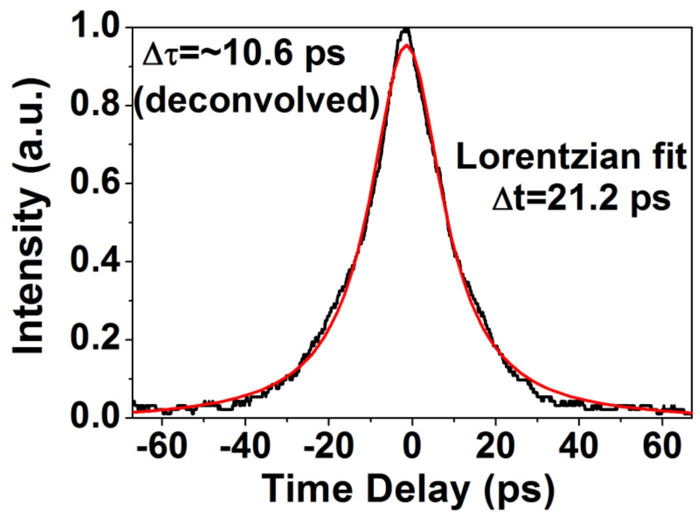
- 10 layers InAs QDs, grown on GaAs substrate
- 6 mm length
- waveguide width changes from 14 μm to 80 μm
- facets AR coated: R ~ 10^{-5}

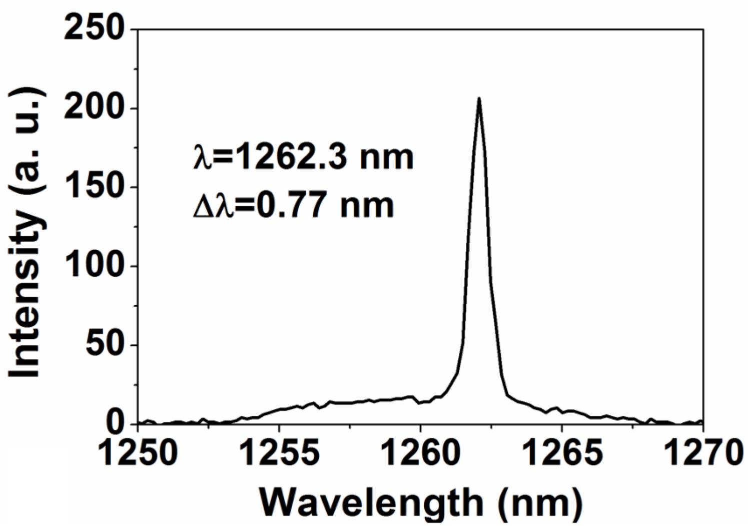
Chirped Bragg grating (CBG)

- center wavelength ~ 1262 nm
- reflectivity ~12-15%

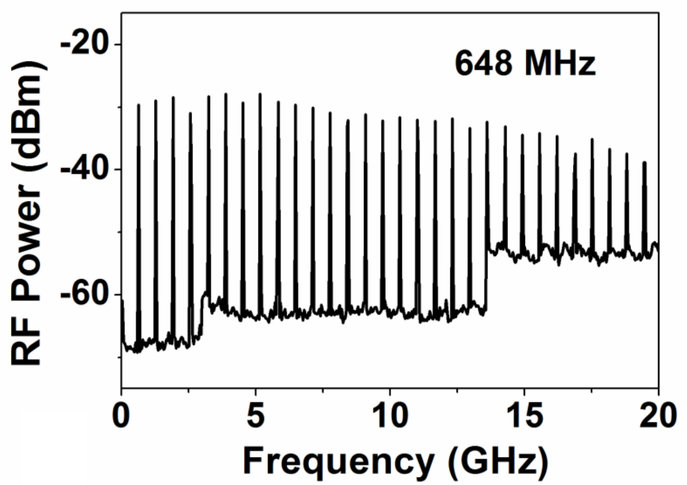
Optics Express, 20(13), p. 14308, 2012

High-power QD-based MOPA





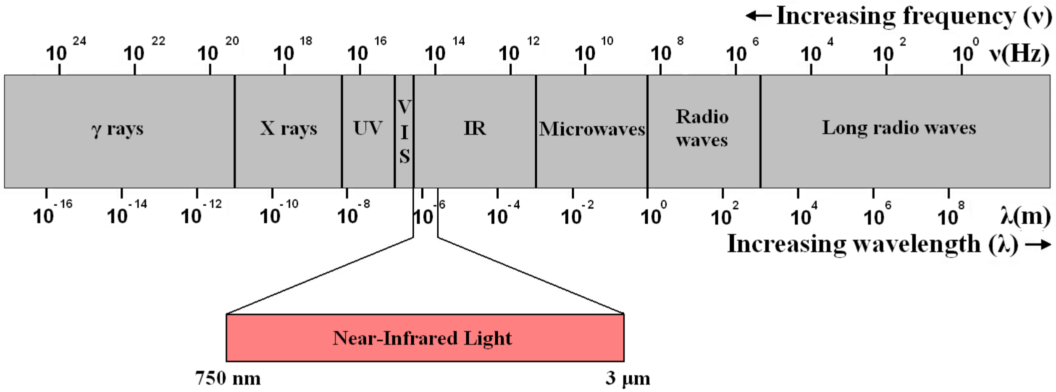
Gain chip current: **200mA**
Reverse bias: **4V**
SOA current: **2.5A**
P_{peak} = **30.3 W (42 W)***
Δ*t* = **10.6 ps**
Repetition rate: **648 MHz**
λ = **1262.3 nm**

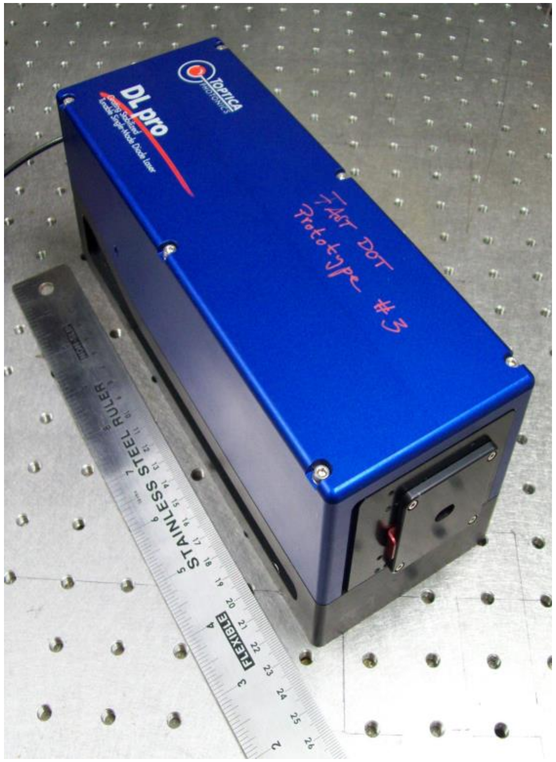


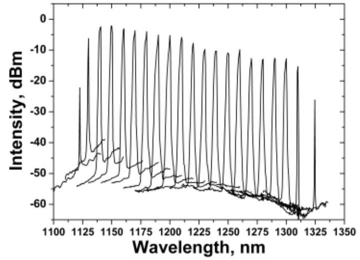
Optics Express, 20(13), p. 14308, 2012

***Optics Lett, 2014 submitted**

Compact QD laser sources

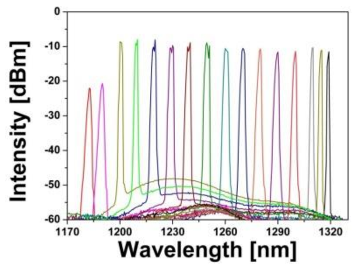






1122 nm – 1324 nm

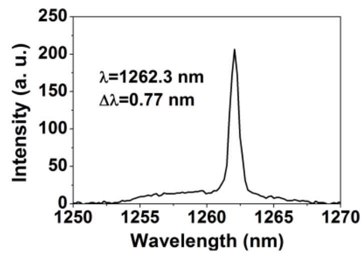
Up to **500 mW** in CW



1182 nm – 1319 nm

Up to **4.39 W** pulsed

(1.3GHz, 15-20ps)



Up to **30.3 W** pulsed

(648MHz, 10.6ps)

Down to **191 MHz** rep. rate

672 fs pulse duration

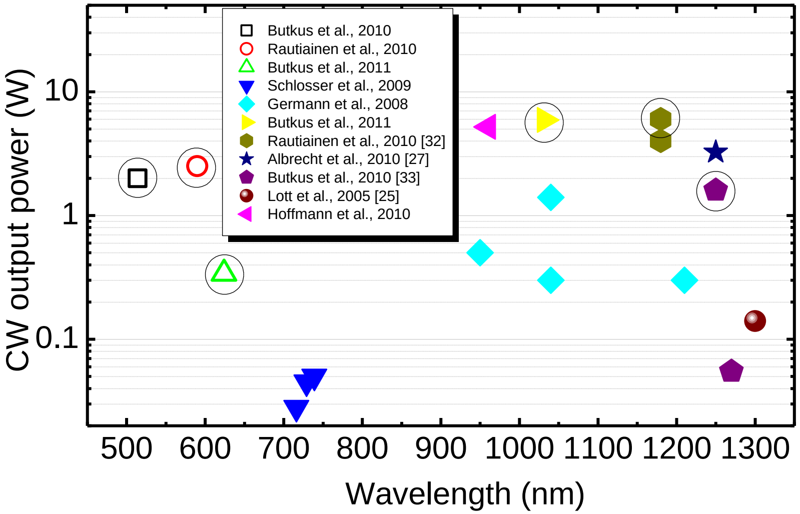
Applications

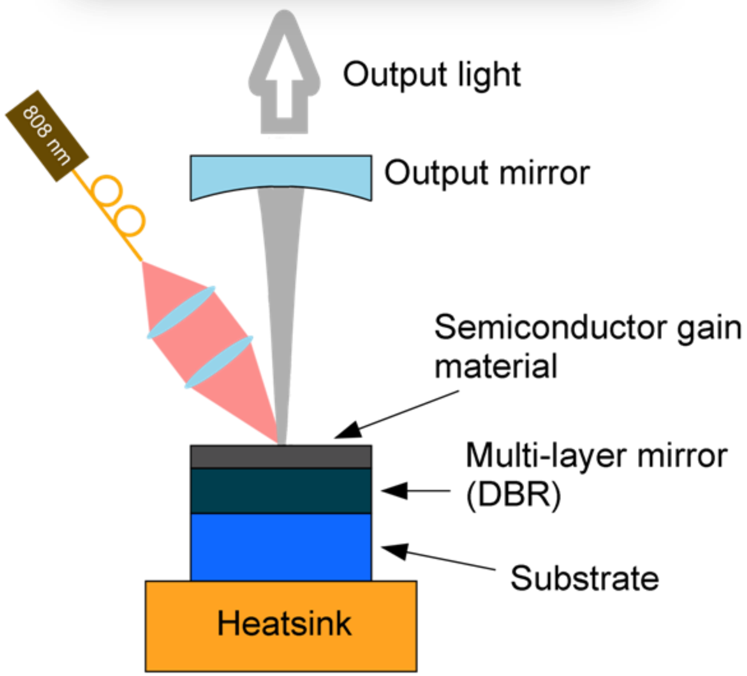
- Fluorescence microscopy
- Spectroscopy
- Optical coherence tomography
- Cell-surgery
- Dermatology (e.g. photodynamic therapy of cancer)
- Cosmetic treatments (tattoo removal, hair removal)
- Ophthalmology
- Dentistry
- Blood analysis
- Frequency-conversion

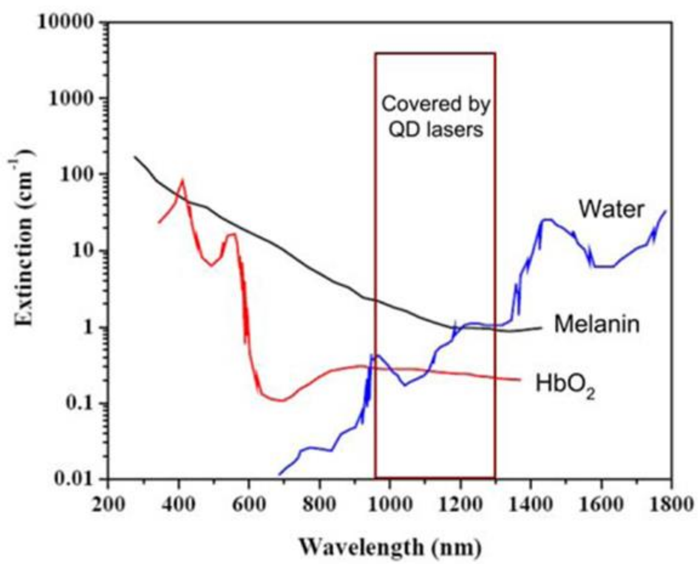
FAST-DOT

QD Semiconductor Disk Laser (SDL)

Vertical External Cavity Surface Emitting Laser (VECSEL)

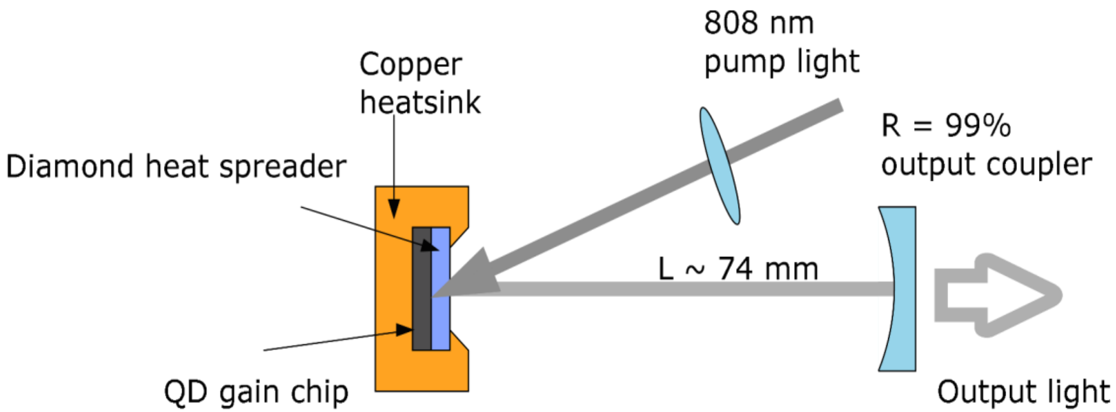


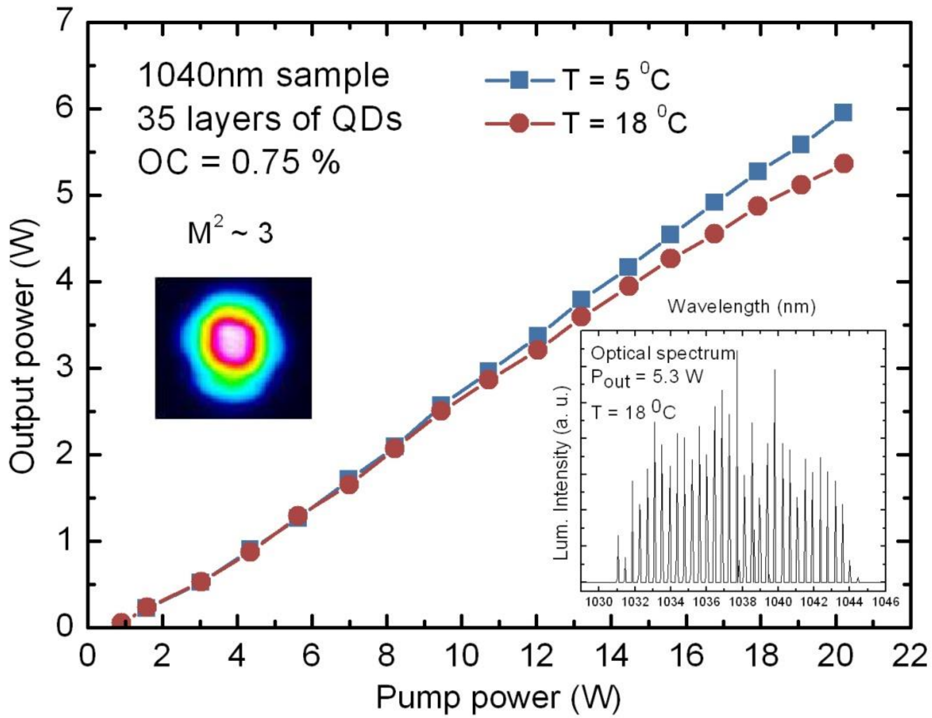


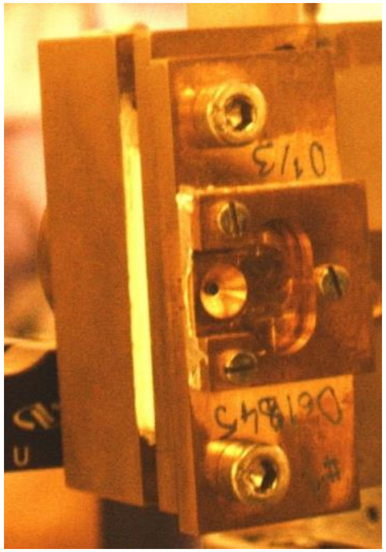


Low light absorption and minimal scattering in human tissue in 1 – 1.3 µm range

6 W (8W*) CW from QD gain at 1040nm





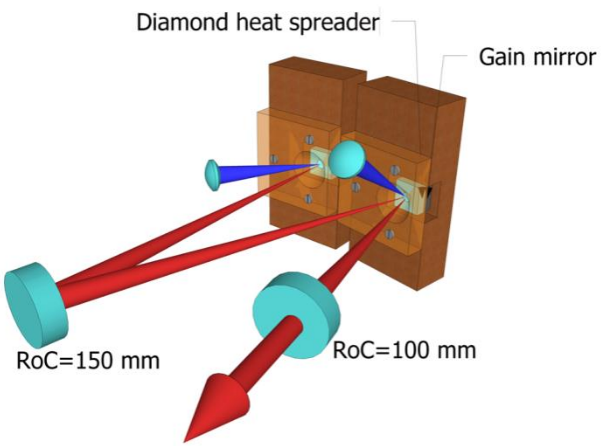


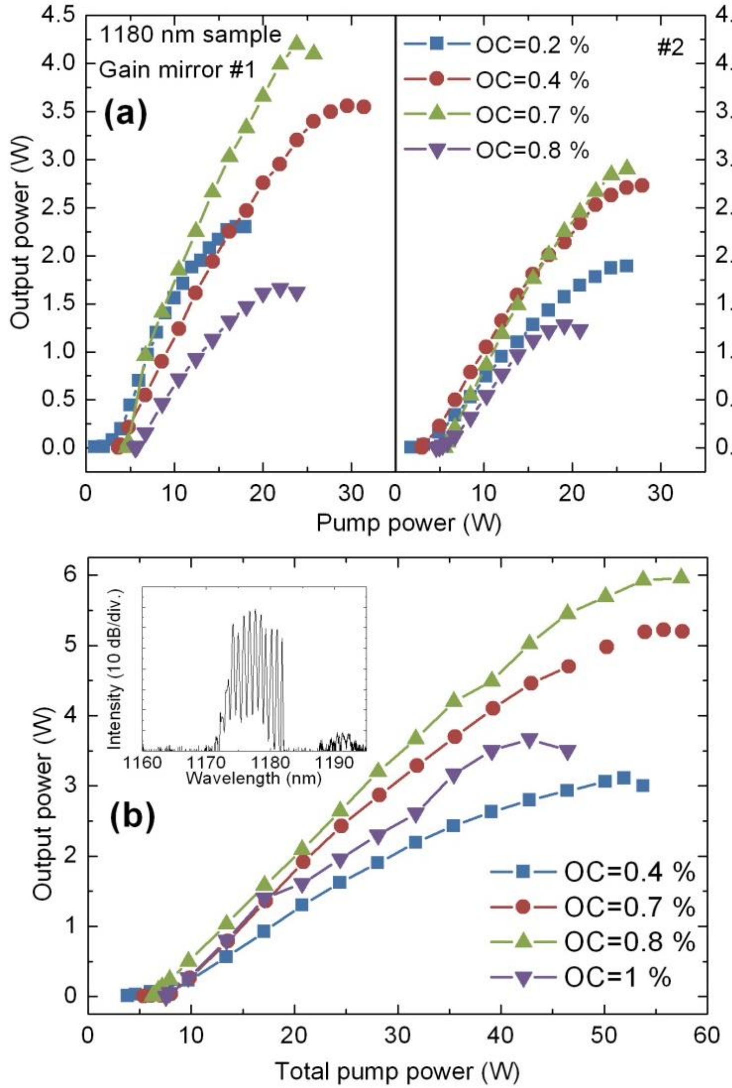
M. Butkus et al., IEEE J. Sel. Top. Quant. Electron., 17, p. 1763, 2011

*IEEE Phot.Tech.Lett, 26, p. 1565, 2014

6 W CW from QD gain at 1180nm

New design with 39 QD-layers: achieve highest average output power of a cw QD-VECSEL operating in the 1.2-µm spectral region





Single gain device P_{max} > 4 W CW

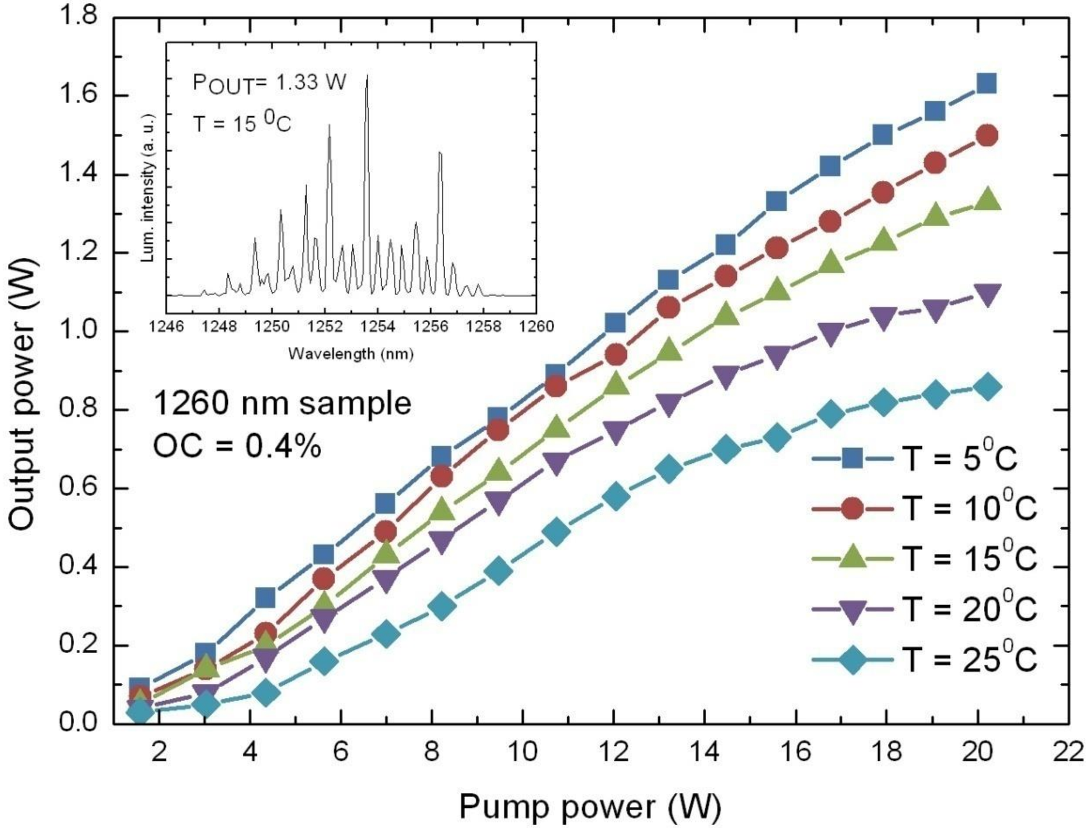
Dual gain device P_{max} > 6 W CW

M. Butkus et al., IEEE J. Sel. Top. Quant. Electron., 17, p. 1763, 2011

1.6 W CW from QD gain at 1260nm

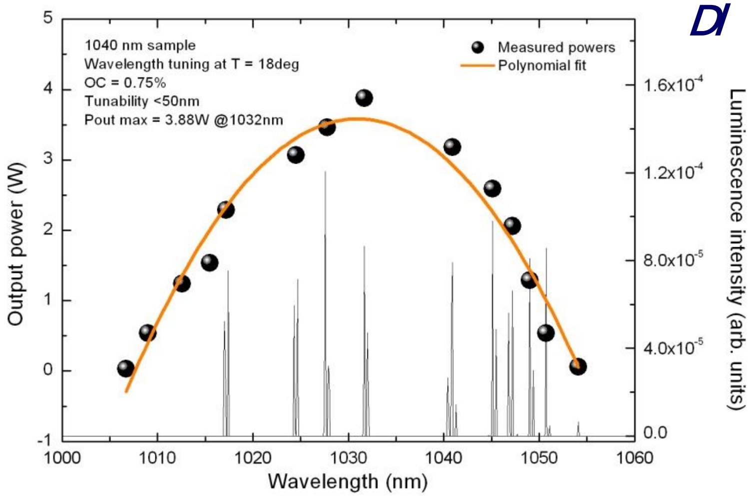
New design with 39 QD-layers: achieve highest average output power of a cw QD-VECSEL operating in the 1.26-µm spectral region

- P_{max} 1.6 W CW
- M^2 ~1.1 up to 0.8 W



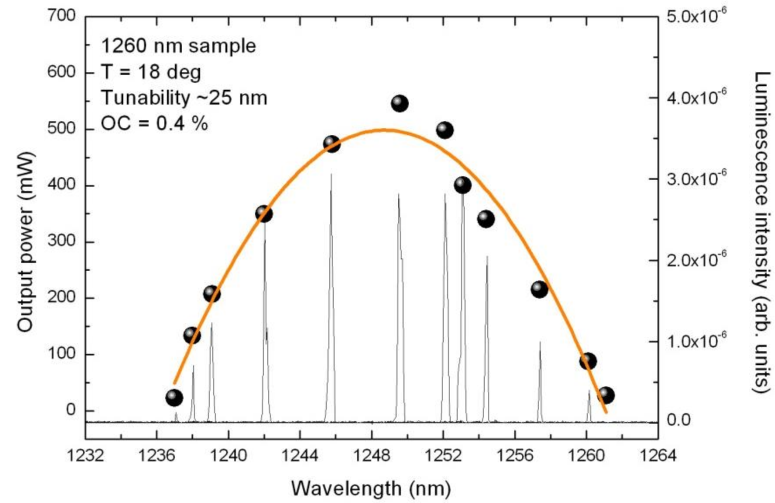
M. Butkus et al., IEEE J. Sel. Top. Quant. Electron., 17, p. 1763, 2011

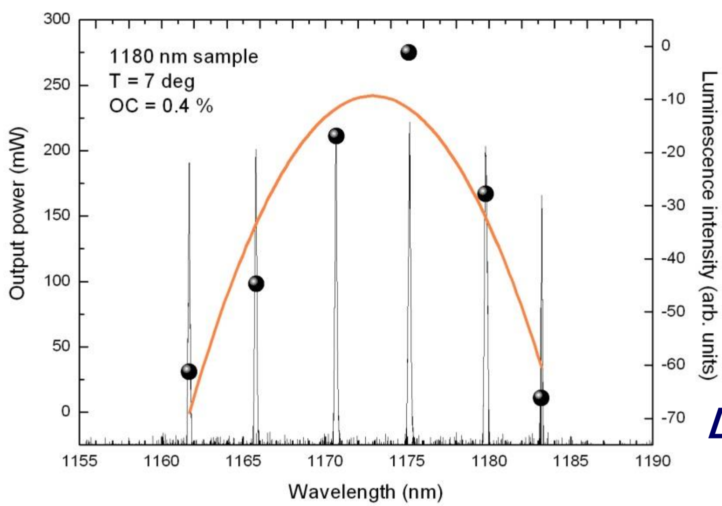
Tunable QD-SDL



Dl ~60nm at 1030nm

Dl ~25nm at 1260nm



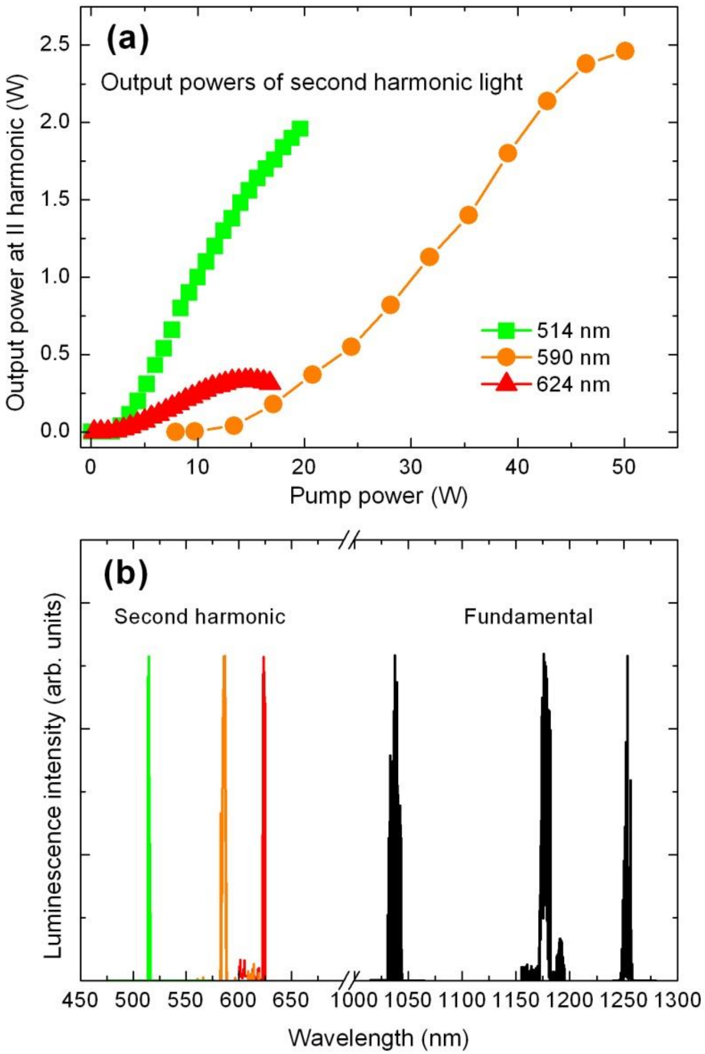


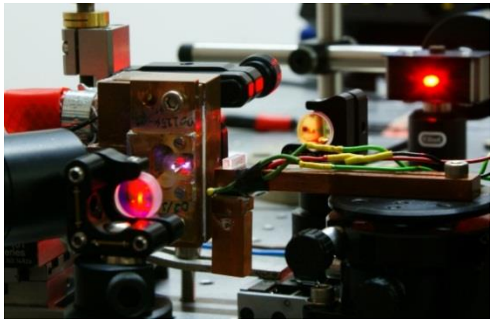
Dl ~69nm at 1180nm

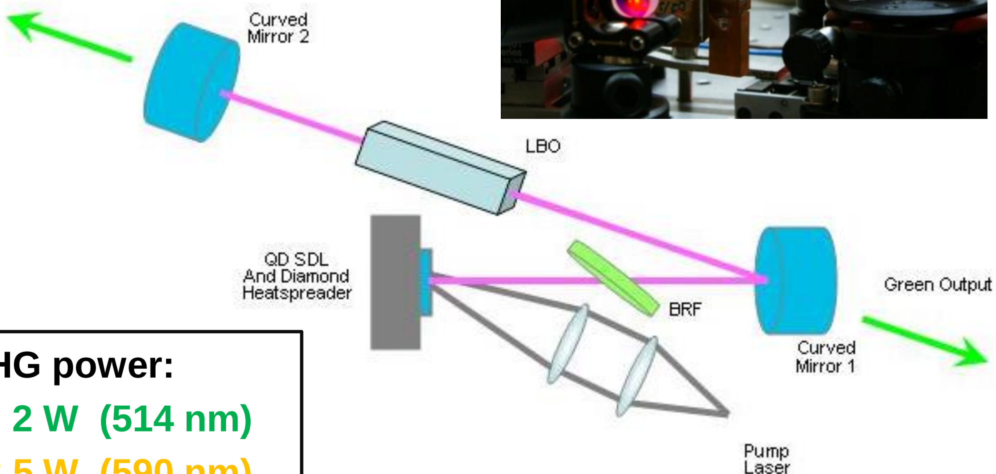
M. Butkus et al., IEEE J. Sel. Top. Quant. Electron., 17, p. 1763, 2011

Aston University
Birmingham

Intracavity SHG in QD VECSEL





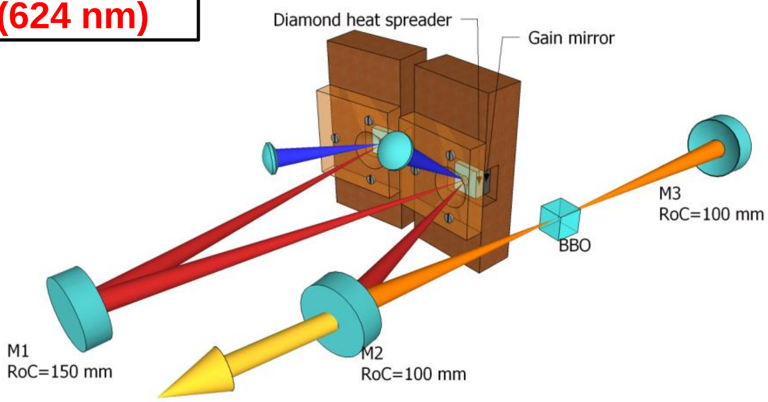


SHG power:

2 W (514 nm)

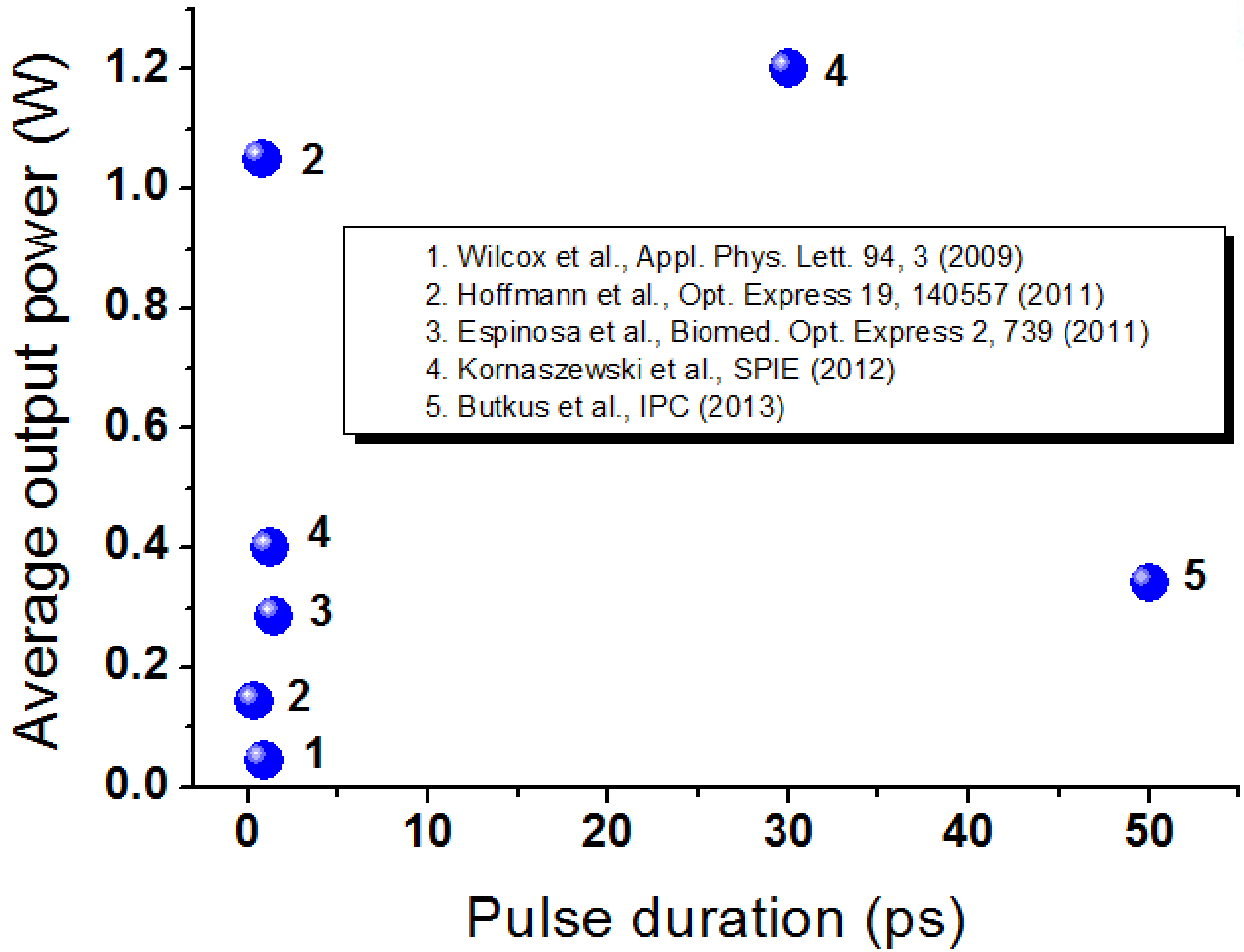
2.5 W (590 nm)

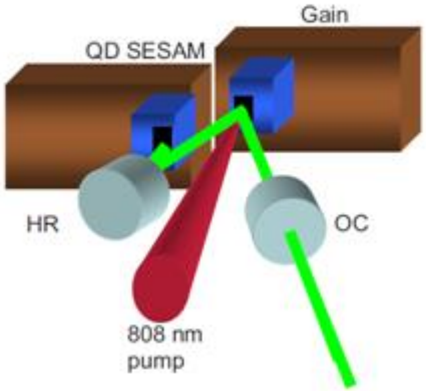
0.33 W (624 nm)



M. Butkus et al., IEEE J. Sel. Top. Quant. Electron., 17, p. 1763, 2011

Recent development of mode-locked SDLs with QD technology





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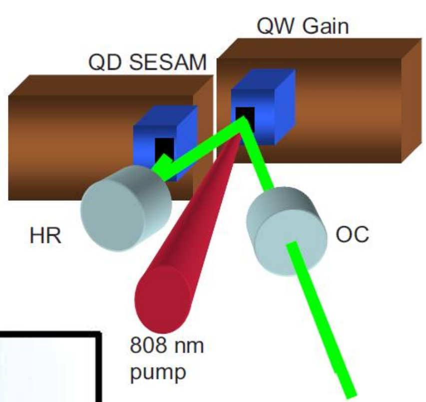
Mode-locked SDL

Mode-lock SDL with QW gain and using QD SESAM

- λ = 965 nm
- Room temperature operation (20°C)

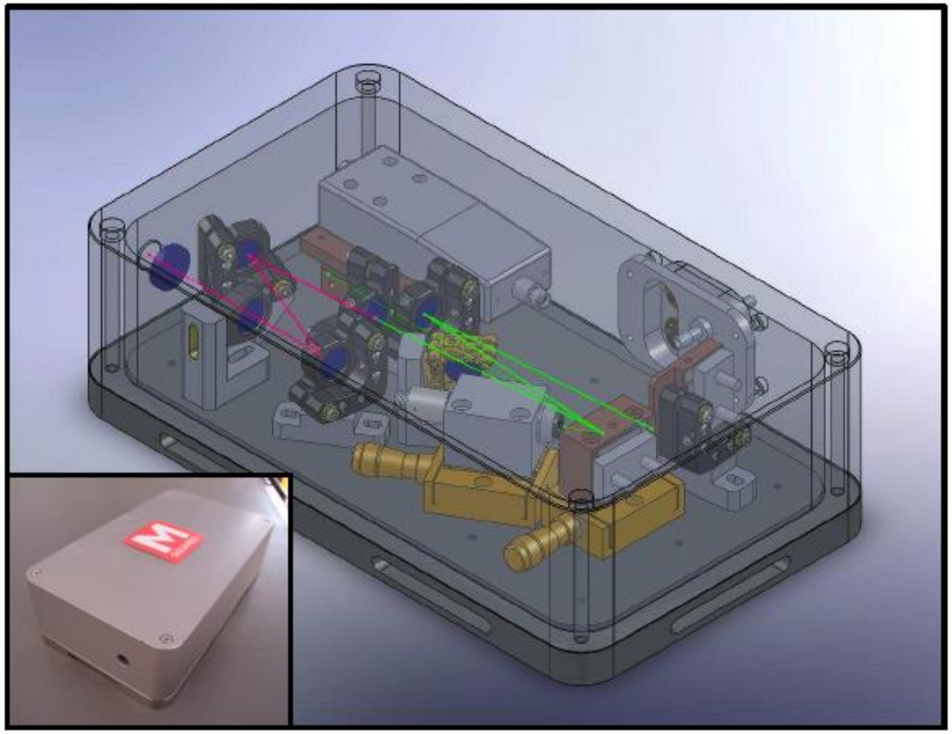


Gain:

- 6 layers of QW

SESAM:

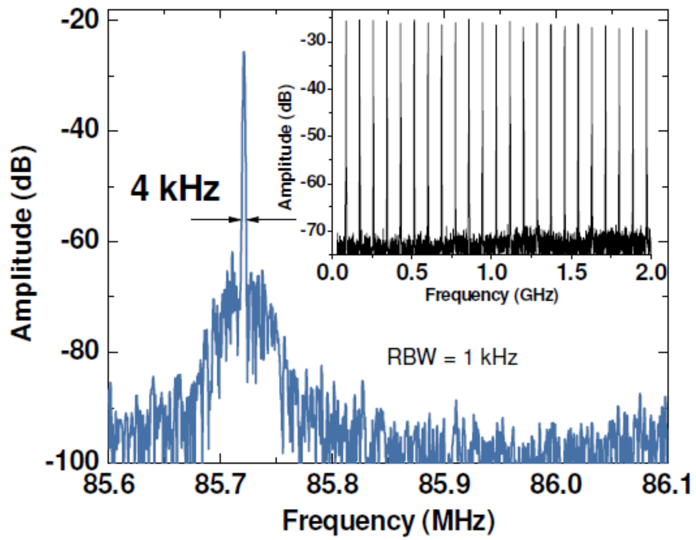
- 5 QD layers

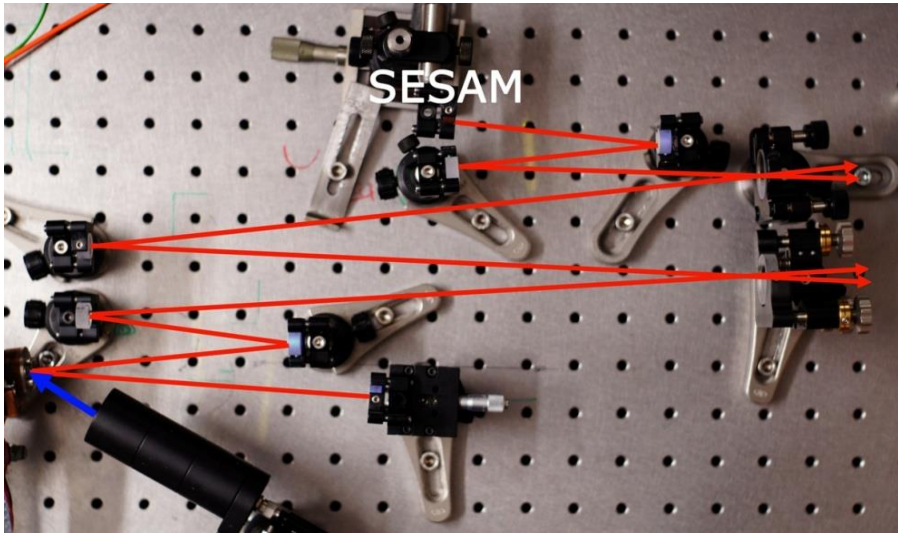


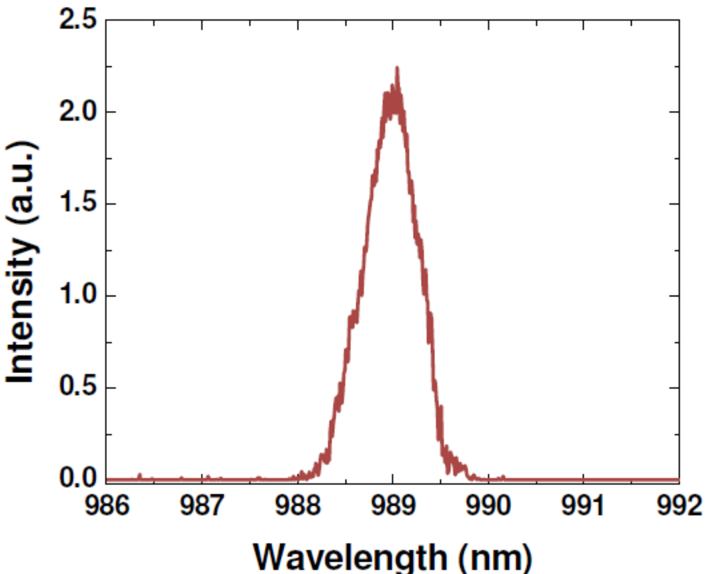
- Output power: **> 1 W**
- Pulse duration **< 1.5 ps**
- Repetition rate: **500 MHz**

Appl. Phys. Lett., 94, p. 251105, 2009

Ultra-low repetition rate mode-locked SDL







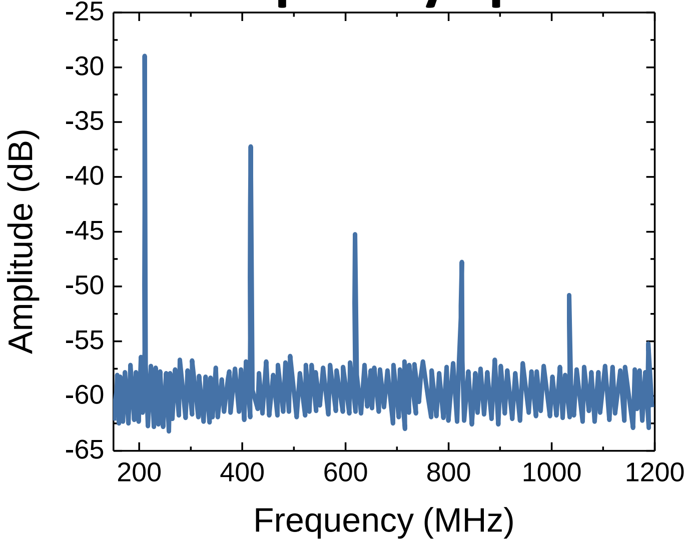
Ultra low repetition rate of **85.7 MHz** is demonstrated in mode-locked semiconductor disk laser overcoming short carrier lifetime limitations. It is shown that fundamental mode-locking in such long cavity is supported by phase-amplitude coupling.

M. Butkus et al., IPC-2013, WE2.3, 2013

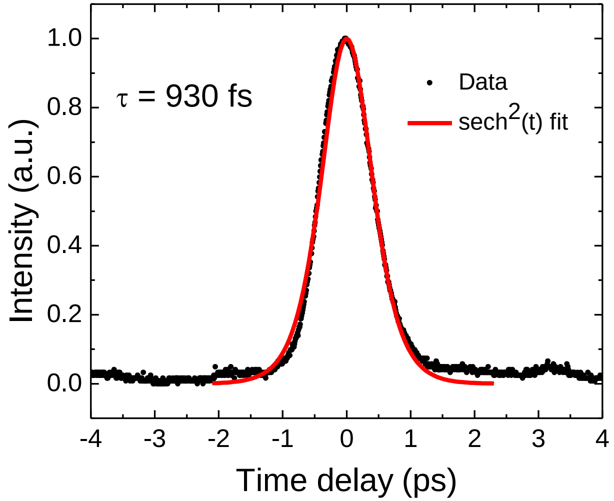
Self-mode-locking in semiconductor lasers

Aston University Birmingham

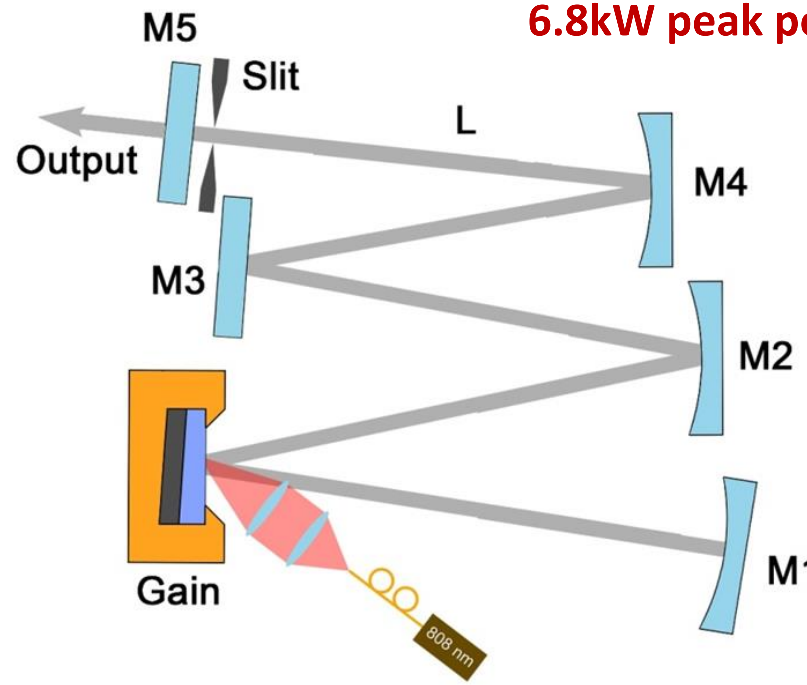
RF frequency spectra:



Autocorrelation trace:



6.8kW peak power



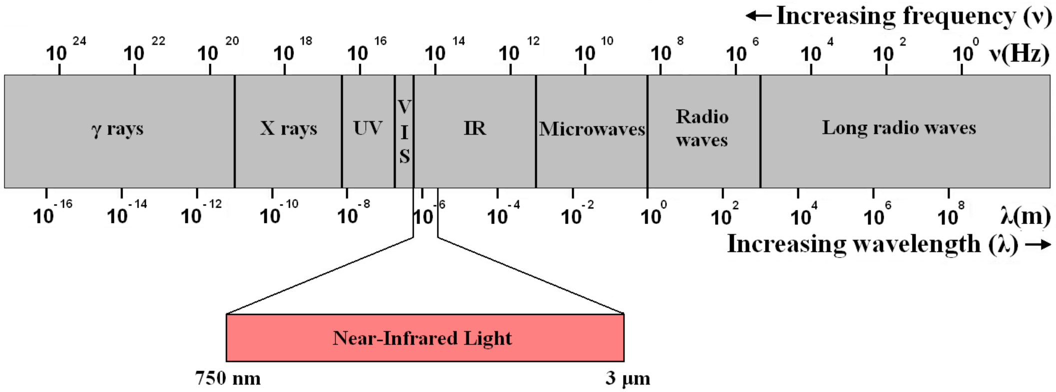
ML observed in two configurations:

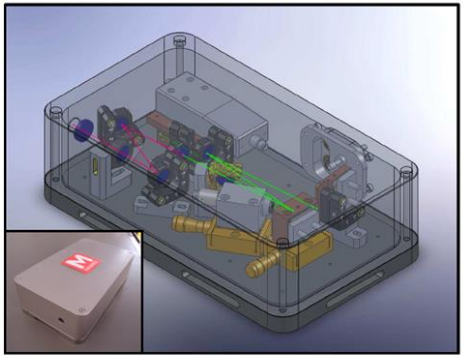
- **Soft aperture** near stability limit
- With **hard aperture** within stability limits

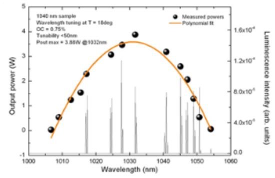
Kornaszewski et al, Laser Photonics Rev., 6(6), L20, 2012

Gaafar et al, Opt. Lett., v.39(15), p. 4623-4626, 2014

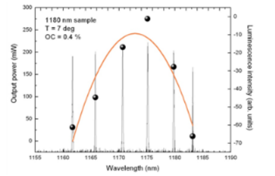
Compact QD-VECSEL sources



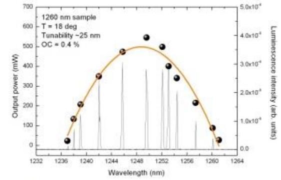




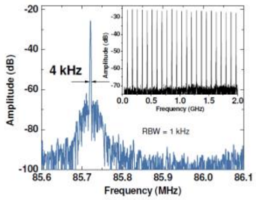
$\Delta\lambda$ ~ **60 nm** at 1030nm
Up to 6 W in CW at 1040 nm
Up to 2 W in CW at 514 nm



$\Delta\lambda$ ~ **69 nm** at 1180nm
Up to 6 W in CW at 1180 nm
Up to 2.5 W in CW at 590nm



$\Delta\lambda$ ~ **25 nm** at 1260nm
Up to 1.6 W in CW at 1270 nm
Up to 0.33 W in CW at 624nm



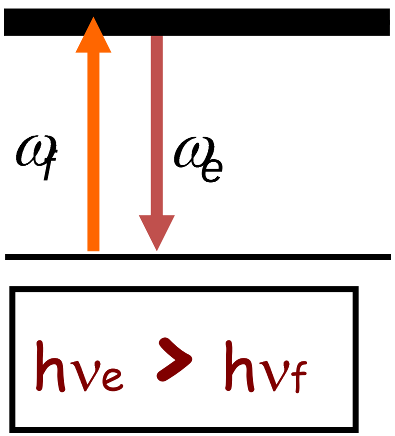
Up to 1 W in pulsed regime
Short pulse duration 870 fs
Ultra low repetition rate 85.7 MHz

Applications

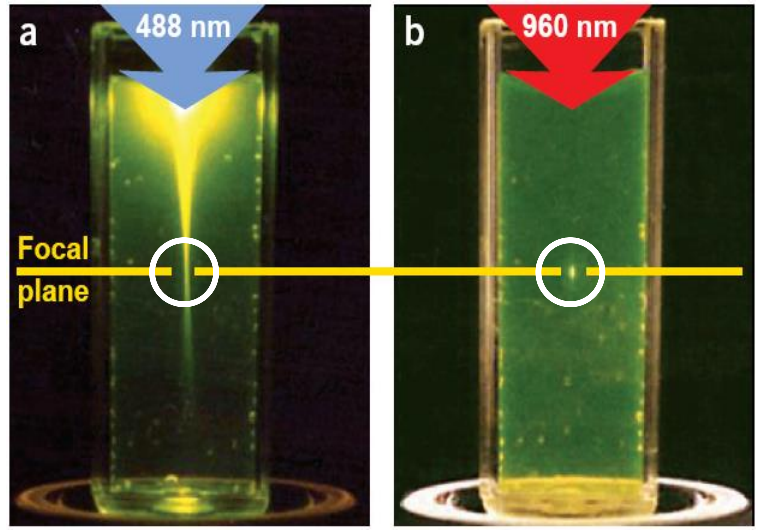
- Fluorescence microscopy
- Spectroscopy
- Optical coherence tomography
- Cell-surgery
- Dermatology (e.g. photodynamic therapy of cancer)
- Cosmetic treatments (tattoo removal, hair removal)
- Ophthalmology
- Dentistry
- Blood analysis
- Frequency-conversion

FAST-DOT

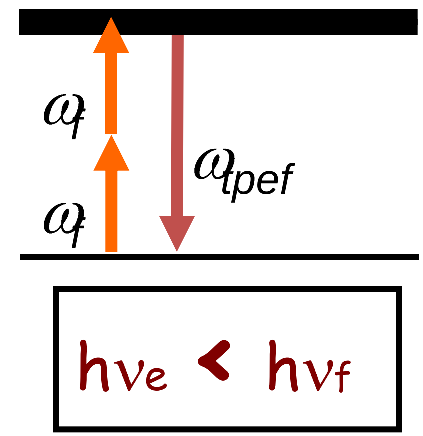
Multi-photon Imaging



Linear excitation fluorescence | **Two-photon excitation fluorescence**



signal is NOT confined | **signal is confined**

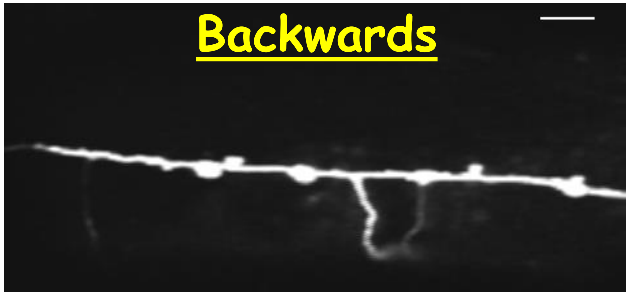


Single Photon Excitation: Lots of absorption everywhere, sample damage and no intrinsic sectioning

Multi-Photon Excitation: Absorption/excitation only in focal volume, less damage, live sample imaging, 3-D scanning, longer wavelength=less scatter

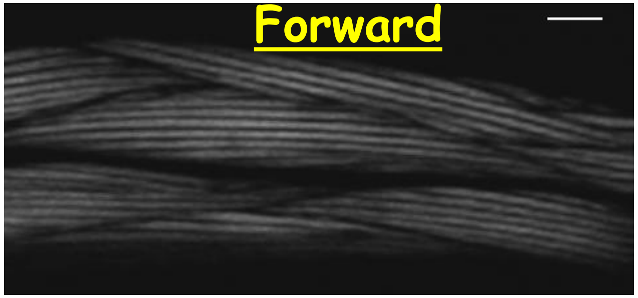
Multi-photon imaging with femtosecond laser

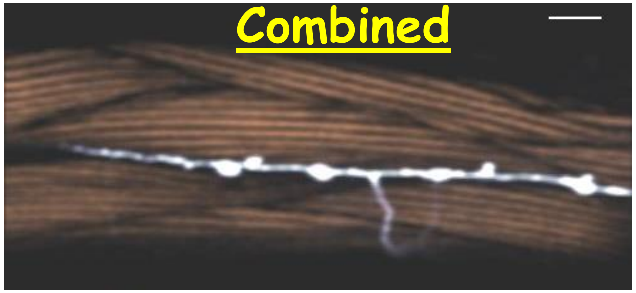
GFP labelled neurons (two-photon excited fluorescence - TPEF)



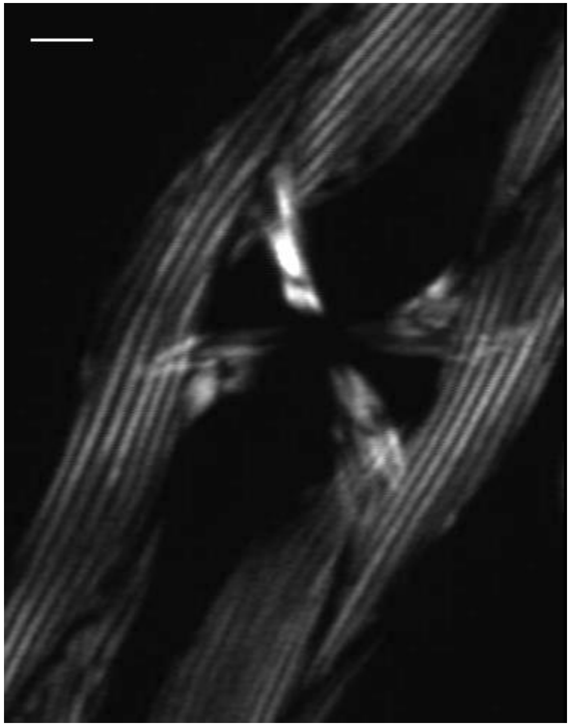
Body wall muscles (SHG)

C. Elegans





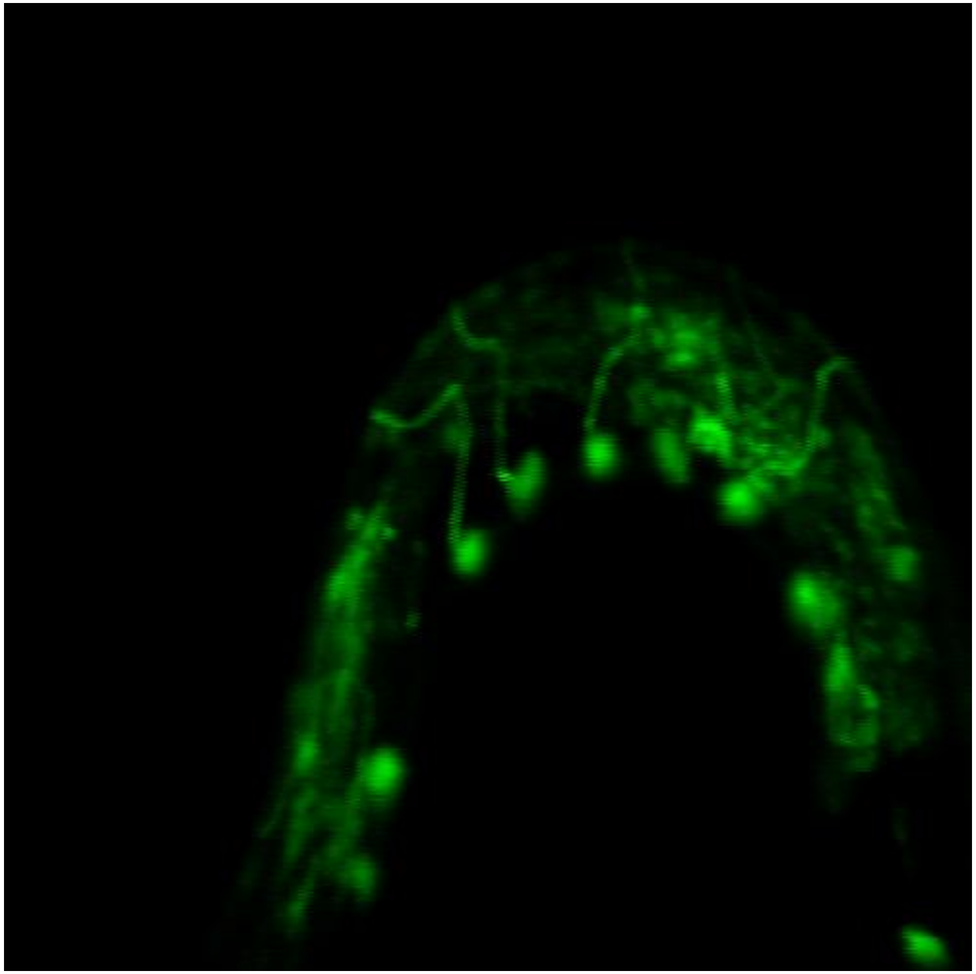
SHG Imaging of Vulva Muscles and body walls

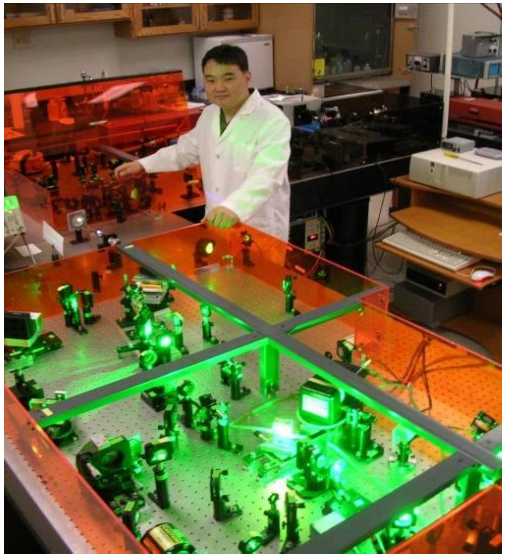


ICFO Barcelona

FAST-DOT

Multi-photon imaging with femtosecond laser

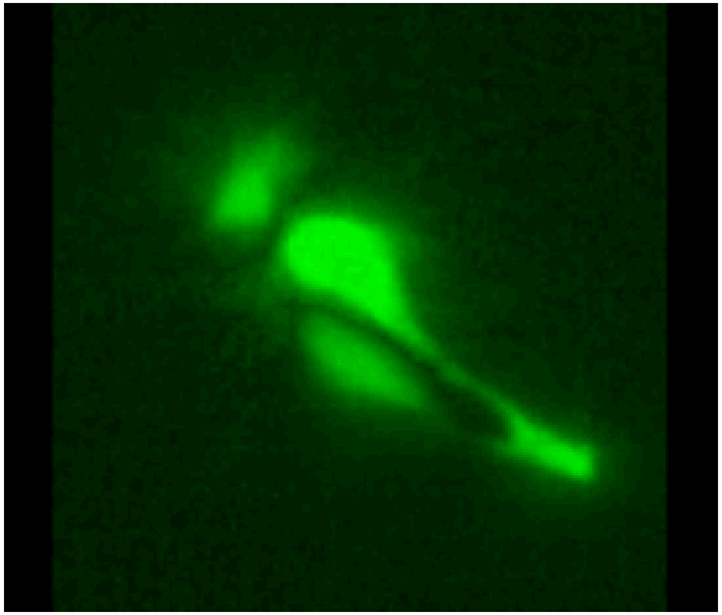


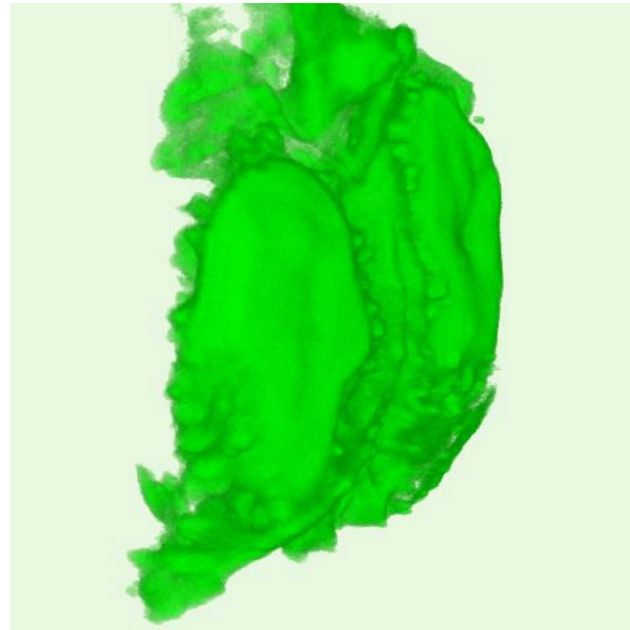


Green fluorescent protein (GFP) labeled Neurons in C.elegans using two-photon excited fluorescence (TPEF) microscopy

Aston University
Birmingham

Multi-photon imaging with compact laser





3D stacks of living C.elegans. Shown here are the 3D-projections of a nerve ring stained with green fluorescent protein (GFP)

3D stacks of mice liver

Courtesy of MMI GmbH

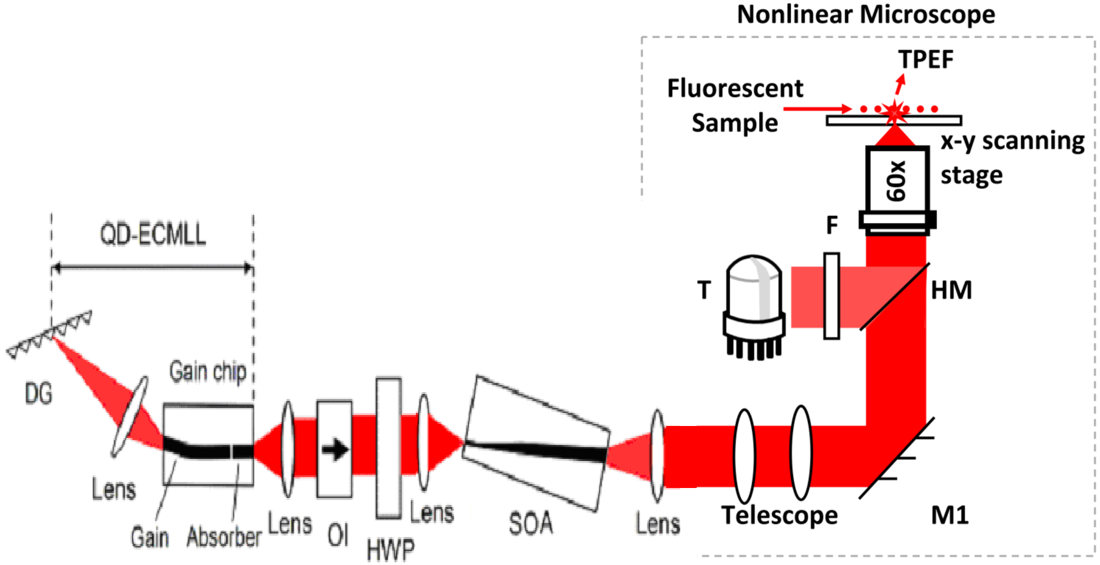
MMI

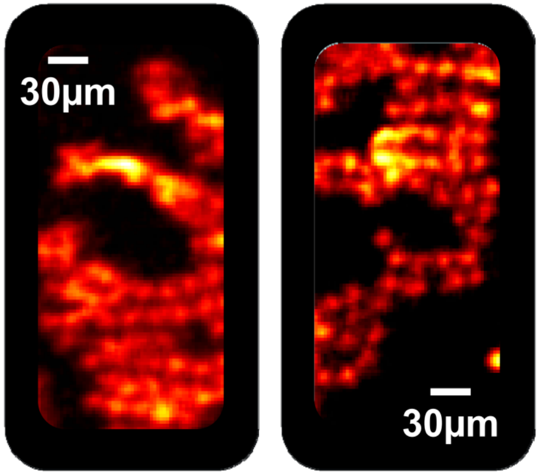
FAST-DOT

TPEF imaging from the MOPA system

Microscopy setup and TPEF acquisition parameters:

Laser	Objective NA	Pulse width [ps]	Avg. Pow. at the S. plane [mW]	Peak Pow. at the S. Plane [W]
SLD + SOA ext Cavity	1.4	~ 9	~ 18-23	~ 3-4





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

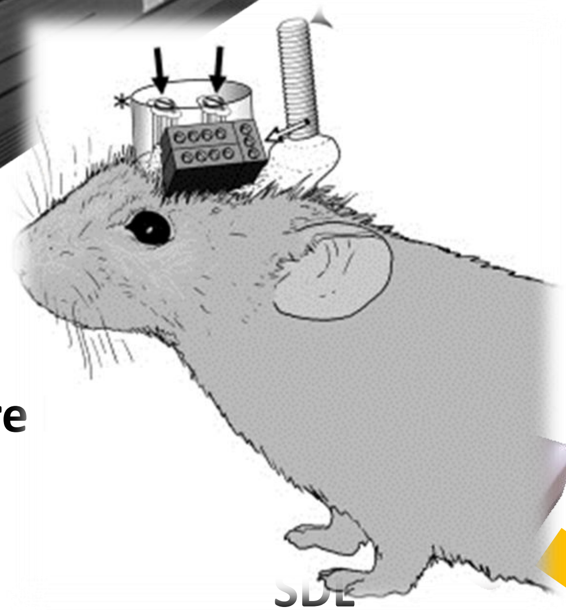
Y. Ding et al, Optics Express, v.20(13), p.14308, 2012

In collaboration with ICFO Barcelona

Future perspectives

Ti:sapphire

Fibre



Florent Haissa et al. Journal of Neuroscience methods 187 (1) 67-72, 2010

- Towards Nonlinear Micro endoscope

Aston University
Birmingham

Conclusions

- The quantum-dot structures demonstrate big potential in ultrafast physics:
  - Broad band tunability
  - Generation of pico- and femtosecond pulses directly from edge-emitting laser diodes
  - Generation of pico- and femtosecond pulses directly from surface-emitting laser diodes
  - High-power
  - Efficient SHG
- The high potential applicability of QD-based lasers in Biophotonics

Acknowledgments

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1. Dr. S. Sokolovski
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5. Dr. Ilya Titkov
6. Dr. Yury Loika
7. Mr. Modestas Zulonas
8. Mr. Amit Yadav
9. New 6 MC Fellows

Our collaborators

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M SQUARED
III-V lab
HCP HC PHOTONICS CORP.
TOPTICA PHOTONICS
ORC
MMI