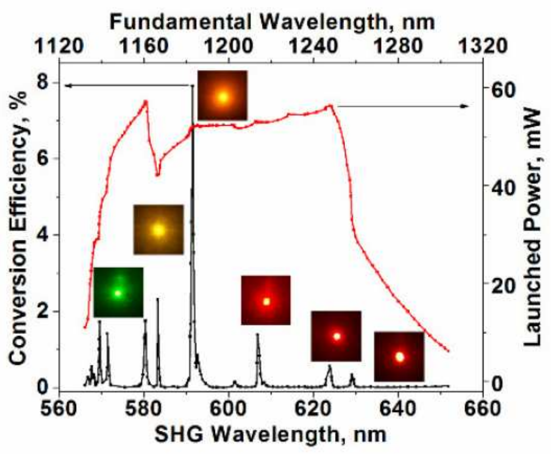
WP2 Highlights

ML QD edge-emitting lasers & amplifiers

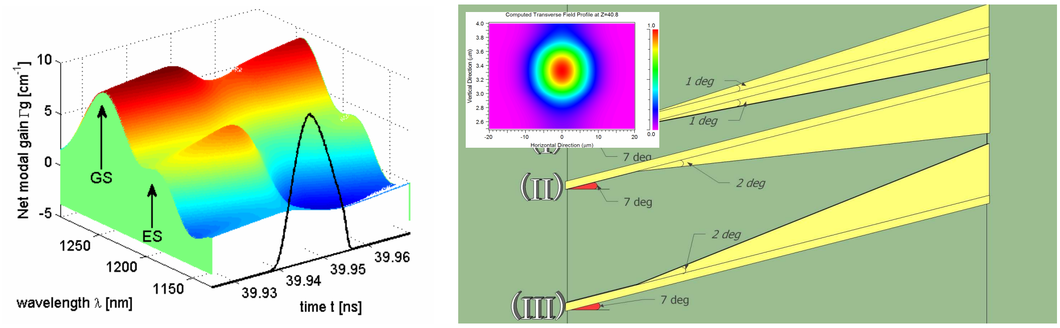


The tunablility wavelength range has been extended beyond the state-of-the-art to ~202 nm (between 1122 nm and 1324 nm) and a new record has been achieved. This offers the prospect of users being able to tune the wavelength of the lasers to suit the needs of their particular applications and several prototype units have been assembled to demonstrate this capability. The potential to amplify ultrashort laser pulses has also been achieved using compact semiconductor optical amplifiers based on quantum-dot materials. Novel device architectures based on tapered devices have been fabricated and tested, and as a result, the generation of picosecond pulses with record high average power directly from "match-box" size electrically pumped devices has been demonstrated.

Design and simulation of Quantum Dot Mode Locked lasers and amplifiers for high power short pulse generation

Within the context of FAST-DOT, the teams at Politecnico di Torino (PoliTo) and the National and Kapodistrian University of Athens (NKUA) have successfully collaborated in the design and modelling of passive mode-locking in quantum-dot (ML QD) lasers and semiconductor optical amplifiers (SOAs). Various theoretical models have been developed:

- Development of novel simulation tools based on FDTW (Finite Difference Traveling-Wave) and DDE (Delay Differential Equation) for the analysis and design of QD ML lasers that gave us the capability to analyze, to simulate and to design new structures
- Design of novel QD ML laser with flared output with good qualitative agreement with the measured results
- Development of a new BPM simulator for QD active material taking into account saturation effects usable both for CW analysis and design of SOA and some kind of QD lasers.
- Development of simulation programs for parameters extraction from experimental data of QD material
- Development of various FDTW programs with various degree of complexity up to that considering inhomogeneous broadening, electron and hole dynamic and acceleration procedure for the field propagation

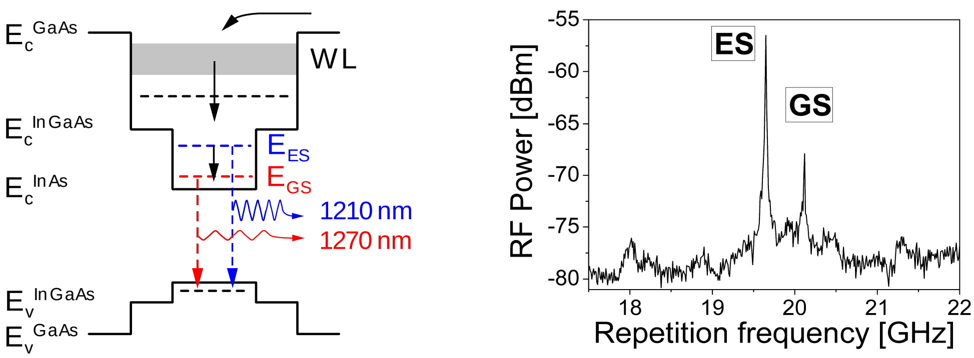


Calculations of passive mode-locking in a two section QD laser (left) and design of a QD semiconductor optical amplifier (SOA) with tapered sections (right).

The outcome of this activity is the accurate description of passive mode-locking dynamics, the investigation of novel ML regimes (dual wavelength ML, reverse state emission etc), the high power short pulse amplification in SOAs. This work was very essential for the achievements of FAST-DOT goals and gave the guidelines to the FAST-DOT partners for the realization of chips delivering high power short pulse generation. A large number of results from this activity have been published.

FAST-DOT researchers have identified novel operating regimes for the mode-locked QD lasers

In QD lasers, emission can occur via ground-state (GS) or excited-state (ES) transitions. The presence of the ES is a unique feature of QD lasers, and offers much potential that only recently started to be explored. FAST-DOT partners investigated the role of the ES transitions in the stability of mode locking in the GS, as new degree of freedom to control ML. Furthermore, the possibility to achieve switchable or simultaneous ML operation from GS and ES has been investigated. FAST-DOT partners form University of Dundee (UNIVDUN), National and Kapodistrian University of Athens (NKUA), Politecnico di Torino (PoliTo), Technical University of Darmstadt (TUD) and Innolume GmbH (INNOLUME) have investigated in depth theoretically and experimentally the GS/ES emission effects.



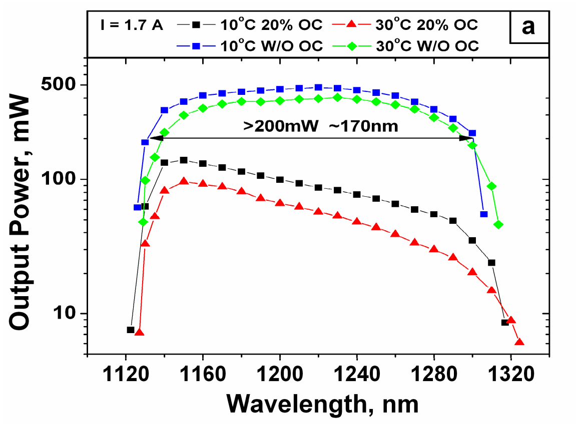
Left: Schematic of GS/ES emission in QD lasers. Right: Experimental demonstration of simultaneous GS and ES emission in a passively QD ML laser (electrical spectrum).

The teams form UNIVDUN, NKUA and INNOLUME demonstrated both theoretically and experimentally a dual-wavelength passive mode-locking regime where picosecond pulses were generated from both ES (λ=1180nm) and GS (λ=1263nm), in a two-section GaAs-based QD laser4. This is the widest spectral separation (83nm) ever observed in a dual-wavelength ML non-vibronic laser. The teams from TUD and PoliTo have also investigated the dual wavelength emission dynamics; the influence of different biasing conditions on the emission properties has been investigated both experimentally and theoretically and identified the origin of the experimentally observed ML regimes. The exploitation of this novel ML regime could enable a range of applications extending from dual-wavelength nonlinear imaging modalities to frequency mixing, time-domain spectroscopy and ultrafast optical processing.

These results have been complemented by the very recent observation of the so-called reverse-state dynamics in a particular designed (strongly inhomogeneously broadened) two-section QD structure by TUD, where lasing first started on the ES and then, with increasing current, a transition from ES to ES+GS emission took place. This fascinating novel concept allows tailored emission wavelengths and picosecond-short mode-locked pulses quasi "on demand" interesting for a lot of applications.

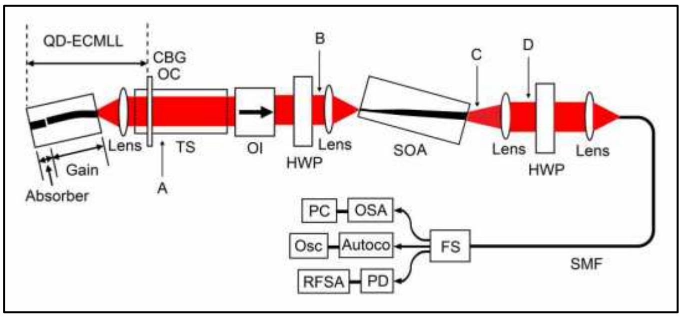
Record-breaking tunability achieved from an external-cavity laser diode with chirped quantum-dot layers

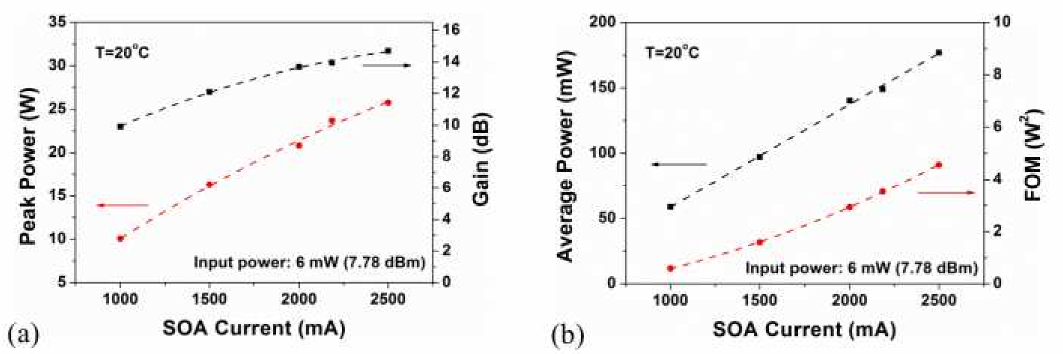
A record broadly tunable high-power external cavity InAs/GaAs quantum-dot diode laser with a tuning range of 202 nm (1122 nm-1324 nm) has been demonstrated - as a result of a FAST-DOT research collaboration between the University of Dundee (UNIVDUN) and Innolume GmbH (INNOLUME). A maximum output power of 480 mW and a side mode suppression ratio greater than 45 dB are achieved in the central part of the tuning range. Such laser performance is poised to have an impact in biomedical applications such as optical coherence tomography, where there is a growing interest in the development of broadly-swept tunable laser sources due to their high spectral bandwidth and output power. Furthermore, the spectral region encompassing 1.1 - 1.3 μm is particularly useful for biomedical imaging due to the low absorption and minimal scattering in human tissue, which can significantly enhance the penetration depth. Other important applications for this spectral range include the generation of coherent radiation in the visible spectral region via second harmonic generation or sum frequency generation, particularly into the yellow-orange spectral region, for which compact and efficient sources are relatively scarce.



High peak-power picosecond pulse generation at 1.26 µm using a quantum-dot-based external-cavity mode-locked laser and tapered optical amplifier

FAST-DOT partners UNIVDUN, ICFO, III-V Lab, PoliTo, NKUA and INNOLUME presented the generation of high peak-power picosecond optical pulses in the 1.26 µm spectral band from a repetition rate tunable quantum-dot external-cavity passively mode-locked laser (QD-ECMLL), amplified by a tapered quantum-dot semiconductor optical amplifier (QD-SOA). The ultrashort-pulsed MOPA system presented is the first demonstration of a low-cost, chip-scale based device in the spectral region 1.0 µm - 1.3 µm, with power levels compatible with NLM. The system generates high-peak power picosecond optical pulses centered at 1.26 µm, which is located within the infrared penetration window of most biological tissues. This asset could potentially offer greater penetration depths and reduced sample damage compared with the ultrashort-pulsed semiconductor laser systems previously demonstrated, which could lead to major progress and a more widespread adoption of nonlinear imaging technology. Moreover, and unlike previous demonstrations of nonlinear imaging with ultrafast laser diode systems, we present for the first time a system which incorporates only a single amplification stage, and does not include external dispersion compensation, enabling a rather more compact and less complex laser system.



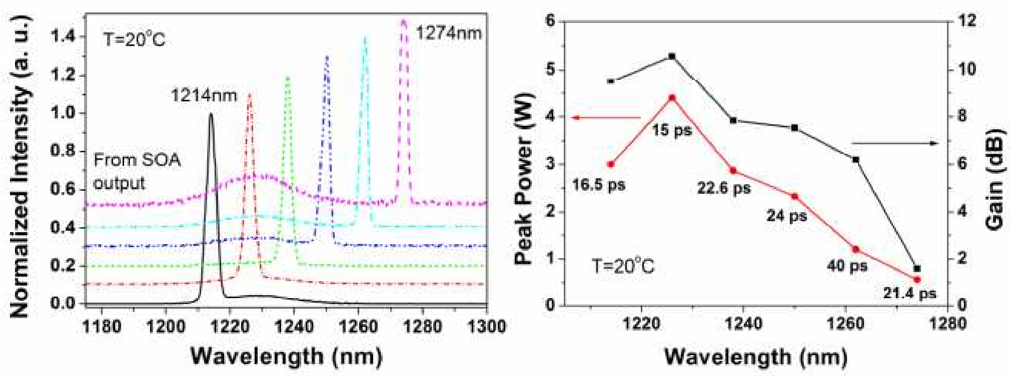


(a) Peak power (red), gain (black), (b) average power (black), and FOM (red) against SOA current for a 648-MHz repetition rate.

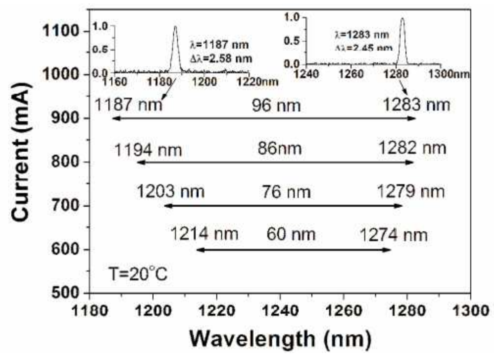
The laser emission wavelength was controlled through a chirped volume Bragg grating which was used as an external cavity output coupler. An average power of 208.2 mW, pulse energy of 321 pJ, and peak power of 30.3W were achieved. Preliminary non-linear imaging investigations indicate that this system is promising as a highpeak-power pulsed light source for nonlinear bio-imaging applications across the 1.0 µm - 1.3 µm spectral range.

Broadly tunable master-oscillator power-amplifier picosecond pulse source

Using similar external-cavity passively mode-locked laser diode with a tapered semiconductor amplifier, a broadly tunable master-oscillator power-amplifier (MOPA) picosecond optical pulse source was demonstrated. By employing chirped quantum-dot structures on both the oscillator's gain chip and amplifier, a wide tunability range between 1187 nm and 1283 nm is achieved. Under mode-locked operation, the highest output peak power of 4.39 W is achieved from the MOPA, corresponding to a peak power spectral density of 31.4 dBm/nm. This MOPA system represents a versatile, compact and low-cost source, well-suited for efficient and tunable second-harmonic generation applications into the yellow-orange spectral regions.

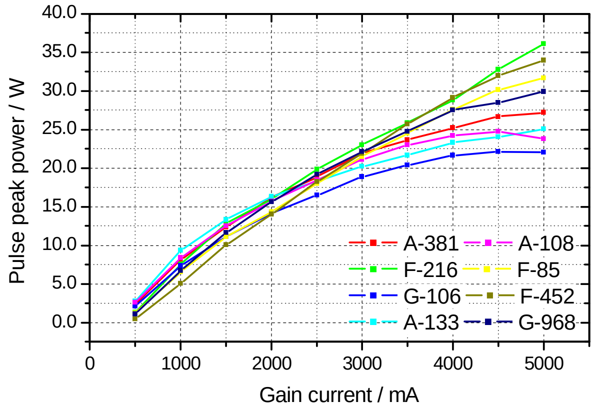


Left: Optical spectra of tunable MOPA in mode-locked operation with gain chip current of 600mA, reverse bias of 0-6 V, and SOA current of 2185 mA (710 A/cm^2). Right: Output peak power and gain from SOA at different wavelengths.



Importantly, it is possible to achieve a wider tunability range in mode-locked operation by increasing the bias current applied to the gain chip, as shown the figure on the left. This widening of the tunability range occurs preferentially on the blue side of the spectrum, which can be attributed to the increasingly stronger carrier filling of the higher-energy, higher-degeneracy ES levels, as previously observed also in CW tunable QD lasers. Under the gain chip current of 900 mA, a 96-nm tuning range was therefore achieved with stable fundamental mode-locked operation. It is important to add in this context that the peak power achieved from the QD-ECMLL oscillator was relatively constant with increasing gain chip current due to the concurrent pulse broadening and increase of average power.

High peak power amplification of ultra short pulses in tapered SOAs



Seeded by a mode locked laser with a pulse width of 1.1 ps and a repetition rate of 16 GHz an amplified pulse peak power of 36W together with an average power of 910mW and a spectral width of 2.8 nm is obtained for the SOA structure F-216 at 5A SOA current. This value takes into account the pulse broadening in the SOA and fibers as well as the underlying SOA ASE reducing the actual peak power. The given peak power refers to the collimated free-space beam. A thermal rollover is not found up to 5A thus allowing further amplification with a current source providing higher currents.

Suppression of Q-switching and self pulsations in mode locked tapered QD-Lasers

A simple passive electrical circuit that is able to suppress Q-switching instabilities and self pulsations in mode-locked semiconductor quantum dot lasers has been demonstrated. By connecting frequency-selective electrical components to the absorber section of a monolithic two section tapered laser, Q-switching instabilities could be suppressed and even eliminated thus extending the stable mode-locking range.

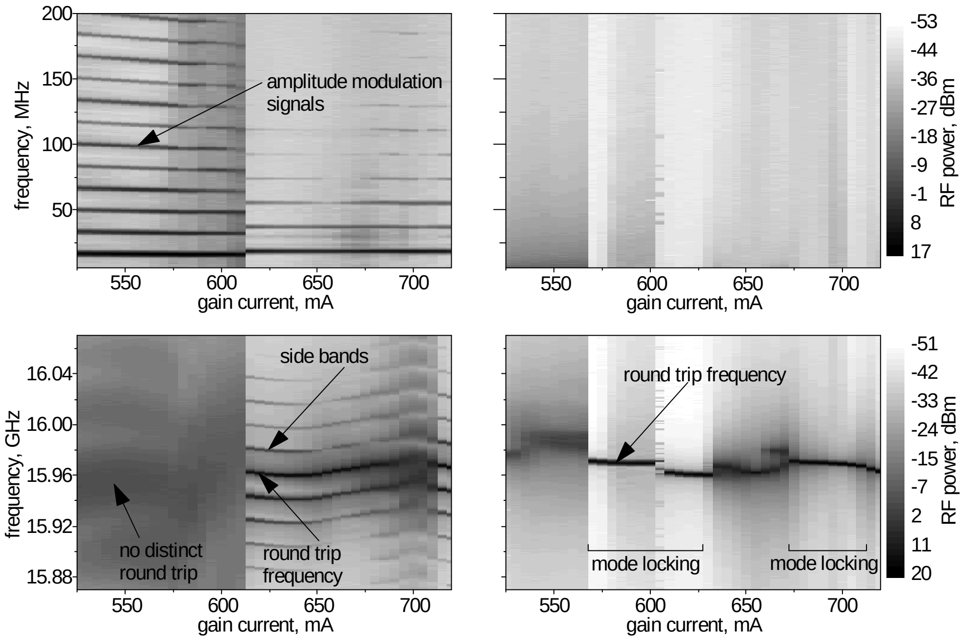


Fig.: RF spectra depicting the low-frequency (top) and roundtrip frequency bands (bottom) in dependence on gain current for an absorber voltage of -6.0 V, without (left) and with (right) suppres-sion circuit for a tapered QD laser.

The absorber section is grounded with an electrical high pass filter while still being reversely biased by the necessary DC voltage source connected via a low pass filter. In Q-switched mode-locking, the amplitude modulated envelope of the optical pulse train directly induces a modulated AC current in the absorber section. The AC grounding reduces this dynamic accumulation of the carriers in the absorber therefore preventing the build-up of these unwanted oscillations.

Recently this stabilizing approach allowed the generation of ultrashort high-peak-power pulses in a three section tapered gain guided quantum dot laser with a pulse width of 492fs ($sech^2$ shape), a peak power of 7.92W, an average power of 68mW and a time bandwidth product of 0.38.

Bright and Colorful - High-power tunable diode lasers with new wavelengths

TOPTICA's high-power, narrow-band diode lasers now provide an expanded color spectrum thanks to newly developed Tapered Amplifiers (TAs). These TAs are available exclusively from TOPTICA and allow for new IR, visible and UV wavelengths!

With the novel TA-chips, TOPTICA's high-power diode laser TA pro now offers output power up to 400 mW around 685 nm and up to 2 W between 1120 nm and 1190 nm. And the frequency-converted systems TA-SHG pro and TA-FHG pro now provide the highest output power also in the green-yellow (560 - 595 nm) and the UV (280 - 297 nm) spectral range. The newly developed TAs replace previously required fiber amplifiers and create a less complex setup for high output power at these wavelengths. These systems generate output power of up to 1000 mW easily and economically.

Major applications benefit from these new systems: laser cooling of stronti-um (689 nm), erbium (583 nm), sodium (589 nm) or magnesium (285 nm); optical clocks based on ytterbium (578 nm) or magnesium ions (281 nm); and high-resolution spectroscopy (e.g. europium yttrium orthosilicate, 580 nm).

Amplified diode lasers: TA pro

TOPTICA's TA pro is an amplified narrow-band, tunable diode laser. It comprises a patented master-oscillator design and subsequent amplification step in a tapered semiconductor amplifier. The TA pro features a linewidth of only 100 kHz and a mode-hop free tuning range of up to 50 GHz. With the newly added wavelengths, it is now available from 645 to 1190 nm with output power up to 3 Watts.

Frequency-converted systems: TA-SHG pro/TA-FHG pro

TOPTICA's frequency-converted diode lasers offer the highest output power even at "exotic" wavelengths. Based on the same configuration as the TA pro, the TA-SHG/FHG pro lasers additionally comprise one or two SHG pro resonators, respectively, for efficient frequency conversion. Both systems feature an excellent beam profile and a high long-term power and frequency stability.

TOPTICA's pro series lasers provide well-known stability and user friendli-ness. The TA pro and TA-SHG/FHG pro lasers achieve this desirable com-bination using a sophisticated laser design with flexure joints, specially developed mirror mounts and a laser head created from a single metal block.

New wavelengths and power

- TA-SHG pro: up to 1000 mW @ 560 – 595 nm,
- TA-FHG pro: up to 50 mW @ 280 – 297 nm
- TA pro: up to 400 mW @ 685 nm
- TA pro: up to 2 W @ 1120 – 1190 nm

Key features

- Widest wavelength coverage
- Ultra stable, typical linewidth 100 kHz (5 µs), low drift
- Mode-hop free tuning range up to 50 GHz
- Nearly diffraction-limited output beam
- Ultra-stable mirror mounts with flexure design
- Air-sealed frequency-doubling resonator SHG pro
- Rigid housing made from a solid metal block

Fast AC and DC current modulation for master and amplifier included