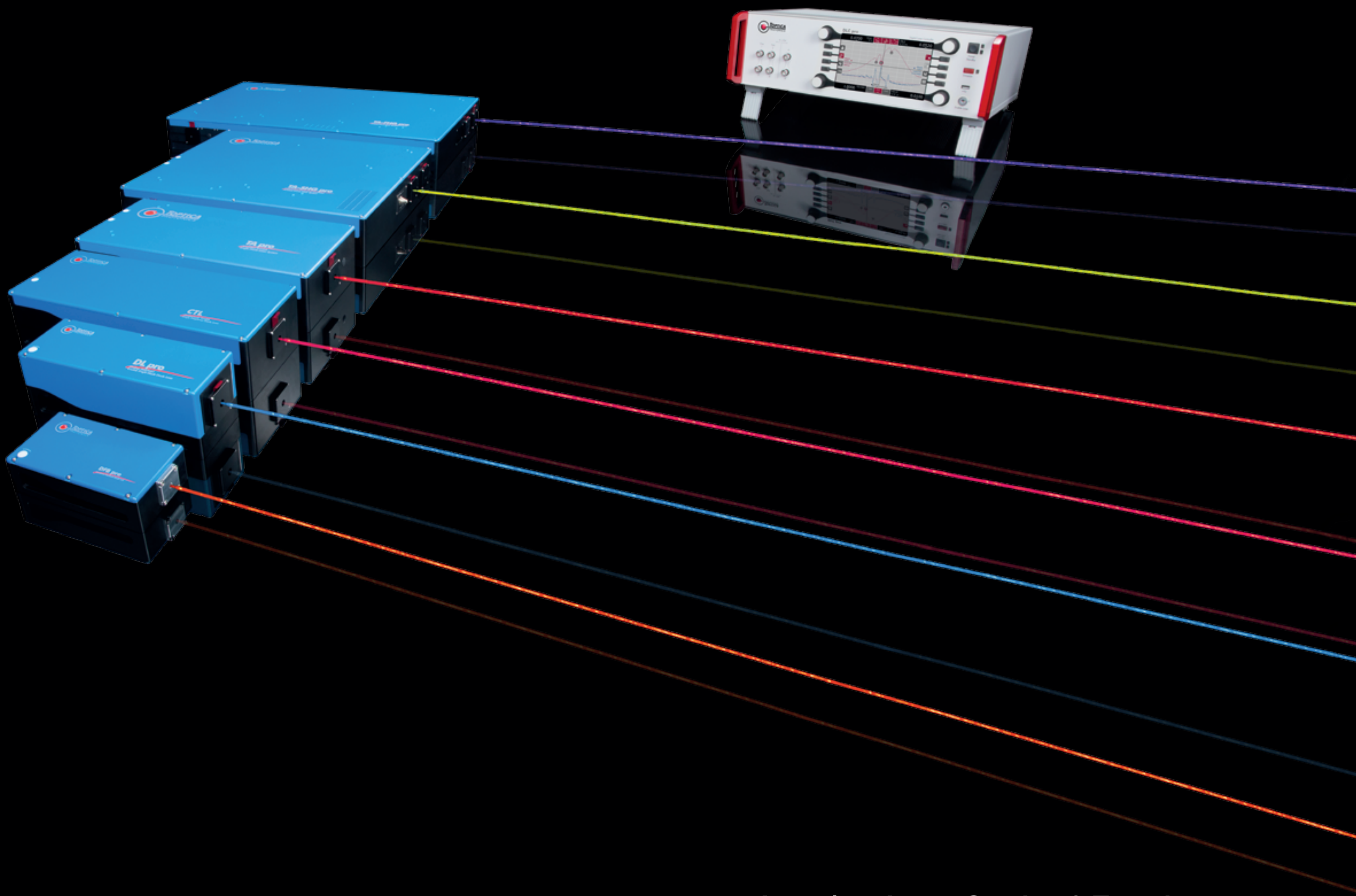
Tunable Diode Lasers

UV, Visible, Infrared - Digital Control - Wavelength Stabilization



Atom / Ion Laser Cooling & Trapping
Degenerate Quantum Gases
Color Centers, Microresonators, Quantum Dots
Quantum Communication, Computation & Simulation
Quantum Metrology, Sensing & Spectroscopy
Nanostructuring & Testing

Version 2018: for latest product information please visit our webpage
https://www.toptica.com/products/tunable-diode-lasers/

TOPTICA PHOTONICS

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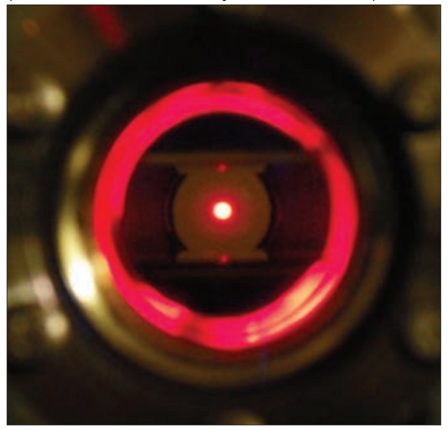
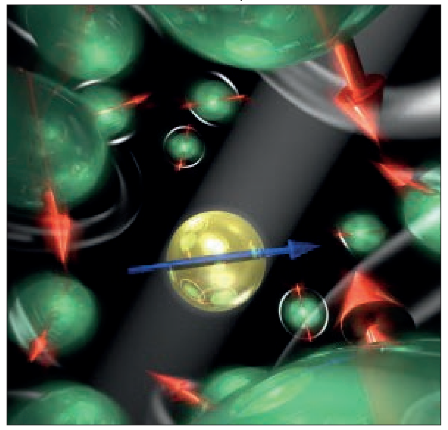
Lithium magneto-optical trap
(R. Hulet, Rice University, Houston, USA).



Atom Laser Cooling & Trapping

- Laser cooling
- Magneto-optical trapping
- Dipole traps and optical lattices

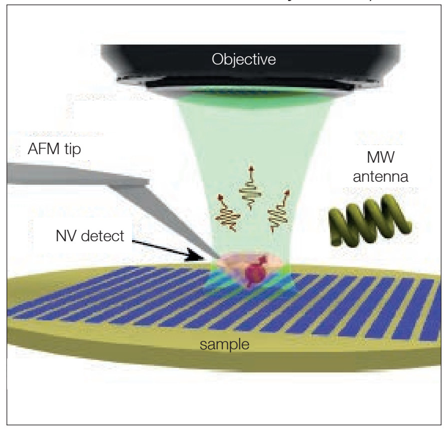
NV center in diamond (Hanson lab@TUDelft & Tremani, The Netherlands).



Color Centers

- E.g. N-V, Si-V, Ge-V in diamond
- Quantum optics
- Spintronics

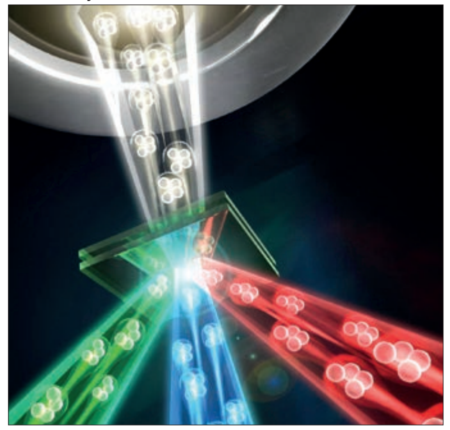
NV Scanning Probe Magnetometry (L. Rodin, Laboratoire Aimé Cotton, Orsay, France).



Quantum Sensing

- Magnetometry
- Electrometry
- Inertial & gravitation sensing

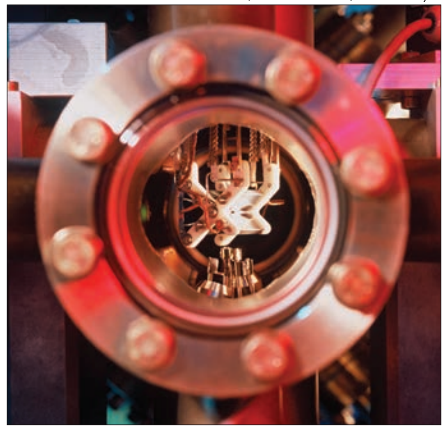
Centre for Quantum Photonics, University of Bristol, UK.



Quantum Communication

- Entangled photons
- Photon storage
- Single photon conversion

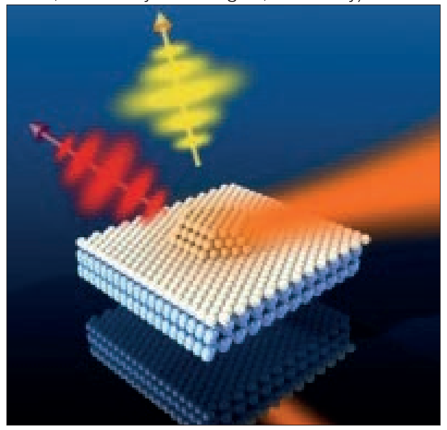
Ion trap (R. Blatt, Institute for Quantum Optics and Quantum Information, Innsbruck, Austria).



Ion Cooling & Trapping

- Ionization
- Laser cooling
- Quantum state manipulation

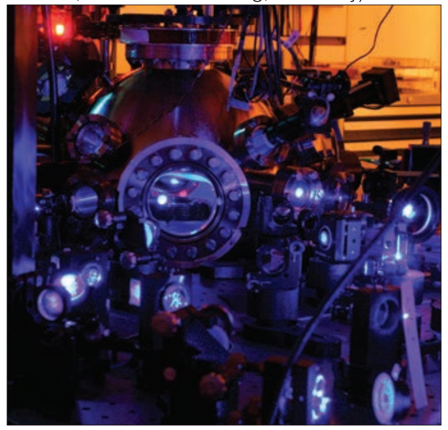
Quantum dot (P. Michler, Physics Department - IHFG, University of Stuttgart, Germany)



Quantum Dots

- Single & correlated photons
- Nanophotonics
- Semiconductor lasers

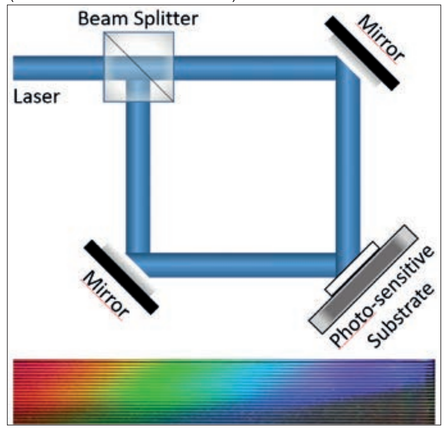
Strontium atom lattice clock (Ch. Lisdat, U. Sterr, PTB Braunschweig, Germany).



Metrology

- Optical atom and ion clocks
- Ultra-stable laser oscillators
- High-resolution spectroscopy

Holography principle for optical gratings (TOPTICA Photonics AG).



Nanostructuring & Testing

- Holography
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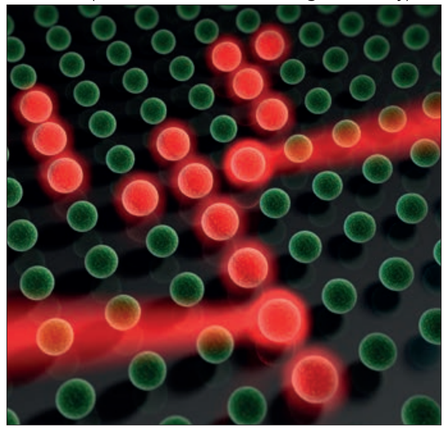
- Interferometry

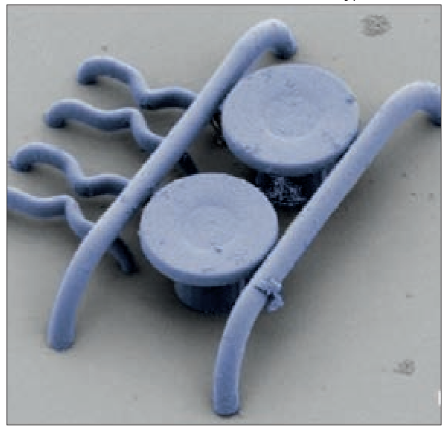
Single-spin addressing in an atomic Mott insulator (I. Bloch, MPQ, Garching, Gemany).



Degenerate Quantum Gases

- Bose-Einstein condensation (BEC)
- Degenerate Fermi gases (DFG)
- Feshbach resonances

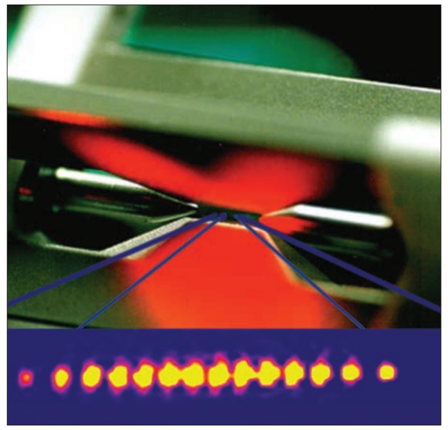
Microdisc resonators and couplers (O. Benson, Humboldt-Universität Berlin, Germany).



Microresonators

- Biosensing
- Near field optics
- Quantum optomechanics

Ion trap with CCD image of fluorescing ions (R. Blatt, University of Innsbruck, Austria).



Quantum Simulation & Computation

- Quantum cryptography
- Quantum teleportation
- Photon storage & EIT

ARCLITE LIDAR system, Greenland (photo by Craig Heinselman).

Sensing & Spectroscopy

- LIDAR & Guide Star
- Trace gas analysis
- Spectroscopy

DIGITAL REVOLUTION IN LASER CONTROL

Lowest Noise and Highest Convenience

In the last years, external cavity diode lasers (ECDLs) have experienced a tremendous improvement. Since its introduction, TOPTICA's DL pro leads the field of tunable diode lasers, thanks to its narrow linewidth, large mode-hop-free tuning range and highest vibration and temperature-change stability.

With TOPTICA's DLC pro, laser control has entered the digital world! The fully digital laser controller sets new benchmarks for lowest noise and drift levels. It provides intuitive touch control and powerful remote operation to run and frequency-stabilize all of TOPTICA's tunable diode lasers: DL pro, CTL, TA pro, DFB pro, DL- / TA-SHG pro and DL- / TA-FHG pro.

Experiments requiring a narrow linewidth or large coherence length as well as setups needing remote laser control will highly benefit from the revolutionary digital laser controller DLC pro.

DLC pro - digital laser control

- All-digital controller for TOPTICA's tunable diode lasers DL pro, TA pro, CTL, DFB pro, DL / TA-SHG pro and DL / TA-FHG pro
- Extremely low noise and lowest drift
- Convenient dials & multi-touch user interface
- Remote PC GUI and command control
- Intelligent locking features

The DLC pro sets new benchmarks: Intuitive control via touch display and excellent noise and drift performance for TOPTICA's tunable diode lasers.

Convenience

The user can operate the digital controller DLC pro via dials, buttons and a user-friendly touch display. The well-organized PC graphical user interface (PC GUI) software and a command line interface allow remote operation via Ethernet or USB. The DLC pro directly displays signals from the experiment or the laser on the touch screen and/or the PC GUI in x/y-, t- or FFT-mode, reducing the need for additional external oscilloscopes. As special feature, one can adjust scan parameters with multi-gestures on the touch screen, as if using a modern smartphone. A software key activates the optionally available package DLC pro Lock. It provides a Lock-in-type locking module with two feedback PID channels. Complex operations like laser locking are now as simple as never before. For example, frequency locking can be activated with the click of a mouse or the touch of a fingertip ("Click & Lock" and "Tip & Lock") to locking points suggested by the DLC pro. In addition, advanced ReLock functions are integrated as well.

The DLC pro can also be combined with TOPTICA's well-established fast locking modules FALC and DigiLock via an external extension rack (DLC ext).

The unprecedented passive stability of the DLC pro simplifies the use of single-frequency tunable diode lasers dramatically. For example, frequency and power drifts are suppressed, and mode-hopping is reduced or even excluded. The DLC pro also comes with integrated power stabilization and for some systems with optional automatic alignment.

Convenient laser control via remote PC-operation: Users can easily set all relevant parameters via the graphical user interface.

Precision

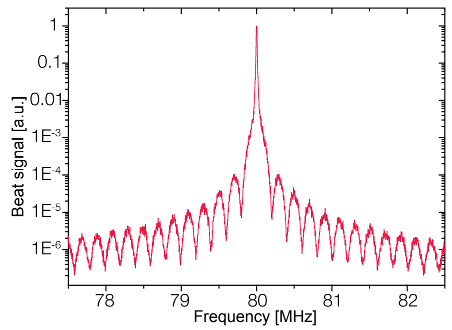
The DLC pro features laser diode current, temperature and piezo drivers with unprecedented noise and stability values, boosting the performance of TOPTICA's established tunable diode lasers.

280 pA/√(Hz) @ 1 kHz and 490 mA with 30 kHz modulation bandwidth and 140 nV/√(Hz) @ 1 kHz and 140 V (small signal modulation bandwidth 3 kHz) are world's best noise figures for laser current and piezo voltage drivers.

Thanks to the lowest noise characteristics, the DLC pro can reduce the free running linewidth of a DL pro even well below 10 kHz. For example, a self-heterodyne linewidth measurement of a free-running DLC DL pro laser at 1160 nm with narrow linewidth option, exhibits a fast linewidth (5 µs) of only 5 kHz.

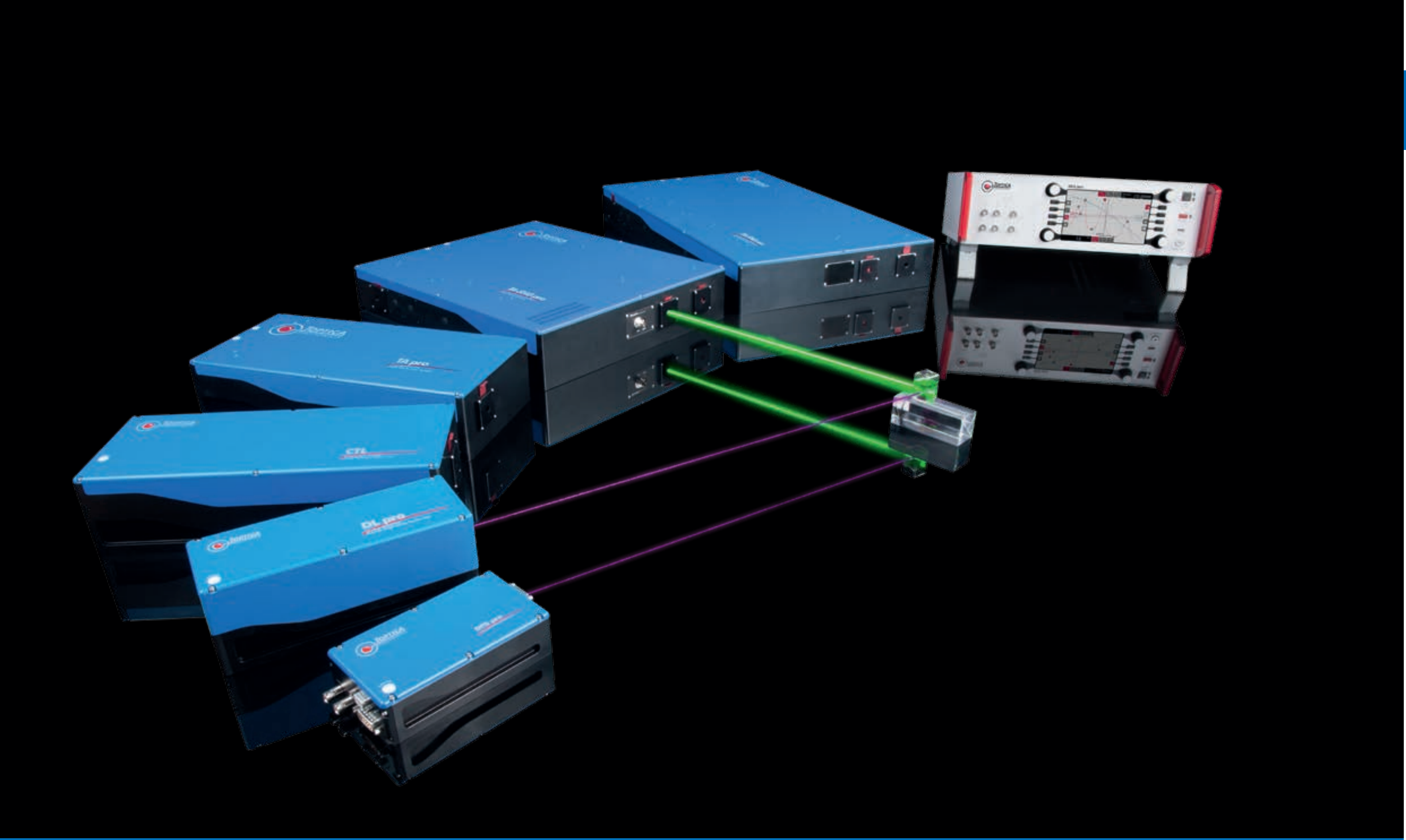
Single-frequency diode lasers in general can exhibit significant frequency drifts if current, temperature or piezo voltages slightly change. With its stability values (< 3 ppm/K, < 140 µK/K and < 40 ppm/K, respectively) the DLC pro sets new standards within this respect. In many cases, the long-term frequency stability of a DLC pro driven laser system is so excellent that active frequency stabilization (locking) is not required. All parameters can be set reliably and with ultrahigh precision. For example, one can directly dial in the laser diode current with steps as small as 15 nA and the ECDL piezo voltage with 10 µV increments. We have integrated high-resolution analog-digital converters (24-bit, 300 kHz) for fast and efficient communication between the main-controller, the laser and the experiment.

Find a more detailed description of the DLC pro features on page 38-40.



A self-heterodyne linewidth measurement shows a short-term linewidth of a free-running DLC DL pro (narrow linewidth option) of only 5 kHz.

DLC DL pro with the external extension rack (DLC ext). The DLC ext allows combining the DLC pro with TOPTICA's fast locking modules FALC and DigiLock.



TUNABLE DIODE LASER TECHNOLOGY

Turning Laser Diodes into Diode Lasers

Laser diodes
Laser diodes are well established subcomponents in a variety of consumer products, like laser pointers, barcode scanners, or CD/DVD/Blu-ray drives. Their success story is driven by the fact that they are compact, conveniently operated, cost effective, and highly efficient. However, the emission spectrum of bare laser diodes is broad, and the lasing wavelength is not well defined.

In general, the two facets of the laser diode form a resonator and determine the (longitudinal) lasing modes. The wide gain profile of the semiconductor supports many modes simultaneously, each with a different frequency. Even diodes with a single longitudinal mode exhibit mode-hopping upon slightest variations of the chip temperature or driver current. The result is an imperfect, spectrally unstable output beam.

TOPTICA converts laser diodes into diode lasers, meaning high-end laser tools, by integrating additional mode selection elements as well as adding best-in-class drivers and optics.

Mode selection
Superior diode laser characteristics – like narrow emission linewidth, large coherence length, precise wavelength selection, and tuning or stabilization of the emission frequency – are achieved by introducing frequency-selective feedback into the laser cavity. TOPTICA offers two realizations of tunable single-frequency diode lasers. Both make use of grating structures to select and control the emission frequency.
One is a grating-stabilized external cavity diode laser (ECDL). It incorporates an optical grating mounted in front of the laser diode while a second resonator forms “externally” between the diode’s back facet and the feedback element. The other approach features laser diodes with gratings built into the semiconductor itself: distributed feedback (DFB) and distributed Bragg reflector (DBR) laser diodes.

The grating filter, the semiconductor gain profile, the internal laser diode modes and – if applicable – the external cavity modes determine the lasing mode(s). Precise temperature and current control as well as proper matching of the components are a must for stable single-mode operation.

Wavelength tuning of an ECDL
DFB and DBR diodes can be wavelength tuned by adjusting the laser diode current and/or temperature. To change the ECDL wavelength, one varies the spectral response of the filter, e.g. by altering the angle of incidence on the grating. Because the laser always runs at the largest overall gain, it hops to another longitudinal mode and emits at a new wavelength.

Fine-tuning of the laser wavelength is achieved by changing the length of the external cavity. This shift of the supported single longitudinal mode the laser is running on. A large mode-hop-free tuning range results from accurate synchronization of as many contributions as possible. TOPTICA’s DL pro laser, for example, achieves largest mode-hop-free tuning by simultaneously varying grating angle, length of the external cavity and laser diode current.

Coarse wavelength alignment is often realized with a micrometer screw (optionally motorized) while fine-tuning is implemented electronically by applying voltages to a piezo actuator that holds the grating or changing the laser diode current directly.

FP, AR, DFB or DBR Diodes
Fabry-Perot (FP) diodes are available at many wavelengths. In an ECDL, the internal resonator of the FP diode acts as an etalon and contributes to the selection of the external lasing mode. The internal resonator is synchronized with the grating movement by changing the diode current simultaneously.

AR diodes with an antireflection-coated output facet do not lase without external feedback and their internal resonator effects the mode selection much less. The AR coating further improves the tuning properties and mode stability of an ECDL. Important specifications for FP- or AR-based ECDLs are the output power available from the stabilized diode, the attainable wavelength range, the mode-hop-free tuning range and the typical linewidth.

Distributed Feedback (DFB) and Distributed Bragg Reflector (DBR) laser diodes feature a grating structure within the semiconductor chip. The grating restricts the laser emission to a single longitudinal mode. In a DFB diode, the grating is integrated in the gain section. In a DBR, the grating is spatially separated from the gain section, and an additional phase section serves to maintain mode-hop-free conditions during a scan. Frequency tuning is accomplished by thermally or electrically varying the grating pitch, it can span many hundred GHz.

ECDL or DFB?
Whether to choose an external cavity diode laser or a DFB/DBR laser depends on the individual application. DFB diodes do not yet offer the wavelength range accessible with Littrow ECDLs. Tunable, narrow-band emission in the blue or red spectral range still remains the realm of external-cavity systems. An ECDL is also the preferred choice for applications that require a broad coarse-tuning range, or an ultra-narrow linewidth below 1 MHz.

Key advantages of DFB lasers are a large continuous tuning range, and a high robustness with respect to acoustic noise and humidity. The mechanical stability results from the absence of any alignment-sensitive optical components. DFBs are thus particularly attractive for applications in rough industrial environments. Mode-hop-free scans of a few nanometers are routinely attained. For measurement tasks that require even wider mode-hop-free tuning ranges, e.g. quantum dot spectroscopy, the new CTL laser (pages 12-15) is the system of choice.

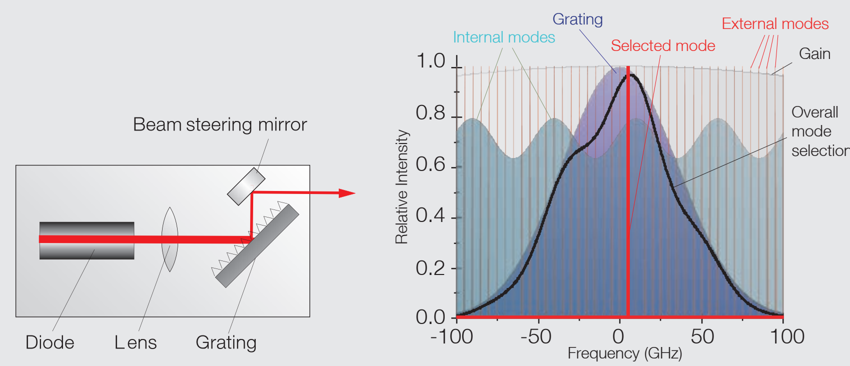
A stock list with laser diodes including all individual specifications in diode laser configurations is available at www.laser-diodes.com

Compact and robust Littrow setup
The most common types of ECDLs are the so-called Littrow and Littman configurations. In both cases, a grating is used to selectively reflect a small range of the diode's emission spectrum back into the laser chip. This optical feedback forces the diode into single-frequency operation. In Littrow configuration, the first-order beam from the grating is directly reflected into the diode.

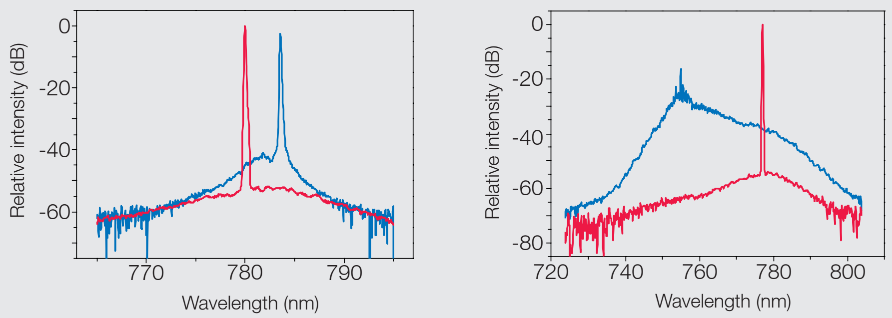
In Littman configuration, the first-order diffracted beam is reflected by a mirror, and passes the grating a second time before being fed back into the laser diode. In both setups, the main contributions to the technical linewidth are usually electronic noise, acoustic noise and vibrations that affect the cavity length.

Since the grating is only passed once, the output power of Littrow lasers is higher than that of comparable Littman setups. Moreover, Littrow lasers can be operated with FP and AR diodes, while the Littman design usually employs AR coated diodes. If properly configured, the ECDL runs on a single-mode of the external resonator, i.e. the mode with the highest overall gain.

To find out on which external mode the laser is running one must consider the gain and the internal mode structure of the laser diode, the grating filter and the external cavity length.



Littrow-type external cavity diode laser (left) and single-mode selection (right).



Laser diode with (red) and without (blue) external grating feedback.
The left graph shows an FP diode, the right graph an AR diode.

The *pro* technology provides best in their class lasers with an optimized opto-mechanical setup in one solid metal block. They are robust and at the same time widely tunable as well as user-friendly. The revolutionary narrow linewidth ECDL DL pro has long proven its invulnerability against temperature changes and acoustic disturbances ever since. Its patented design incorporates wire-eroded flexure joints and a virtual pivot point allowing alignment-free wavelength selection and large mode-hop-free tuning.

The amplified TA pro and the frequency-converted DL/TA-SHG/FHG pro systems build on the superior DL pro. The TA chip unit includes collimation optics and can handle currents up to 10 A thanks to an optimized heat conductivity. The proprietary SHG/FHG cavities are air-sealed and allow for adjustment of key optical components from outside. If required, we employ patented kinematic mirror mounts based on flexure technology. They ensure the highest stability of beam steering and are easily accessible from the top.

The new DLC pro controller gets the best out of our *pro* technology lasers. It provides lowest noise, best passive electronic stability, touch screen and remote control, frequency locking and other digitally enabled features. Together, they deliver that extra bit "more" that is required for leadership in instrument manufacturing or state-of-the-art physics experiments. One can focus fully on the task while the laser will simply do its job.

***pro* technology**

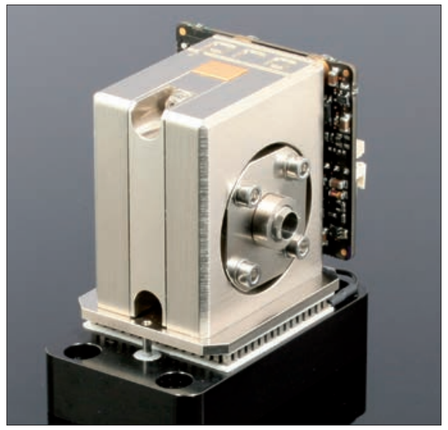
- Stability
- Ease of use
- Thermal and acoustic ruggedness
- Hands-off operation wherever possible
- Flexure joints wherever expedient
- Internationally patented design (DE 1 2007 028 499, US 7,970,024)

***pro* electronics (DLC pro)**

- All digital controller for TOPTICA's tunable diode lasers DL pro, TA pro, CTL and DL-SHG pro
- Extremely low noise and precise control
- Intuitive and convenient

Patented resonator design (master)

- Largest mode-hop-free tuning range
- Highest acoustic and thermal stability
- Latest production technologies (wire erosion)

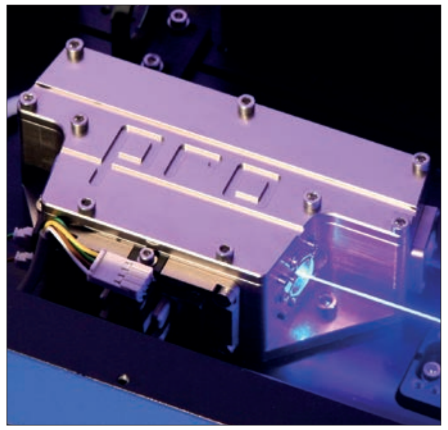


Optimized TA pro mount

- Modular setup
- On-site exchange of pre-aligned components
- Optimized heat management
- DC & AC - coupled modulation board

Patented flexure-based ultra-stable kinematic mirror mounts

- Accessible from top with closed laser head
- Wire erosion technology based
- Independent horizontal and vertical adjustment



Proprietary resonator design (SHG-unit)

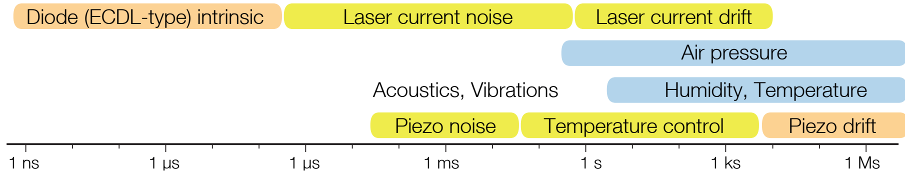
- Air-sealed resonator
- Manufactured from one solid metal block
- Mirror mounts and SHG crystal adjustable with closed resonator lid

Laser head machined from a solid metal block

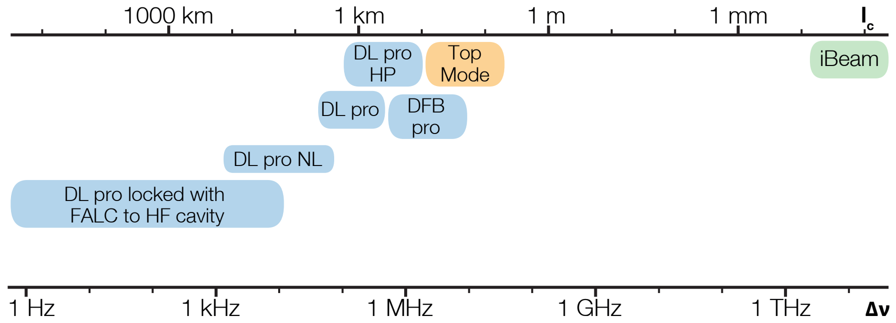
- Highest stability against vibration and acoustic noise
- Reduced long-term and temperature drift

Linewidth, frequency noise and drift

The Schawlow-Townes formula provides a theoretical minimum of a laser's linewidth, which can be very narrow in case of ECDLs. In reality, many processes affect the optical path length of the laser resonator and hence the laser frequency. Current fluctuations change the refractive index and the temperature within the laser diode. Acoustic noise and vibrations directly affect the mechanical resonator length. In an ECDL, temperature, air pressure and humidity modify the refractive index of air in the external resonator. Processes that are faster than the laser frequency measurement itself add to the laser's technical linewidth. Slower processes will "only" lead to a frequency drift between successive measurements. When comparing linewidth values, it is important to consider the time scale of the measurement.



Main causes for frequency variations in ECDLs and their respective time scales.



Typical coherence length l_c and linewidth Δν of TOPTICA diode lasers.

Laser linewidth and coherence length

Laser linewidth and coherence length are inverse proportional with a numerical factor that depends on the exact spectral line shape. For a Gaussian profile, the coherence length is 132 m / linewidth [MHz] as long as the result is smaller than the product of the speed of light and the linewidth measurement time, i. e. 1500 m for 5 µs.

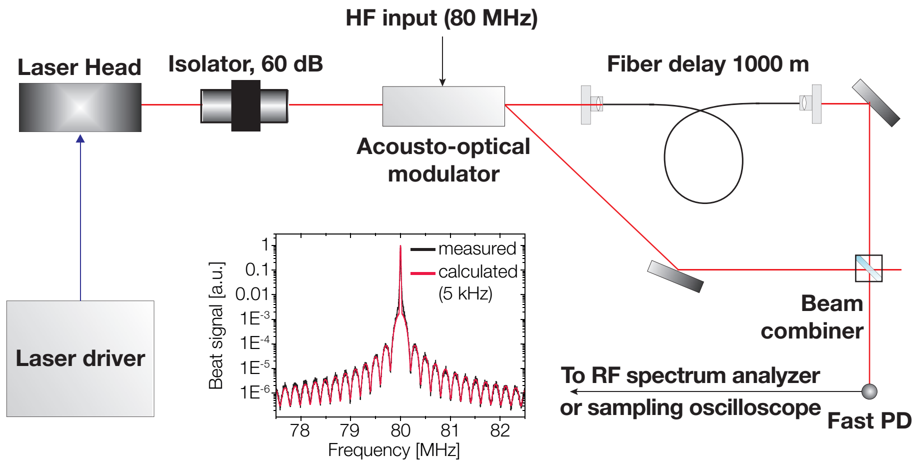
Linewidth measurement

In a delayed self-heterodyne linewidth measurement, one splits the laser beam into two parts. One part is frequency-shifted by an acousto-optical modulator and delayed in a long fiber. Both beams are then overlapped on a fast detector. The resulting beat signal between the laser and its delayed self can be observed e.g. with a RF spectrum analyzer. 1 km fiber length corresponds to a time delay of 5 µs and only frequency fluctuations within this time contribute. The laser linewidth is 1/2 … 1/√(2) times the width of the beat signal's central peak as long as the corresponding coherence length is smaller than the optical fiber length.

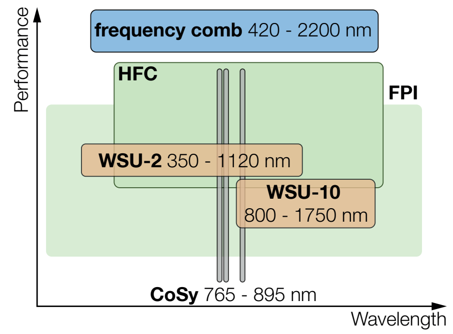
If the laser's coherence length is much larger, an interference modulates the beat signal and one can extract a linewidth value by matching the modulation depth with a parameterized model. Linewidth measurements on longer time scales are accomplished by measuring the beat width of two identical lasers with a fast detector and an RF spectrum analyzer, by using a Fabry-Perot interferometer or by directly determining the coherence length with a Michelson interferometer.

Frequency references

Active frequency stabilization of a laser calls for an external reference that serves as a frequency discriminator. Atomic or molecular absorption lines, spectral lines of a frequency comb or wavelength meters are used for absolute stabilization and drift compensation. Relative frequency references include high-finesse optical resonators or etalons.



Delayed self-heterodyne linewidth measurement and typical result.



Comparison of frequency references. The performance represents aspects like accuracy, repeatability or achievable linewidth. Shown are: Frequency comb (DFC) wavelength meters (WSU), spectroscopy cells (CoSy), Fabry-Pérot interferometers (FPI), and high finesse cavities (HFC).

To actively frequency stabilize a laser, the laser frequency is compared with a set value, and a feedback circuit corrects any deviations from this set value. Besides the accuracy or the stability of the frequency reference, an important parameter is the rate of correction – in other words the bandwidth of the control loop. It is limited by the time required for the frequency comparison and the design of the feedback circuit, i. e. the used regulator modules and the feedback elements. For active linewidth narrowing or phase locking, one even has to consider the lengths of the optical beam path and the cables. Operation convenience strongly favors digital locking.

Side-of-fringe lock

One can stabilize a laser to a spectroscopic reference or the transmission of an FPI with a "side-of-fringe" lock. Subtracting a constant offset voltage from the original signal ("fringe") such that the difference between the two is around zero with non-zero gradient an error signal is generated on the side of the fringe. An appropriate locking regulator adjusts feedback elements such that the error signal in lock is zero and the laser frequency is stabilized to the corresponding side of the fringe zero-crossing of the error signal.

Top-of-fringe lock

To lock to the maximum of a spectroscopic signal ("top-of-fringe locking"), a signal generator modulates the laser frequency incident on a spectroscopy setup. The observed signal is demodulated at the modulation frequency with proper phase. The resulting derivative of the spectroscopic signal forms an error signal with zero-crossing and non-zero gradient at the frequency corresponding to the spectroscopy maximum. Again, a locking regulator stabilizes the laser frequency, this time to the top of the fringe. The modulation can be applied to the laser diode current or just to the light of the reference setup using an EOM or an AOM.

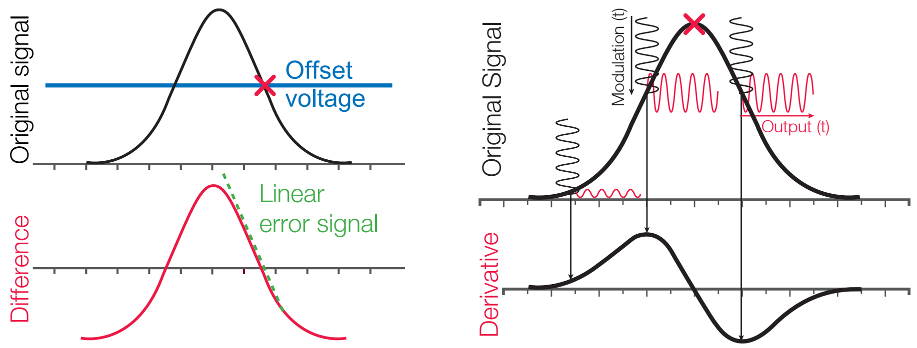
Linewidth narrowing & phase locking

One can reduce the linewidth of a laser and even lock its optical phase to a reference if the response of the locking circuit to deviations of the laser frequency/phase is much faster than the speed at which these changes occur. For linewidth narrowing, one uses the Pound-Drever-Hall technique together with high finesse resonators while optical phase locking is performed by beating the laser with a second one or a frequency comb. In both cases, the error signal generation is extremely fast and one can fully exploit the performance of special high-bandwidth locking electronics.

TOPTICA locking modules

TOPTICA takes pride in having the largest portfolio of locking units with outperforming characteristics: highest speed, maximum comfort, largest versatility, lowest noise and minimum drift. Whatever is important and whatever locking task has to be accomplished – the TOPTICA solution is already there. A description of our locking modules can be found on pages 38-42 of this catalog and on www.toptica.com. One can also use the integrated PID option of our wavelength meters if a laser has to be stabilized to them with relatively low bandwidth < 100 Hz, i.e. against drift.

Principle of side-of-fringe (left) and top-of-fringe locking (right).



	DLC pro Lock*	DigiLock 110	FALC 110	mFALC	PID 110	PDD 110/F
Description / Type	PID regulator, lock-in error signal generator	PID regulator, lock-in/PDH error signal generator	PID regulator	mixing PID regulator	PID regulator	PDH error signal generator
Specials	all-digital, low noise, convenient	versatile digital locking solution	fast, analog, for experts	fast, analog, for experts	analog, slow	analog, high bandwidth
Main application	spectroscopy lock	all	linewidth narrowing	phase locking	side of fringe spectroscopy	PDH locking, FM or modulation transfer spectroscopy
Side-of-fringe	✓	✓	✓		✓	
Top-of-fringe	✓	✓	with PDD		with PDD	✓
Pound-Drever-Hall (PDH)	slow with PDD	fast, super fast with PDD	super fast with PDD			with FALC, DigiLock, DLC pro Lock, PID
Max. regulator bandwidth	≈ 30 kHz	≈ 10 MHz	≈ 45 MHz	≈ 45 MHz	kHz .. 100 kHz	≈ 7 MHz
Modulation frequency	11 Hz .. 30 kHz	17 Hz .. 25 MHz				12 - 35 MHz**
Signal analysis	FFT	✓				
Relock mechanisms	✓	✓			✓	
Computer control	✓	✓				
High bandwidth output		✓	✓	✓		✓
No. of feedback channels	2	2 (+1)	2	2	1	n.a.

*software license for DLC pro **5- 70 MHz versions available

Amplifying laser diodes

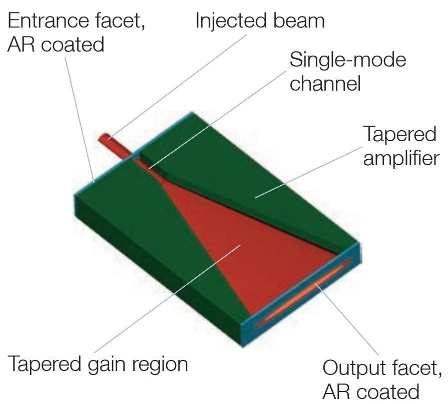
Specially shaped semiconductor optical amplifiers, or Tapered Amplifiers (TAs), serve to increase the power available from single-mode diode lasers in a Master Oscillator Power Amplifier (MOPA) configuration. The master laser beam is coupled into the single-mode channel of the TA chip, which mainly acts as a spatial mode filter. In the subsequent tapered section, this "perfect" beam is further amplified in single pass while freely diverging in the tapered plane but being confined in the orthogonal plane.

After exiting the large AR-coated output facet of the amplifier chip, this light can be shaped again into a high-quality beam with similar spectral quality as before. Typically, a small-signal gain of up to 20 dB and maximum output levels of up to 3.5 W can be achieved.

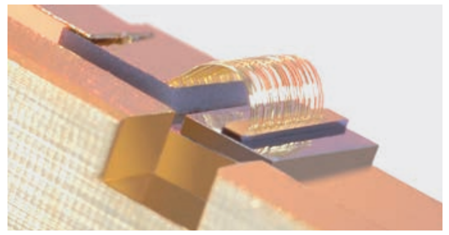
TOPTICA is constantly working together with renowned partners on TA chip development. The main aims of this initiatives are:

- to provide TAs chips at new wavelengths
- to improve the output power of TA chips
- to maintain the availability of TA chips

Examples for successful developments are the extension of the NIR-A wavelength limit from 1083 nm to 1357 nm by several novel TA chips with multi-Watt output power, the introduction of a new TA chip for amplification around 690 nm and the re-establishment of TA chips that reliably provide > 500 mW at 670 nm. TOPTICA's high power diode lasers are presented on pages 24-29.



Geometry of a tapered amplifier chip.



Amplifier chip mounted on TOPTICA's proprietary heat sink.

Frequency conversion

Despite the impressive success story of semiconductor lasers, some wavelength or power regions cannot be directly accessed with current laser diode technology. Nonlinear frequency conversion techniques close these gaps. TOPTICA's frequency-converted laser systems (pages 30-37) generate tunable cw laser radiation in the DUV, UV, blue, green, yellow, orange, and red spectral ranges. We take pride in providing highest power levels with unprecedented stability.

Second Harmonic Generation (SHG)

The SHG process can be explained in two ways. In the wave picture, the fundamental electromagnetic wave with frequency ω_1 drives the polarization of a non-linear optic (NLO) crystal. Due to the non-linearity, the polarization oscillates also at the "second-harmonic" frequency $\omega_2=2\cdot\omega_1$.

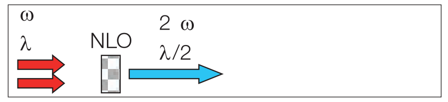
This causes the emission of a coherent electromagnetic wave at the frequency ω_2. In the photon picture, two photons of the fundamental laser wavelength λ_1 are converted inside the NLO crystal into one photon with half the original wavelength $\lambda_2=0.5\cdot\lambda_1$. The SHG efficiency increases with the fundamental power, the non-linearity of the utilized crystal and proper phase matching.

Phase matching: $n(\lambda_1) = n(\lambda_2)$

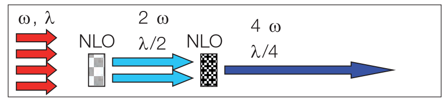
Phase matching implies that the refractive indices $n(\lambda)$ of the fundamental and the frequency-converted light are equal within the NLO crystal. This leads to a constructive interference of second-harmonic partial waves generated at different positions within the crystal along the direction of light propagation (wave picture). It also guarantees momentum conservation: Two photons of momentum $p_1 = n(\lambda_1)\cdot h/\lambda_1$ are converted into one photon of momentum $p_2 = n(\lambda_2)\cdot h/\lambda_2 = 2\cdot p_1$. Dispersion usually prevents phase matching. But it can be achieved using birefringent crystals and different polarizations of the light waves. Depending on crystal type and operating wavelength, one can fine-tune the phase matching by proper adjustment of the crystal temperature or the angle between crystal axis and light propagation.

Resonant enhancement

TOPTICA's SHG systems use a compact rugged bow-tie resonator with optimized mirror coatings to enhance the fundamental laser power resonantly by a factor of 50 to 100. For this, the resonator length has to be actively stabilized with respect to the fundamental wavelength. Employing the Pound-Drever-Hall method allows for tight locking with high long-term stability and guarantees high power with lowest noise figures. Together with our best-of selection of NLO crystals, we achieve highest conversion efficiencies and easiest handling in the market.



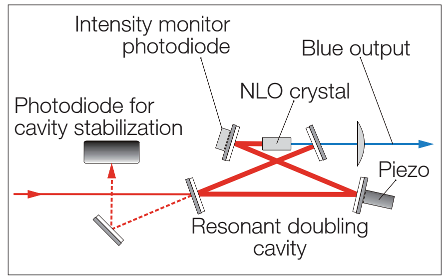
Principle of Second Harmonic Generation (SHG).



Principle of Fourth Harmonic Generation (FHG).

Fourth Harmonic Generation (FHG)

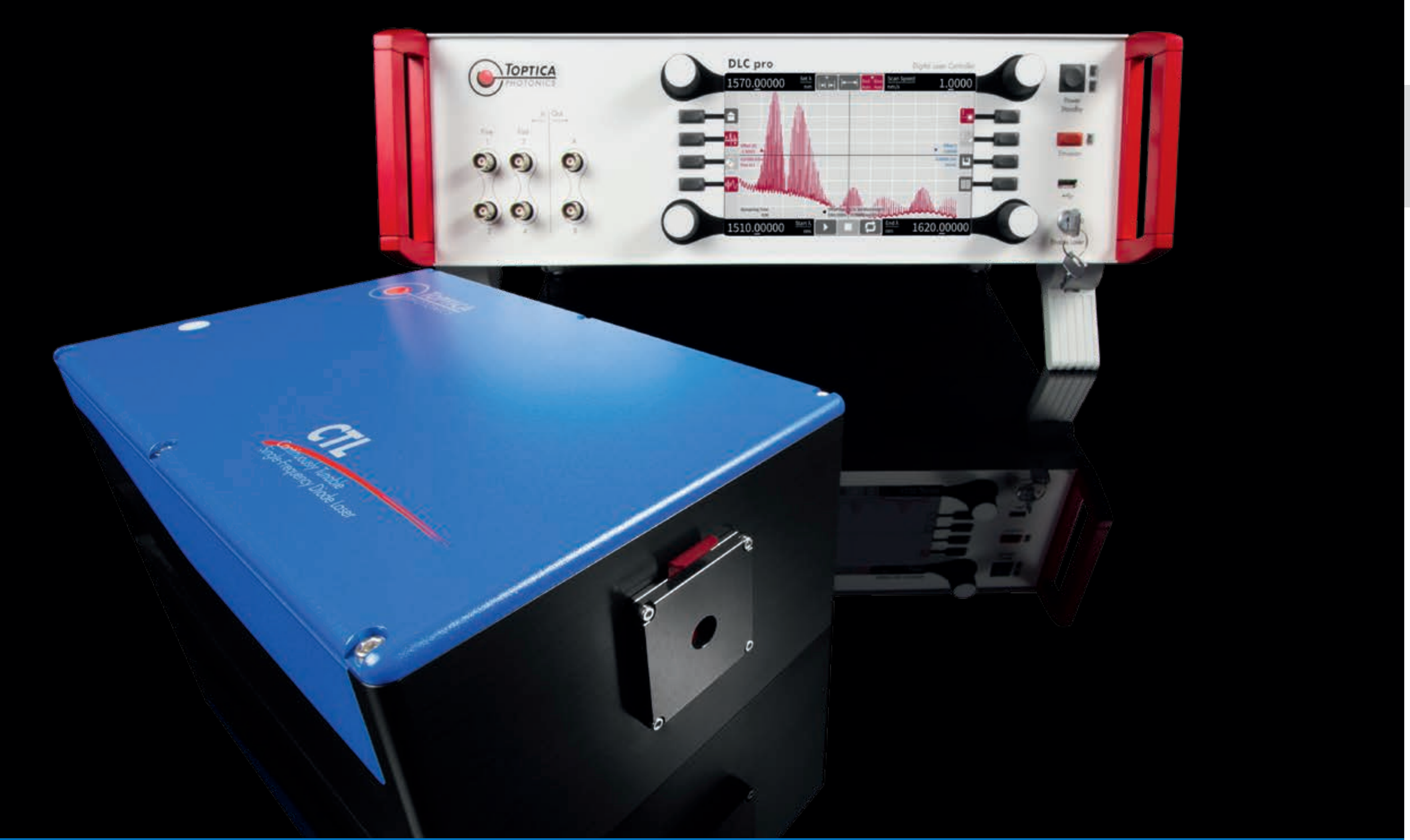
Fourth harmonic generation quadruples the frequency of an electromagnetic wave. TOPTICA's FHG systems use two consecutive SHG stages in one laser head. In total, four photons of the fundamental laser with frequency ω_1 are converted into two photons with frequency $\omega_2=2\cdot\omega_1$ and then into one photon with frequency $\omega_4=2\cdot\omega_2=4\cdot\omega_1$ and wavelength $\lambda_4=0.25\cdot\lambda_1$. By this method, we have demonstrated cw laser radiation down to 190 nm (1) with more than 15 mW at 193 nm (2).



Second Harmonic Generator (sketch).

[1] Scholz et al., Optics Express 20, 18659 (2012)

[2] Scholz et al., Appl. Phys. Lett. 103, 051114 (2013)

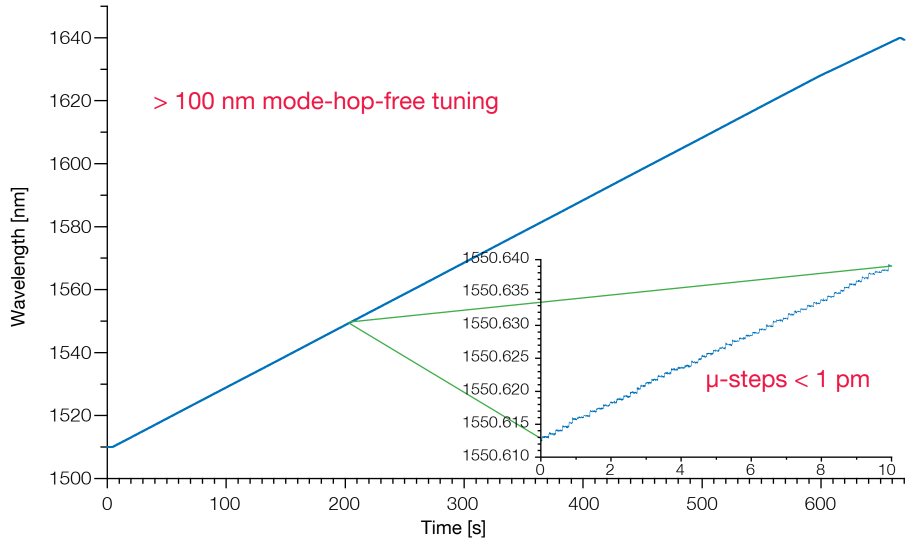


CONTINUOUSLY TUNABLE DIODE LASERS

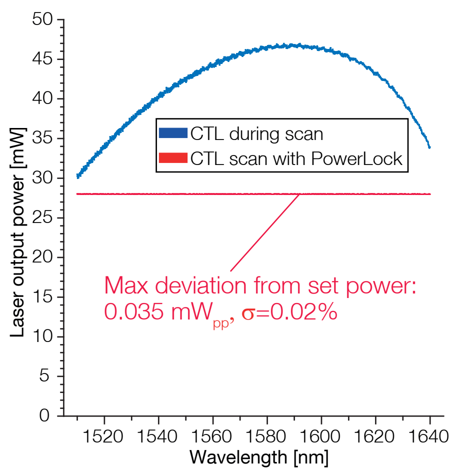
Mode-hop-free tuning across the full diode spectrum

Wide mode-hop-free tuning
Our Continuously Tunable Lasers (CTLs) scan smoothly without any mode-hopping over very wide ranges. Generally, wide mode-hop-free tuning requires excellent mechanical design and perfect alignment – the optical resonator has to be stable on a nm scale. Laser systems with passive resonator design can only achieve mode-hop-free tuning across a few nm up to a few 10 nm.
In order to achieve wider and guaranteed mode-hop-free tuning – even across the full gain spectrum of the diode – not only excellent mechanical design is essential, but also active control is required. The unique SMILE technology (Single Mode Intelligent Loop Engine, patent pending) ensures mode-hop-free operation across the complete gain spectrum of the diode.

The active control loop analyzes several signals in the laser head and optimizes the involved tuning elements. With TOPTICA's SMILE, no mode-hopping occurs.



Motorized mode-hop-free tuning over more than 100 nm. Microsteps (< 1 pm) are visible for very slow scan speeds. Piezo scans over > 30 GHz are possible with < 10 kHz step size.



Output power as a function of the wavelength of the CTL 1550. The smooth power variation of only ~20 % over the whole specified tuning range can be reduced to below 0.1 % with PowerLock.

High resolution
Motorized coarse tuning and scanning happens with steps down to 0.3 pm in size. While individual steps can be seen in slow scans with a highly sensitive measurement, above a certain scan speed, scans are smooth. The maximum scan speed is 10 nm/s. If even higher resolution is desired, piezo sans can be performed across more than 500 motor steps. The piezo is addressed with 24 bits resolution, and the smallest piezo step size is smaller than 5 kHz.

For even more precise and high bandwidth modulation or regulation, direct access via a safe modulation circuit in the laser head offers modulation bandwidths of approx. 100 MHz. Utilizing this input, it is possible to phase lock or stabilize CTL down to the Hz level.

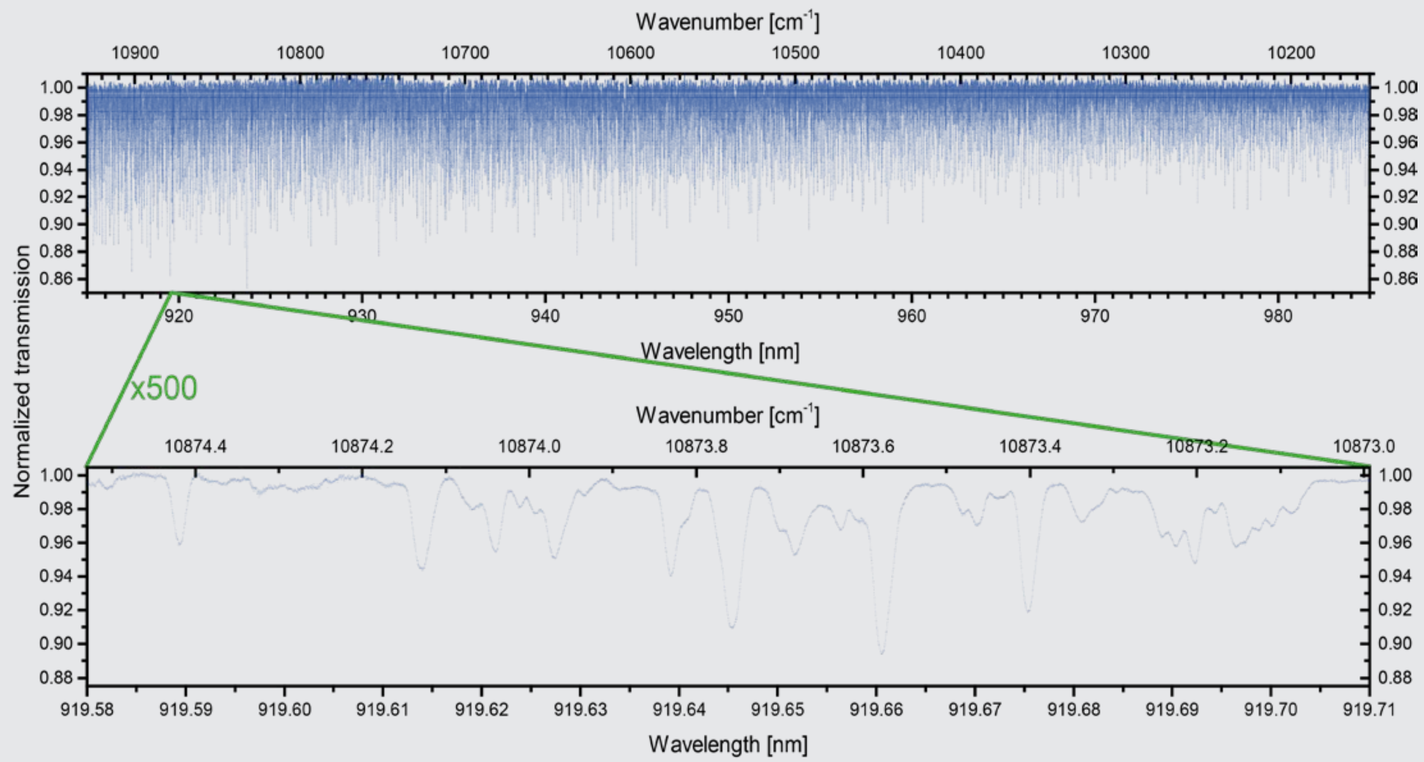
Low noise & drift
Narrow linewidth as well as low noise and drift, are important requisites for high resolution and repeatable spectral measurements. The linewidth of the CTL is smaller than 10 kHz (measured with delayed self-heterodyne setup with 5 µs delay) and allows highest resolution, while the completely digital electronics DLC pro offers the lowest drifts of diode current, temperature and piezo voltage commercially available – allowing for excellent stability and repeatability.

Examplary measurements of the passive frequency stability and the linewidth of the DLC CTL laser system are shown on pages 14 and 15.

Laser system DLC CTL: The mode-hop-free widely tunable laser is equipped with TOPTICA's all digital controller DLC pro.

Key Features

- Wide mode-hop-free tuning:
  Up to 110 nm
- High resolution:
  Step size as small as 5 kHz
- Low noise & drift:
  Linewidths below 10 kHz
- Total touch, knob & remote control:
  All digital DLC pro – hands off
- Reliable: SMILE & FLOW



High resolution spectrum of iodine measured with CTL 950 from 915 to 985 nm. The zoom shows the immense resolution.
With piezo scanning more than two additional x500 zooms are possible to measure even finer features and resonances.

Total touch, knob & remote control

The CTL series lasers are operated with TOPTICA's all digital and versatile DLC pro diode laser controller. This ensures not only flexibility and future compatibility, but also lowest noise and drift (digital signals do not drift) and convenient operation via touch screen, knobs and remote control. Remote control of the laser operation is possible via USB and TCP/IP, either with a PC graphical user interface or by integrating the DLC pro into customers' software via a powerful command language.

User interfaces

Two comfortable user interfaces are provided for intuitive operation and control. A touch screen with four additional knobs shows the most important information and offers direct access to all necessary controls. Remote control via computer/ethernet is possible with the supplied comprehensive and powerful PC graphical user interface.

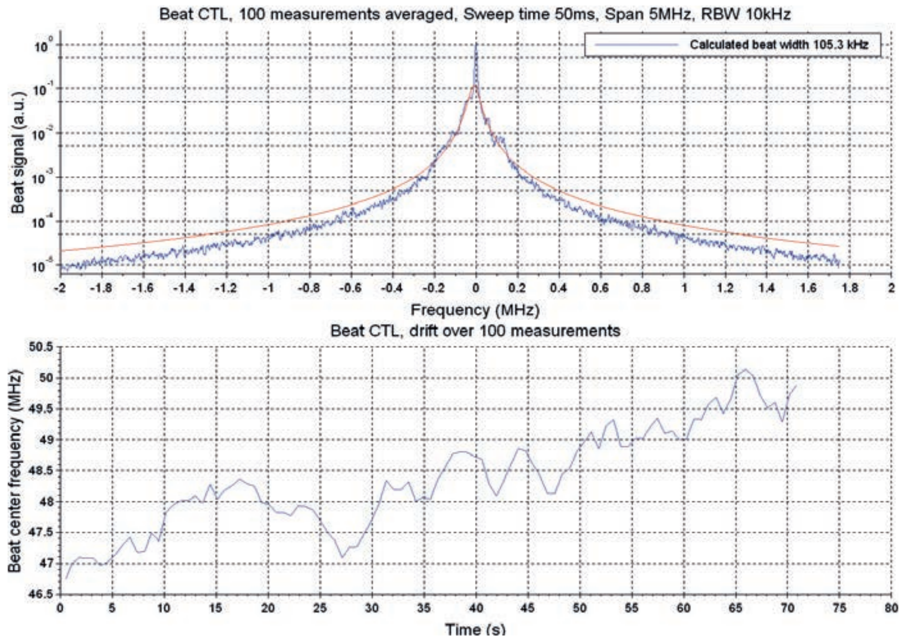
Reliable – hands-off

The DLC CTL is a hands-off laser system that requires no alignment or maintenance. The cavity is optically closed and stable by design, usually without the necessity of readjusting movable parts for cavity optimization.

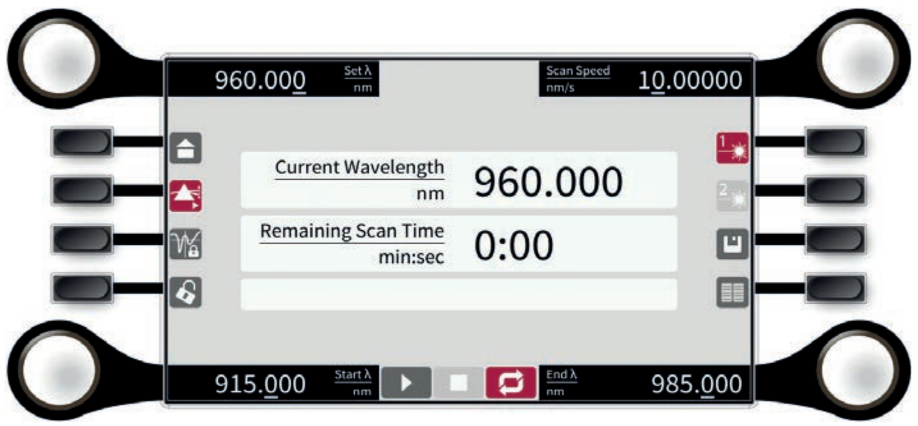
If ever required, the integrated FLOW feature (Feedback Light Optimization Wizard) optimizes the cavity upon the touch of a button. This optimization reestablishes stable and mode-hop-free operation across the complete tuning range. It can be performed in the field (no shipping back to the factory is necessary). Due to the excellent and innovative patent pending design of the CTL, activation of the FLOW will only be necessary if the laser has experienced large mechanical shock or temperature changes. Together with the SMILE, the CTL is a worry-less and hands-off laser system ready for use when you are.

Future ready

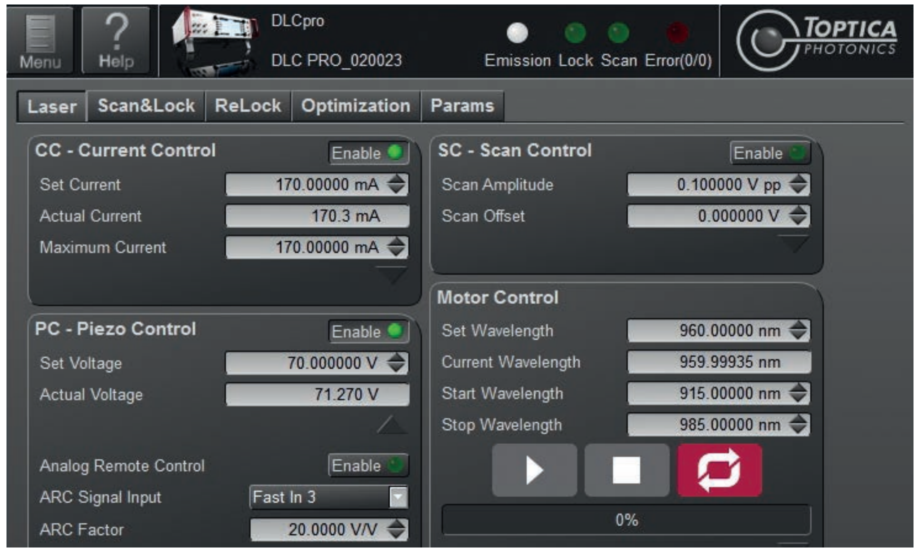
The digital nature and the future-oriented design of DLC pro allow for easy integration of new features. Already, micro-steps and power stabilization have been added by the last firmware upgrades, and we keep adding improvements and new features continuously.



Top: Average of 100 individually centered beat measurements with 50 ms sweep time each: Beat width ≈ 100 kHz. **Bottom:** Change of center frequency in 70 seconds: Drift < 5 MHz.

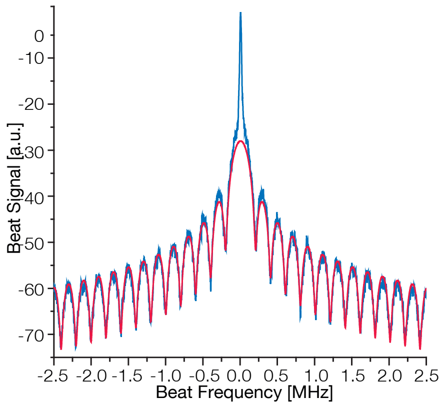


More than motor control: The DLC CTL digital control electronics features also all functionality of the DLC pro for DL pro lasers, including the optional DLC pro Lock for frequency stabilization.

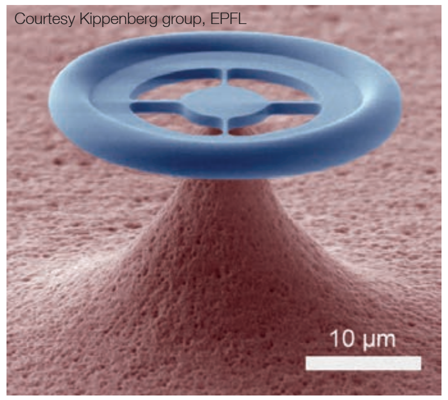


Specifications						
	CTL 950	**CTL 1050**	**CTL 1320**	**CTL 1470**	**CTL 1500**	**CTL 1550**
Wavelength	915 - 985 nm	1020 - 1070 nm	1290 - 1350 nm	1420 - 1530 nm	1460 - 1570 nm	1530 - 1620 nm
Absolute accuracy	< 100 pm	< 110 pm	< 130 pm	< 140 pm	< 150 pm	< 150 pm
Relative accuracy	< 10 pm	< 10 pm	< 10 pm	< 10 pm	< 10 pm	< 10 pm
Typ linewidth (5 µs)	< 10 kHz	< 10 kHz	< 10 kHz	< 10 kHz	< 10 kHz	< 10 kHz
Power at Max	> 80 mW	> 50 mW	> 50 mW	> 40 mW	> 50 mW	> 50 mW
Power at Edges	> 40 mW	> 25 mW	> 30 mW	> 20 mW	> 25 mW	> 30 mW
Max. scan speed	10 nm/s	10 nm /s	10 nm/s	10 nms/s	10 nm/s	10 nm/s
Motor step size	5 pm	6 pm	7 pm	8 pm	8 pm	8 pm
Micro step size (average)	0.3 pm	0.4 pm	0.5 pm	0.5 pm	0.5 pm	0.5 pm
Piezo scan	55 GHz	45 GHz	40 GHz	35 GHz	35 GHz	35 GHz
Piezo step size	< 10 kHz	< 10 kHz	< 5 kHz	< 5 kHz	< 5 kHz	< 5 kHz

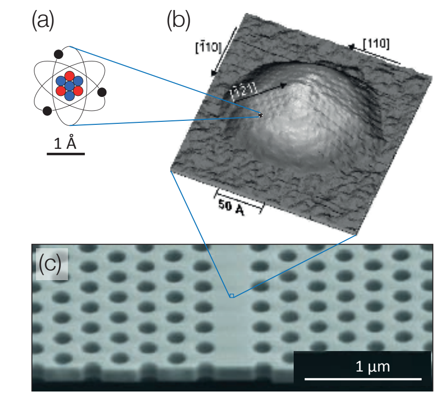
* Wavelength range will be continuously expanded. Please inquire for your wavelength of choice.



Measurement of the CTL 950 linewidth with a self-heterodyne beat experiment with a 1 km (5 µs) delay fiber. The result is a linewidth of approximately 5 kHz.



The CTL is ideally suited to investigate microcavites. Such cavities are useful for sensing applications, investigating quantum-mechanical coupling, and to create microscopic frequency combs.



Another important application for CTLs are quantum dots. These act as artificial atoms in in solid-state systems. Unlike real atoms, semiconductor quantum dots can be grown and placed in a controlled fashion, e.g. in photonic crystal cavities and even enable cavity QED experiments in the solid state (taken with permission from Peter Lodahl et al., Reviews of modern physics 87, p. 347 (2015)).

TUNABLE DIODE LASERS

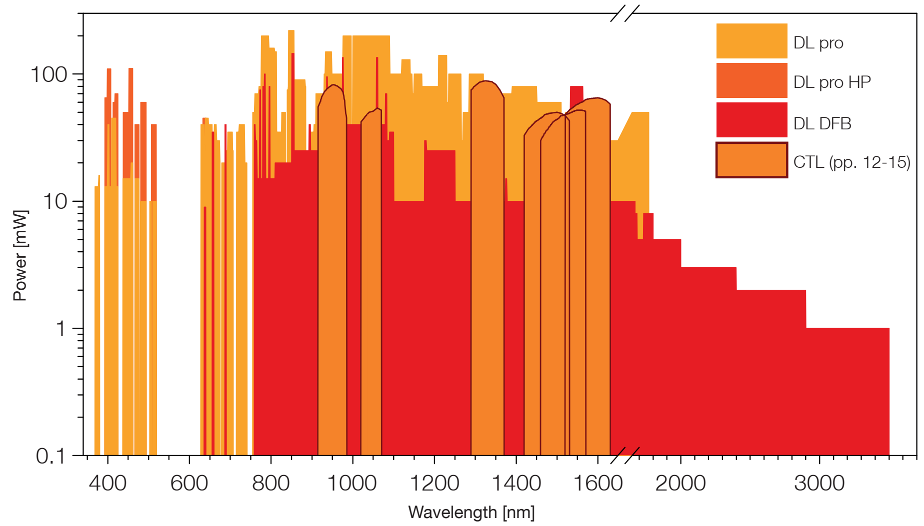
External Cavity and DFB Diode Lasers

Tunable diode lasers have been TOPTICA's core expertise since 1995, when the first DL 100 lasers found their way into scientific laboratories. Many years of continuous development followed - along with thousands of individually manufactured and customer-proven diode lasers.

Thanks to the introduction of the patented pro technology in 2007, TOPTICA has consolidated and enlarged its market leadership in external-cavity diode laser (ECDL) technology. The popular DL pro has surpassed the DL 100 in the installed base. Researches all around the world enjoy its stability and longevity from undergraduate students to Nobel laureates. The DL pro is the laser of choice particularly for demanding experiments that need stable locking of several lasers, narrow linewidth (available as a special option at many wavelengths) and easy tuning. The DFB pro is TOPTICA's new tunable laser incorporating DFB or DBR diodes. It offers larger mode-hop-free tuning ranges at reduced coarse-tuning ranges and increased linewidth compared to the DL pro. Due to the lack of alignment sensitive optical elements, DFB pro lasers are suited particularly for applications in noisy environments.

With the first all-digital control electronics DLC pro TOPTICA has taken yet another big step in laser operation. The DLC pro sets new standards with respect to noise figures, stability values and user friendliness. New features become available such as the power stabilization with updates of the software, even for systems already in operation in the laboratories worldwide.

All lasers of the *pro* series may now be driven with the DLC pro and hence operated not with its intuitive touch screen and turn-key interface but also from a remote control computer using the provided software or the powerful command language. The laser control electronics has successfully arrived in the digital age and the DLC pro outperforms its analog counterpart SYST DC 110 system, which remains available as economic solution.



DLC DL pro

Ultra-Stable Tunable Diode Laser with Digital Control

The **DLC DL pro** unites TOPTICA's well-established DL pro laser head with its patented resonator design and the all-digital control electronics DLC pro. Owing to its low noise and drift values, the DLC DL pro achieves even narrower linewidths and better stability.

At the same time, the system provides a most convenient user interface with intuitive touch, dial and total remote control. For detailed specifications of the DLC pro, please see page 38-40. Just like the first laser of the *pro* series, the DL pro, demonstrated how much even a a well-established instrument like the DL 100 can be further improved, the first *pro* laser control electronics, the DLC pro, leads to a huge improvement in performance.

Options

- Single and double-stage isolators (page 45)
- Fiber-coupled output with FiberDock (single-mode, polarization-maintaining)
- DLC pro Lock, integrated digital frequency stabilization (page 39)
- DLC ext allows to combine the DLC pro with advanced locking modules DigiLock 110 and FALC 110 (p. 41-43)
- Beam shaping (page 22)
- Motorized wavelength selection with an accuracy of approximately ± 0.2 nm (for most wavelengths, page 22)

Main advantages

The main advantages of the DLC DL pro for the user include large mode-hop-free tuning, alignment-free operation and the highest acoustic and thermal stability of any ECDL on the market.

This translates to a product that delivers the most reliable and convenient operation for high-end laboratory work.

Sophisticated and patented technology

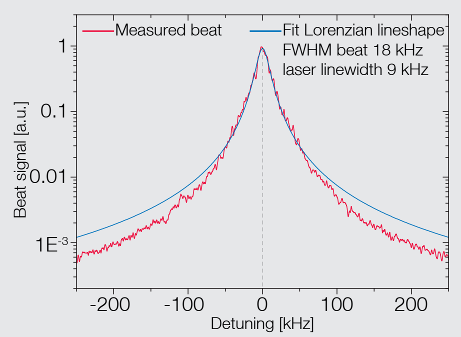
To achieve the highest performance and ease of use, the DL pro mechanics possesses degrees of freedom exactly where they are needed. Coarse and fine-tuning have been skillfully separated: A well-defined rotation of the grating performs coarse tuning and precisely selects any requested wavelength within the gain spectrum of the diode. Mode-hop-free tuning is realized by a system of robust flexure joints that require only tiny adjustments. They rotate the laser's grating around the perfect "virtual" pivot point.

The compact and stable external-cavity resonator has its first mechanical resonance above 4 kHz - one reason for its superior acoustic stability. Special care has been taken in choosing dimensions and materials with reduced sensivity to variations of the ambient temperature. In addition to its stability, the DL pro is easy to align: The experienced user can even exchange the laser diode on-site.

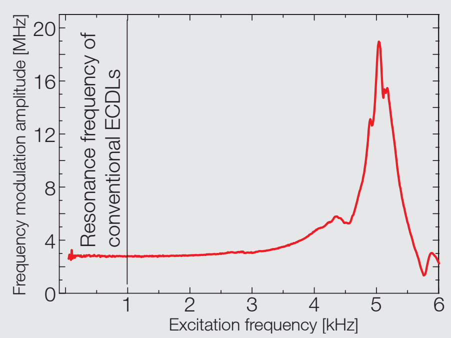
Laser system DLC DL pro with well established laser head and all-digital control electronics.

Key Features
· Available between 369 nm..1770 nm
· All-digital, intelligent control electronics DLC pro
· Power stabilization to external signal and pressure compensation included
· Ultra-stable patented resonator design (DE 10 2007 028 499 and US 7970024)
· Optimized virtual pivot point
· 20 - 50 GHz mode-hop-free tuning
· Convenient alignment-free coarse-tuning from outside the laser head
· Fast current AC & DC modulation

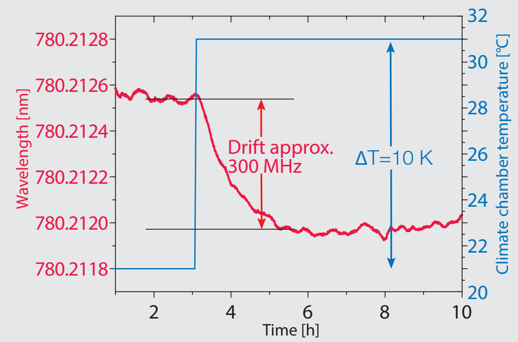
Check our regularly updated diode stock list:
www.laser-diodes.com



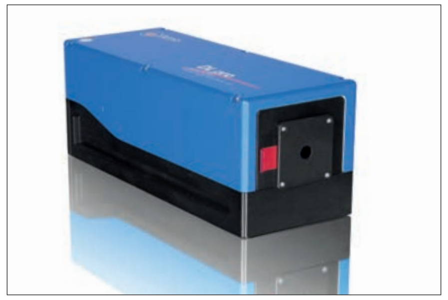
Measured beat signal of two free-running DL pro at 1160 nm. 100 scans with sweep times of 50 ms have been averaged. The two laser systems are of the same built and contribute equally to the residual noise.



DL pro piezo transfer function. Below 4 kHz no acoustic resonances can be detected.



Laser frequency response to a 10 Kelvin air temperature change (laser and electronics inside a climate chamber).



DL pro HP laser head.

Key Features

- Available between 394 nm .. 640 nm
- Up to 110 mW single-frequency, tunable output
- Excellent stability against mode-hopping
- Typical linewidth 100 .. 500 kHz
- For details of the laser controler DLC pro see page 38-40.

Check our regularly updated diode stock list:
www.laser-diodes.com

Due to new laser diode developments, the maximum single-frequency output power of visible and UV tunable diode lasers is no longer limited by the damage threshold of the laser diode. However, achieving reliable single-frequency operation of an external cavity diode laser (ECDL) becomes increasingly difficult at high power levels.

Small variations of the laser diode current or its temperature can cause mode-hopping - which corresponds to an abrupt jump in laser frequency by several GHz - or even lead to multi-mode operation of the laser.

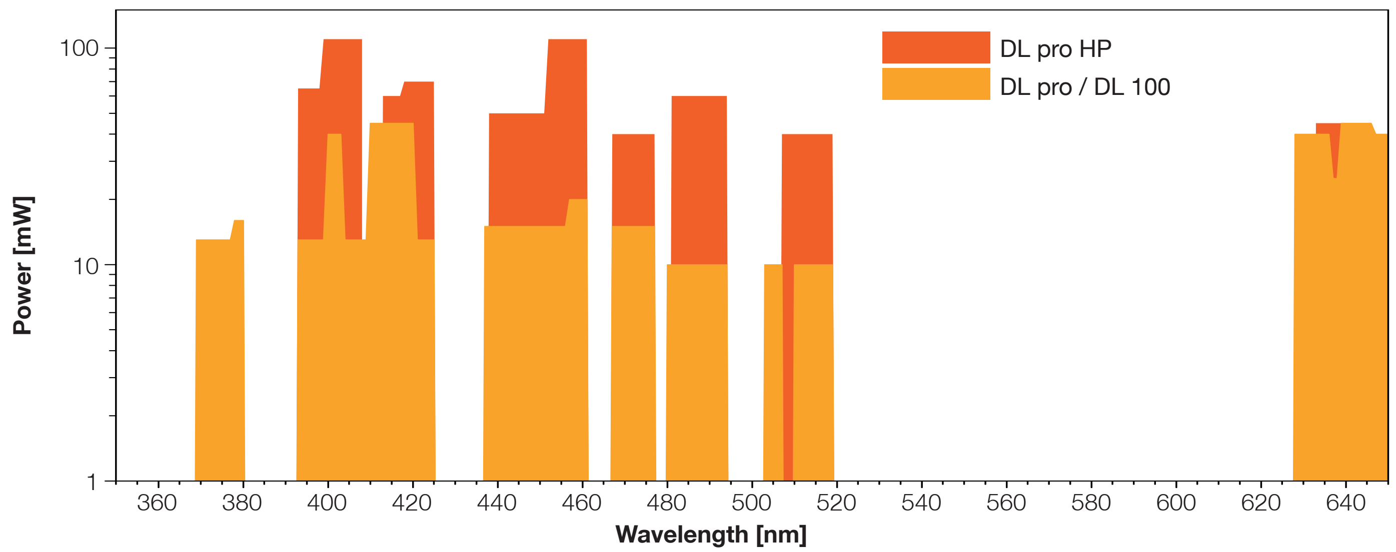
Higher power from visible & UV ECDLs
The new DLC DL pro HP diode laser overrides former output power limits of ECDLs in two ways. First, it features a specific version of the DL pro laser head with a proprietary resonator design and provides increased single-mode power at „visible“ wavelengths. Second, the new digital driving electronics DLC pro enables unmatched current and temperature stability. The combination of both achievements delivers record values of stable single-frequency output power from visible or UV ECDLs, for example 110 mW at 399 nm or 461 nm.

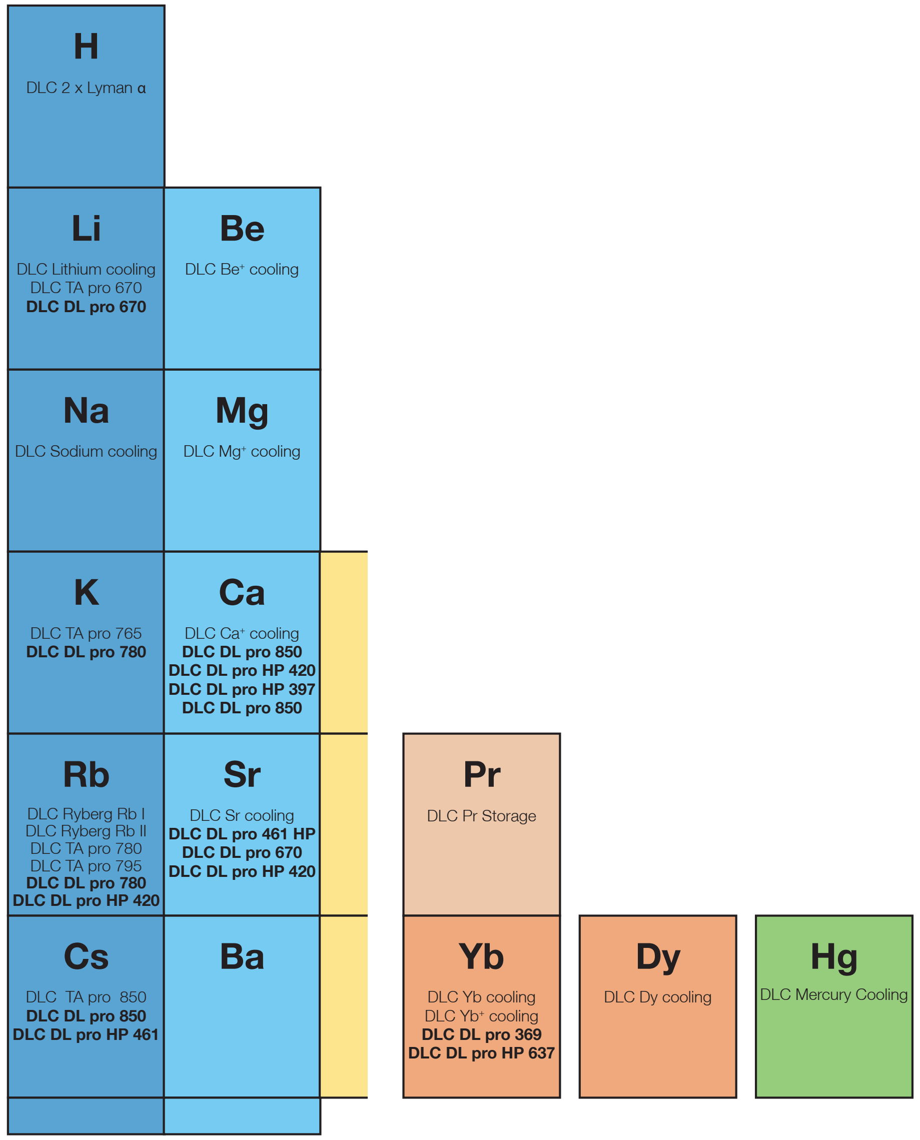
Coarse- and fine-tuning
Manual coarse tuning of the wavelength is possible across the full gain spectrum of the laser diode (for blue and UV diodes approximately 2-3 nm) and mode-hop-free fine-tuning covers scan ranges up to 50 GHz. Typical short term linewidths are below 150 kHz, corresponding to coherence lengths of > 600 m. Standard wavelengths include 399 nm, 423 nm and 633 nm. Other wavelengths between 394 nm and 640 nm are available on request. See preconfigured TOPSeller on the next page.

Integrated optical isolator
The DL pro HP laser head features two inputs with protection circuit for fast AC & DC modulation of the laser diode current. These are typically used for fast frequency modulation or locking. A preselected 35 dB optical isolator is also integrated. The DLC pro digital electronics (see page 38-40) allows convenient operation via touch screen and remote control.

Options

- Fiber-coupled output with FiberDock (single-mode, polarization-maintaining)
- DLC pro Lock, integrated digital frequency stabilization (p. 39)
- DLC ext allows to combine the DLC pro with advanced locking modules DigiLock 110 and FALC 110 (p. 41/42)
- Beam shaping
- Motorized wavelength selection with an accuracy of approximately ± 0.2 nm





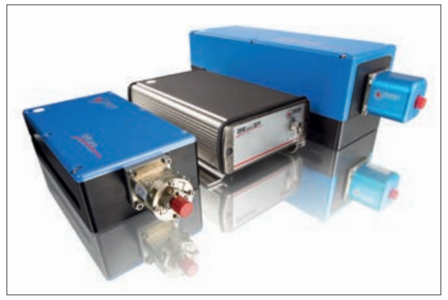
A number of TOPSeller systems are available, e.g. for laser cooling or excitation of specific transitions. Listed in this cut-out of the periodic table are all TOPTICA TOPSeller solutions for each element. Direct diode lasers are marked in bold letters. TOPSellers based on amplified TA solutions (see page 26) or frequency-converted NLO systems (see page 34) are mentioned for completeness.

The DLC DL pro is used in various applications and it is designed to be used with various laser diodes. TOPTICA is in close contact with researchers to identify and meet the specific needs. Some applications are in fact so popular that we have defined laser systems specific to them. For example the most popular application of the DL pro is the laser cooling of rubidium, in which the laser wavelength is tuned very close to the Rb D1 line at 780.24 nm.

The ten TOPSellers of the DLC DL pro and DLC DL pro HP are direct solutions for the most popular applications. They are configured just in the way they are required for the immediate integration to the lab. The fitting laser diode and optical isolator are included. This allows for shorter delivery times of a few weeks and, due so simplification in the production process, for reduced prices relative to the configurable systems.

Magneto-optical trap of rubidium atoms.
I. Bloch, MPQ Garching, Germany.

DLC DL pro	**850**	**780**	**670**	**633**	**369**
Typical applications	Cs cooling, Ca ion repump	Rb cooling and repump, K cooling and repump	Li cooling and repump, Sr ion clock transition	HeNe laser wavelength	Yb ion cooling
Peak power (mW) behind isolator, specified (typical)	70	105	25	32	13
Wavelength (nm)	840 - 875	765 - 805	664 - 674	631 - 635	369.2 - 370.2
Linewidth (kHz @5 µs delay)	100	100	200	200	100
Included optical isolator	> 60 dB	> 60 dB	> 60 dB	> 60 dB	> 28 dB
DLC DL pro HP	**637**	**461**	**420**	**399**	**397**
Typical applications	NV center, Yb ion clear out laser	Sr cooling, Cs Rydberg	Ca cooling, Sr ion cooling, Rb Rydberg	Yb cooling	Ca ion cooling
Peak power (mW) behind isolator, specified (typical)	45 (50)	110	70	50	65
Wavelength (nm)	635 - 639	457 - 461	420 - 423	399 - 402	396.5 - 398.5
Linewidth (kHz @5 µs delay)	500	150	150	150	150
Included optical isolator	> 35 dB	> 35 dB	> 35 dB	> 35 dB	> 35 dB



DFB pro laser heads.
Left to right: Compact DFB pro, DFB pro BFY (for butterfly diodes) and DFB pro L (for complete range of options).

Key Features

- Single-frequency lasers with distributed-feedback diodes
- Available wavelengths: 633 nm, 760 nm .. 3500 nm
- Mode-hop-free tuning range: Up to 1400 GHz
- Up to 150 mW output power
- Reliable operation even in harsh environments
- 3 different laser heads – wide range of options

Check our regularly updated diode stock list:
www.laser-diodes.com

High stability & ease of use

Distributed feedback (DFB) and Distributed Bragg-reflector (DBR) lasers unite wide tunability and high output power. The frequency-selective element, a Bragg grating, is integrated into the active section of the semiconductor and ensures continuous single-frequency operation. Due to the absence of alignment-sensitive components, DFB lasers exhibit an exceptional stability and reliability. The lasers work under the most adverse environmental conditions – even in the Arctic or in airborne experiments.

Three laser heads

The new DFB pro laser series integrates both DFB and DBR diodes. Three laser heads accommodate different diode packages: the compact DFB pro and its "big brother" DFB pro L integrate 9 mm or TO3-type diodes. The DFB pro BFY offers a dedicated laser head for butterfly-type diodes.

Available wavelengths include 633 nm and the entire range from 760 nm to 3500 nm.

Thermal and electric frequency tuning

Frequency tuning of DFB/DBR lasers is accomplished by varying either the chip temperature or the operating current. Typical thermal tuning coefficients are ~25 GHz/K at 780 nm and ~10 GHz/K at 1.5 µm. Thermal tuning achieves mode-hop-free scan ranges of several hundred GHz, at a moderate tuning speed of ~100 GHz/s. This tuning mode lends itself to applications that require wide, continuous scans, such as molecular spectroscopy, gas sensing, or the generation of continuous-wave terahertz waves.

By contrast, laser-current tuning spans a smaller frequency range, but works up to MHz rates. The electric tuning coefficient usually amounts to 1-10 GHz/mA. Electric tuning thus enables fast and highly precise scans, as required for atomic physics or phase-shifting interferometry.

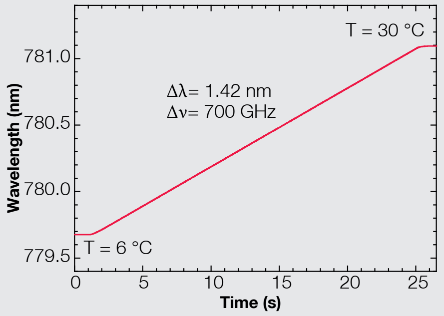
Touch-panel control

The new DFB pro lasers are conveniently controlled with the DLC pro. All of the popular features of the DLC pro are supported: the user-friendly touch display, remote control via Ethernet, "click and lock" operation. In addition, users can choose between a "wide scan", which changes the laser temperature in a well-controlled manner, and a fast scan that acts on the laser current.

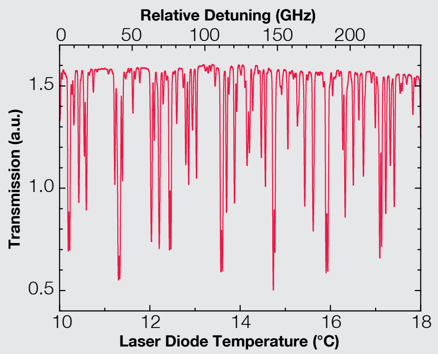
Laser frequency control has never been that easy!

Options

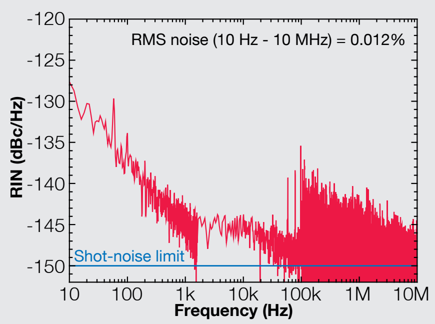
- Beam shaping
- Single-stage or double-stage optical isolation
- Fiber coupling
- Frequency stabilization option DLC pro Lock (see page 39)



"Wide scan" of a DFB pro laser at 780 nm: A temperature sweep from 3 °C to 30 °C changes the frequency by 700 GHz.



Absorption spectrum of iodine, recorded with a thermally tuned DFB pro laser at 633 nm. The scan in the figure covers a range of approx. 250 GHz.



Relative intensity noise (RIN) of a DFB pro laser at 780 nm. The integrated RMS noise amounts to 0.01%.

Principle of operation

The well-proven performance of the DL 100 results from its Littrow-type external cavity laser setup in a simple but rugged design. All over the world, scientists and engineers use the DL 100 for numerous experiments, from simple absorption spectroscopy to multi-species BECs.

Fine thread screws permit coarse manual tuning, while precise mode-hop-free scans are driven by a piezo actuator. Lockable, three-dimensional adjustments together with metal flexures provide rigid control of both the laser beam collimation and the grating feedback. The laser resonator is thermally stabilized by means of a Peltier cooling element, connected to the DTC 110 Diode Temperature Control.

Low noise operation of the DL 100 is achieved by means of the Diode Current Control DCC 110. In addition, TOPTICA offers a variety of regulator modules to stabilize the laser frequency.

Options

- Optical isolators
- Beam shaping
- Fiber-coupling
- DC / AC coupled modulation board
- Locking modules for SYS DC 110:
- DigiLock 110, FALC 110, PID 110, PDD 110

Modular design

The DL 100 diode laser head comprises a mounting base which serves as heat sink, a temperature sensor and Peltier cooling element for active temperature control, a laser base plate, a laser diode holder with a collimator and a grating mount with a piezo actuator for precise tuning.

The laser diode itself can be easily exchanged by replacing the diode holder without dismantling the setup. The DL 100 is available with AR and FP-type diodes. FP diodes deliver higher power at lower cost, while AR-coated diodes offer wider tuning, more stable single-mode behavior and narrower linewidths. The control and supply units are designed as modular plugins which can be combined to meet any application requirement. Further modules like Scan Control, PID regulator and Pound-Drever-Hall detector complete the modular electronics setup.

Hands-on setup

The DL 100 has evolved in research laboratories and therefore offers the necessary versatility for a changing environment. For instance, all important alignment parameters are easily accessible from above and are adjustable by lockable fine threadscrews. If an OEM application requires a fixed laser setup with limited user access, TOPTICA can also provide "hands-off" laser systems.

Reasonably priced

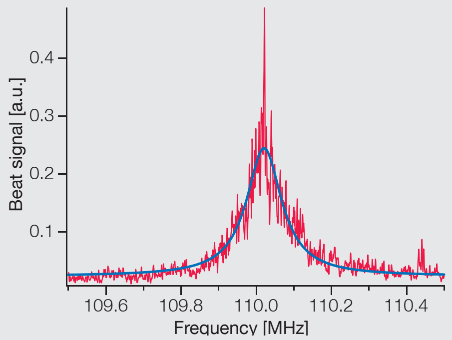
A DL 100 laser system is the most economic and flexible step into the "World of Tunable Diode Lasers". If even more stable and convenient operation is required, the DL pro systems are the recommended alternatives (see pages 17-19).

SYST DL 100, the classic workhorse for many quantum optics experiments.

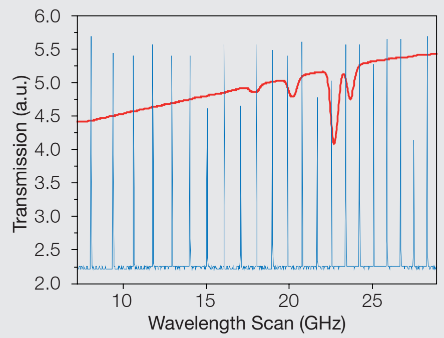
Key Features

- Widest wavelength coverage 370 .. 1770 nm
- High power up to 300 mW
- Mode-hop-free tuning up to 30 GHz
- Free-running linewidth 100 kHz .. 1 MHz (5 µs)
- AR and FP diodes

Check our regularly updated diode stock list:
www.laser-diodes.com

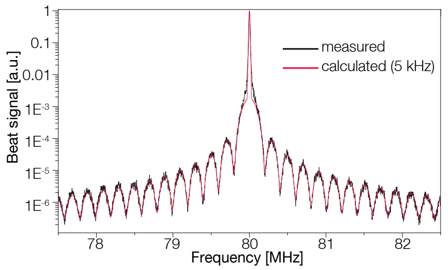


Linewidth measurement of DL 100 with delayed self-heterodyne beat setup (delay 5 µs). The resulting linewidth is below 100 kHz.

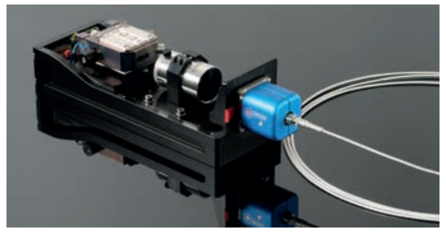


DL 100 frequency sweep over four Rb absorption lines (red). FPI transmission peaks (blue, FSR 1 GHz) are shown for reference.

A number of options allow to optimize the laser system towards the specific needs of the application. While our TOPSeller provide pre-configured solutions to a number of applications, the DLC DL pro and DLC DL pro HP systems is customizable with the following options:

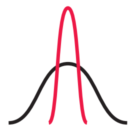


Self-heterodyne linewidth measurement of DLC DL pro with narrow linewidth option.



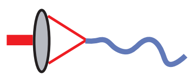
DL pro with integrated optical isolator and fiber coupling using a FiberDock

Narrow linewidth



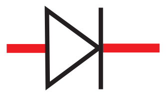
With this option DL pro laser systems are optimized for narrow linewidths. It is also suited for seed lasers of TA pro or NLO systems but not for DL pro HP, DFB pro or DL 100 lasers.

Fiber Coupling (FiberDock)



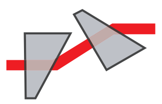
TOPTICA's patented fiber coupler provides highest single-mode fiber-coupling efficiencies, easy alignment and at the same time highest stability. TOPTICA additionally offers a wide range of single-mode and polarization-maintaining fibers, including fiber-optic beam splitters. Optical isolation is mandatory for fiber-coupled diode laser systems. This option is also available for TOPSeller DLC DL pro and DLC DL pro HP.

Optical Isolation



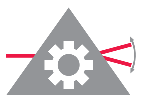
Isolators are used to protect the laser diode against back reflections. This not only prevents damage to the diode but also ensures untroubled tuning and single-frequency operation. Fiber-coupling with angle-polished fibers (both ends) requires at least a single-stage isolator (> 30 dB). Double-stage isolators are needed if reflections from the experiment into the laser are expected. Fiber-coupling with non-angle-polished fibers also requires a double-stage isolator (> 60 dB). TOPSellers are always equipped with the appropriate optical isolator. See page 45 for details of the isolators.

Beam Shaping



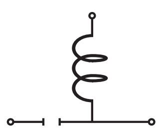
To shape elliptical laser beams into round profiles, either an anamorphic prism pair (APP) or cylindrical lenses are used. The compressed circular beam is small enough for using inexpensive small-aperture isolators, and the fiber-coupling efficiency is enhanced by approximately 10 %. The compression ratio is set at the factory.

Motorization



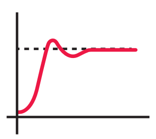
The motorization of the coarse tuning offers manual control and operation via software interface. This option is available for most DL pro laser systems (most AR laser diodes and some FP diodes) including DL pro HP laser systems. Please note that unlike for the DLC CTL systems (p. 12) mode-hopping during the scan may occure. This leads to an approximate accuracy and repeatability specification of ±0.2 nm of the laser wavelength. Not available for the DL 100 or for DFB pro.

Bias-T



The DL pro (HP) has two modulation inputs that allow current modulation frequencies of up to 150 MHz. A Bias-T allows even higher current modulation frequencies of up to several GHz, depending on the diode. It is also suited for seed lasers of TA or NLO systems. DL 100 laser have a Bias-T included that may be activated by setting of a jumper.

Electronics Modules



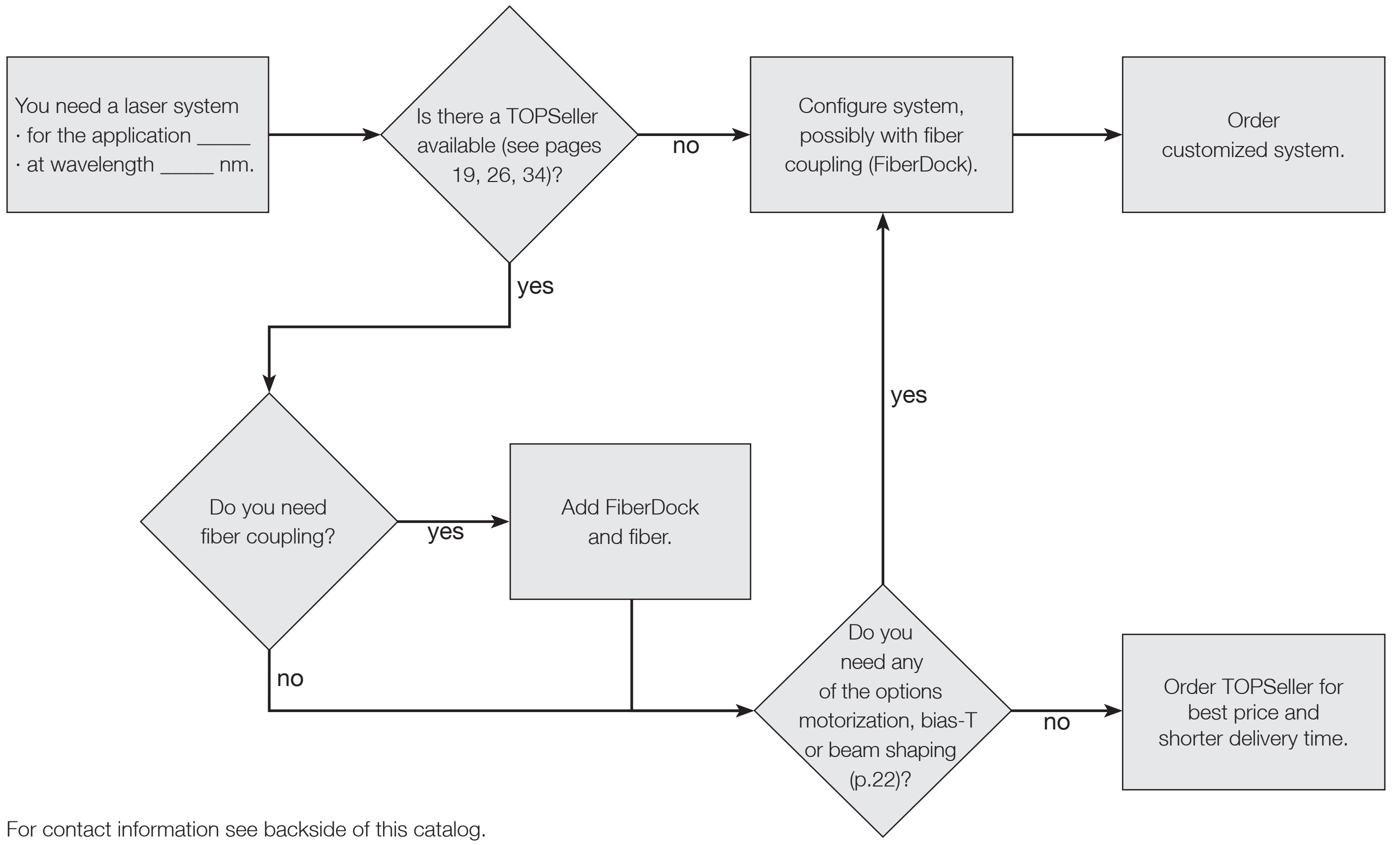
A broad variety of electronic locking modules is available for frequency stabilization. See pages 41-43 for details of the modules like DigiLock 110 and FALC 110 etc.

Class 3B Laser Product EN 60825-1:2007. Visible or insible laser radiation. Avoid direct exposure to beam. Caution - Class 3B visible or insivisble laser radiation when open. Avoid exposure to the beam. Magnetic fields may be present which may affect the operation of certain pacemakers.

Specifications	DL pro	DL pro HP	DL 100	DFB pro
Type of laser	ECDL	ECDL	ECDL	Direct diode
Laser diodes	AR coated and FP laser diodes	AR coated and FP laser diodes	AR coated and FP laser diodes	DFB and DBR diodes
Best for	high resolution, long term operation	high power	flexible economic lab system	rugged environments, wide continuous tuning
Typical linewidth (5 µs)	10 kHz .. 300 kHz	100 kHz .. 500 kHz	30 kHz .. 300 kHz	300 kHz .. 2 MHz
Wavelength range	369 nm -1770 nm	394 nm - 637 nm	369 nm - 1770 nm	633 nm, 760 nm - 3500 nm
Coarse Tuning	mechanical*	mechanical*	mechanical (service operation)	thermal or electric
Mode-hop-free tuning-range (MHFTR)	20 GHz .. 50 GHz	20 GHz .. 50 GHz	20 GHz .. 50 GHz	600 .. 1200 GHz
Temperature sensitivity	<< 100 MHz / K	<< 100 MHz / K	400 MHz / K	100 MHz / K
Optical isolator	optional, included in TOPSellers	included	optional + recommended	optional + recommended
Replacement of laser diodes	possible	at the factory	easy	at the factory
Wavelength switch	available	not available	available	available
Laser system with DLC pro	DLC DL pro	DLC DL pro HP	not available	DLC DFB pro, DLC DFB pro L, DLC DFB pro BFY
Laser system with SYS DC 110	SYST DL pro	not recommended	SYST DL L	DFB pro (L / BFY) and SYS DC 110

Specifications are typical values and can vary with integrated laser diode.
Please see laser diode stock list for details or inquire: www.laser-diodes.com.
*Motorization available, see page 22.

How to choose your DL series configuration



For contact information see backside of this catalog.

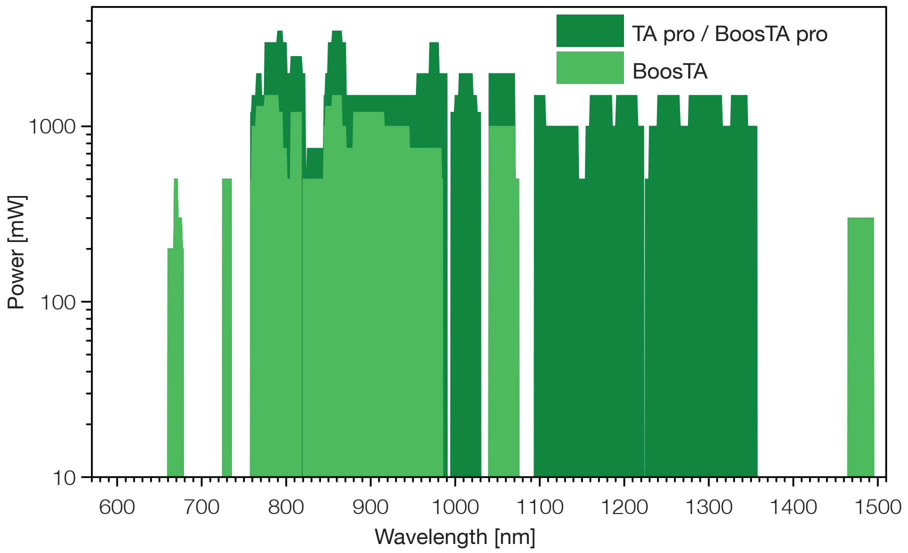
HIGH POWER
Tunable Laser and Amplifier Systems in the Watt Regime

Single-mode diode lasers often do not meet the power requirements of applications. With tapered amplifiers (TAs, see page 11) the power can easily increase to the Watt level without impairing the spectral quality of the seed laser. Besides, TAs offer excellent beam quality (M^2 < 1.5 or 2).

TOPTICA offers complete and integrated Master Oscillator Power Amplifier (MOPA) systems with stable beam pointing and output power (TA pro) as well as amplifier only solutions (BoosTA pro). Both offer power levels up to 3.5 W, while the BoosTA is the most cost efficient solution providing up to 1.5 W output power.

The **TA pro** is a member of TOPTICA's pro series and consistently follows the concept of maximum stability and ease of use. This product consists of a grating stabilized diode laser and a tapered semiconductor amplifier. The Master-Oscillator Power-Amplifier (MOPA) concept combines the tunability and linewidth of the DL pro seed laser with the high power and excellent beam quality available from tapered amplifiers. Master oscillator and power amplifier are independently driven by a pair of temperature and current controllers. Patented, highly stable, flexure based mirror mounts ensure easy coupling of the master laser into the tapered amplifier and prevent intensity fluctuations caused by beam pointing variations. For beam shaping, TOPTICA uses custom-made optical components, achieving an excellent beam profile and highest single-mode fiber-coupling efficiencies.

The DLC TA pro comes with TOPTICA's new all digital laser driver DLC pro. The digital control elecronics deliver the highest currents (powers), lowest noise and drift (narrow linewidth) and the most convenient user interfaces. SYST TA pro is the more cost efficient alternative with analog double stage SYS DC series electronics.



Integrated system with high-quality components

The TA pro consists of a grating-stabilized diode laser and a tapered semiconductor amplifier. A high-quality optical isolator placed between master laser and amplifier eliminates spurious back-reflections and thus guarantees spectrally robust operation.

Between isolator and tapered amplifier a probe beam is tapped off and made available for spectral stabilization and monitoring purposes. All mechanical and optical components are integrated in a housing that is machined from one solid block. The complete system has proven its stability in numerous tests both in TOPTICA's laboratories and in many customers' experiments.

Active power stabilization included

DLC TA pro systems feature integrated photo diodes that monitor the seed and output powers to prevent damage to and premature aging of the amplifier chip. With the free DLC pro firmware update to version 1.4 or higher we have added active power stabilization. Not only can the power be stabilized at the integrated photo diodes, but also on external photo diodes in your experiment – exactly where you need it.

Key advantages

The integrated MOPA (Master-Oscillator Power-Amplifier) system provides unmatched stability against acoustic noise, vibrations and ambient temperature changes. The TA pro is easy to align, very stable when aligned, and it offers the best possible beam quality available from tapered amplifiers. The TA pro comes in five standard wavelengths, but further wavelengths between 632 nm and 1495 nm are available as well. The output power at a specific wavelength depends on available TA chips and master laser diodes. Thanks to a new high-current laser driver, the most powerful TA pro systems now achieve power levels up to 3.5 W.

Prepared for high bandwidth locking

The TA pro system is ideally prepared for high bandwidth power and frequency stabilization as well as linewidth reduction by acting on the laser and/or amplifier current through several high bandwidth modulation inputs. TOPTICA offers various solutions for stabilization tasks, e.g. Pound-Drever-Hall or phase locking.

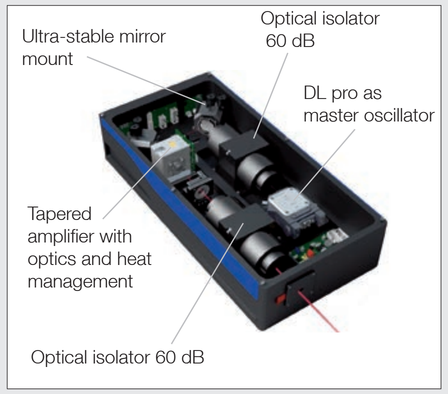
DLC TA pro systems come with TOPTICA's all digital DLC pro. It delivers lowest drift and noise and at the same time highest amplifer currents: 5 A with CC-5000 and with the optional surcharge SUR TA / HP up to 10 A. DLC pro is conveniently controlled via touch display, knobs or remotely via TCP/IP or USB. More information on DLC pro can be found on pages 39 & 40. Alternatively, the TA pro is still available with TOPTICA's proven analog electronics SYS DC 110 as SYST TA pro.

Please inquire.

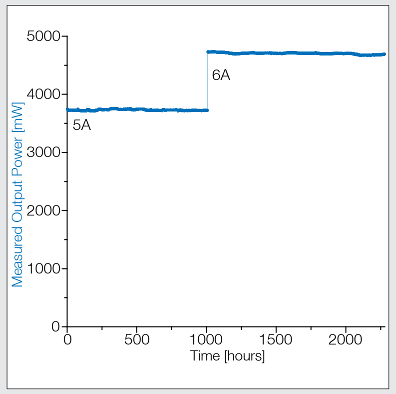
DLC TA pro - next generation of amplified tunable diode lasers - with the all digital DLC pro driving electronics.

Key Features
· MOPA concept with DL pro master and tapered amplifier
· Powers up to 3.5 W
· Amplifier currents up to 5 A / 10 A
· Excellent beam quality: typ. M^2 < 1.5
· DC & AC-coupled modulation ports for both master laser and amplifier
· Probe-beam output
· Output power stabilization

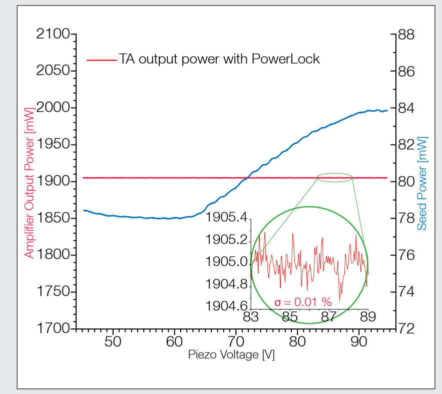
Check our regularly updated diode and TA chip stock list: **www.laser-diodes.com**



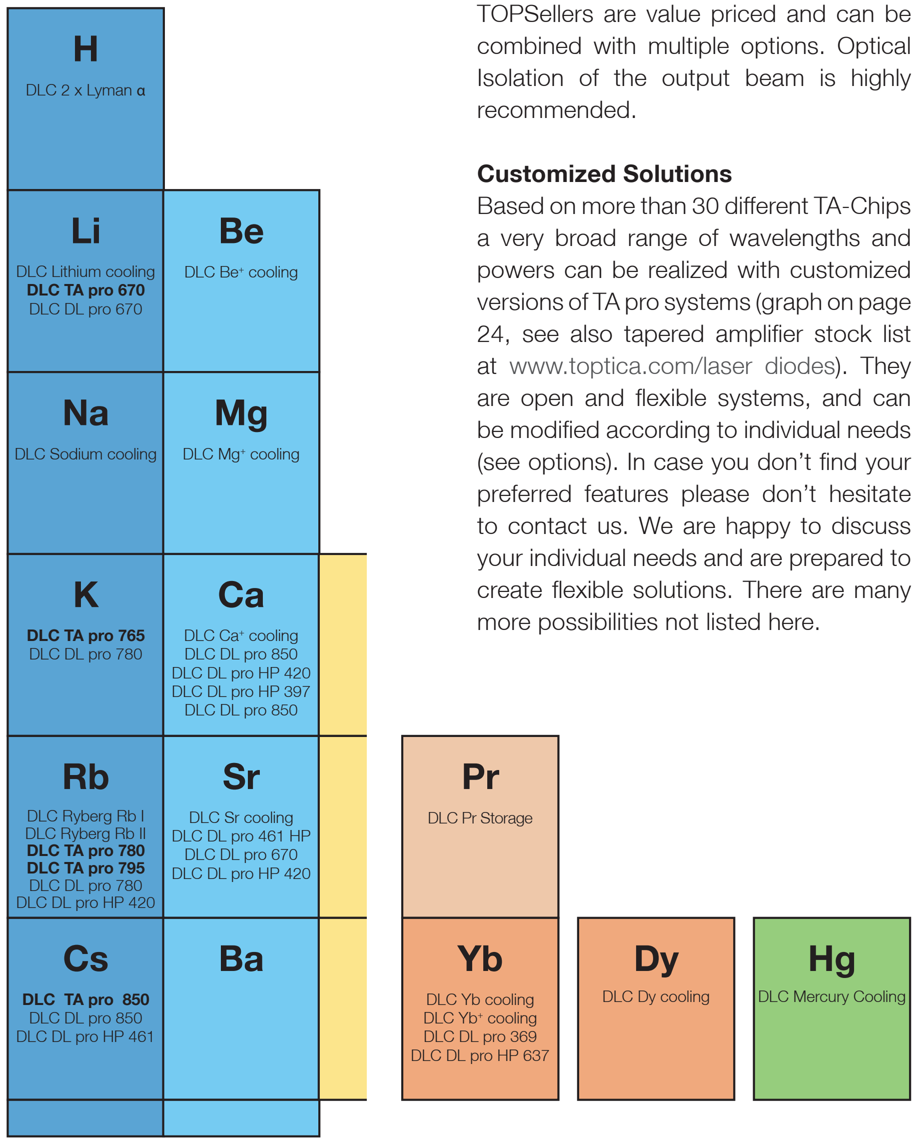
TA pro laser head with integrated 60 dB output isolator.



Excellent output power stability (example of testing a new chip at two different amplifier currents).



DLC TA pro system master and amplifier powers with PowerLock during a 10 Hz piezo scan. While the master fluctuates approx. 8%, the TA output is stable (σ=0,01%).



A number of TOPSeller systems are available, e.g. for laser cooling or excitation of specific transitions. Listed in this cut-out of the periodic table are all TOPTICA TOPSeller solutions for each element. Amplified diode lasers are marked in bold letters. TOPSellers based on direct diode lasers (see page 19) or frequency-converted NLO systems (see page 34) are mentioned for completeness.

Optimized Systems for Selected Applications

Pre-configured TA pro systems have proven themselves as workhorses in numerous quantum optics laboratories around the world. TOPTICA's TA pro TOPSellers are value priced and can be combined with multiple options. Optical Isolation of the output beam is highly recommended.

Customized Solutions

Based on more than 30 different TA-Chips a very broad range of wavelengths and powers can be realized with customized versions of TA pro systems (graph on page 24, see also tapered amplifier stock list at www.toptica.com/laser diodes). They are open and flexible systems, and can be modified according to individual needs (see options). In case you don't find your preferred features please don't hesitate to contact us. We are happy to discuss your individual needs and are prepared to create flexible solutions. There are many more possibilities not listed here.

Options

- Optical isolator for TA output (recommended)
- Surcharge SUR TA / HP for higher currents (DLC pro: 10 A, SYST: 5 A)
- Fiber-coupling of TA output and/or probe beam (output FiberDock requires optical isolation)
- Narrow linewidth resonator
- DFB master laser
- Motorized wavelength selection
- Bias-T for high bandwidth frequency modulation
- Locking option DLC pro Lock and DigiLock 110, PDD 110, FALC 110, etc.

Magneto-optical trap of lithium atoms.
T. Esslinger, ETH Zürich, Switzerland.

DLC TA pro TOPSeller	670	765	780	795	850
Wavelength range [nm]	664 .. 674	760 .. 775	765 .. 795	780 .. 800	850 .. 870
Max. output power [W]	0.5	2	3	3.5	3.5
Beam quality [M²]	< 1.5	< 1.5	< 2	< 2	< 2
Mode-hop-free tuning [GHz]	30 - 50	30 - 50	30 - 50	30 - 50	30 - 50

For customers who wish to boost the power of existing lasers, coherent stand-alone amplifiers offer an attractive solution.

TOPTICA's BoosTA product line provides efficient optical amplification without compromising the high spectral and spatial beam quality of the master laser.

Semiconductor optical amplifier for more laser power

TOPTICA's new stand-alone optical amplifier BoosTA pro increases the output power of a DL pro or any other linearly polarized master laser by up to 20 dB.

Following TOPTICA's well-established pro-technology, the TA chip is mounted in a compact unit with optimized heat management and beam-shaping optics.

Options

- Optical output isolator, 30 or 60 dB (integrated in amplifier head)
- Fiber-coupled input
- Fiber-coupled output (requires optical isolation)
- Operation with standard rack SYS DC 110

A compact, external power supply (DC HP) drives the amplifier head and allows effortless operation - even of current-hungry TA chips at wavelengths with lower gain. Researchers thus benefit from output power levels up to 3.5 W with currents up to 7 A.

The BoosTA pro head also includes a high-bandwidth current modulation board, which - when used in a closed feedback loop - allows compensating power fluctuations of the master laser by adjusting the amplifier gain. The board features a protective circuit to avoid the risk of chip damage. The beam management of the seed laser can be greatly simplified by fiber input coupling, which is optionally available as well as fiber-output coupling. Optical output isolation is provided by TOPTICA. The BoosTA pro head has sufficient space for a 60 dB isolator to protect the TA chip from back reflections.

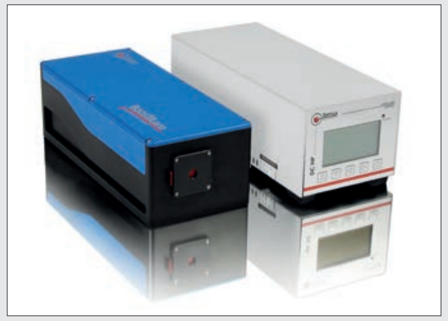
To determine the available tuning range and output power for your desired wavelength, please contact TOPTICA. For an overview, please see the table on page 28, the graph on page 24 and check our regularly updated tapered amplifier stock list on www.laser-diodes.com. The stock list shows the required amplifier current for achieving the maximum specified output power. BoosTA pro offers a maximum current of 7 A.

BoosTA pro — High-power optical amplifier.

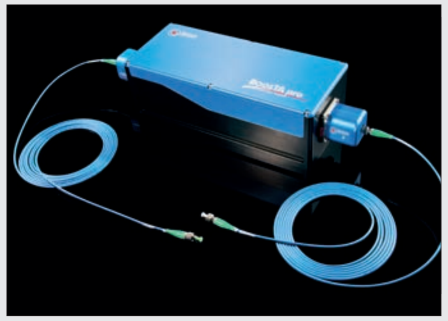
Key Features

- Compact amplifier module
- Gain up to 20 dB (x 100)
- Output power up to 3.5 W
- Amplifier currents up to 7 A
- External control electronics (DC HP)
- Maintains spectral properties of master oscillator
- Many wavelengths available (660 .. 1495 nm)

Check our regularly updated TA chip stock list:
www.laser-diodes.com



BoosTA pro with DC HP.



BoosTA pro laser head with Fiber-in, Fiber-out (FiFo).

Class 4 Laser Product EN 60825-1:2007. Visible or insible laser radiation. Avoid eye or skin exposure to direct or scattered radiation. Caution - Class 4 visible and/or insivisble laser radiation when open. Avoid exposure to the beam, avoid eye or skin exposure to direct or scattered radiation. Magnetic fields may be present which may affect the operation of certain pacemakers.

BoosTA — Economic optical amplifier.

Key Features

- Compact amplifier module
- Gain up to 20 dB (x 100)
- Output power up to 1.5 W
- Amplifier currents up to 2.5 A
- Integrated, compact control electronics
- Maintains spectral properties of master oscillator
- Many wavelengths available (660 .. 1495 nm)

Check our regularly updated TA chip stock list:
www.laser-diodes.com

Compact and cost efficient semiconductor optical amplifier
For customers with moderate power requirements, the BoosTA offers a cost efficient alternative to the BoosTA pro while still being superior to self-built solutions. It comes pre-aligned and tested with a suitable seed laser, and users can readily insert it into their experimental set-up.

The BoosTA comprises a selected tapered amplifier chip as well as proprietary collimation optics, which help to achieve the best possible output beam profile. Control electronics for TA chip temperature and driver current is integrated into the laser head. The current can either be set manually via a rotary potentiometer, or remotely via an RS 232 interface. An external power supply minimizes the impact of thermal and electronic radiation (EMC) on the amplifier head.

Fiber input and output coupling as well as integration of an optical output isolator in the amplifier head are optionally available like for the BoosTA pro. The fiber-coupled system provides high flexibility in the optical beam path, reduces complexity on the optical table and increases the long-term stability of the experimental set-up. It is even possible to combine two different seed lasers, e.g. in a polarization-maintaining fiber array, and amplify both wavelengths simultaneously in a single BoosTA system. This concept is widely used for the generation of tunable, continuous-wave terahertz radiation.

Available BoosTA power levels depend on the particular TA chip and the available current. The BoosTA offers a maximum current of 2.5 A - sufficient for output powers up to 1.5 W.

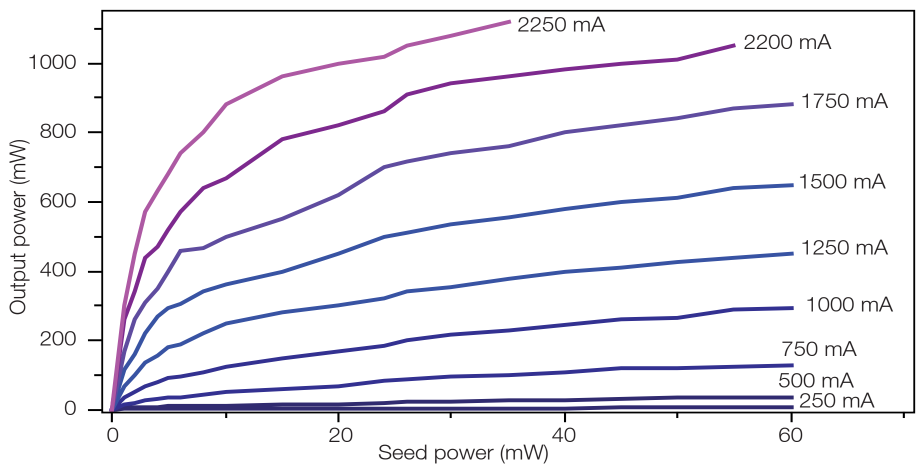
The table below lists common wavelengths and available powers from BoosTA and BoosTA pro with typical required amplifier currents.

Options

- Optical output isolator, 30 or 60 dB (integrated into amplifier head)
- Fiber-coupled input
- Fiber-coupled output (requires optical isolation)

BoosTA vs. BoosTA pro - Power at selected wavelengths

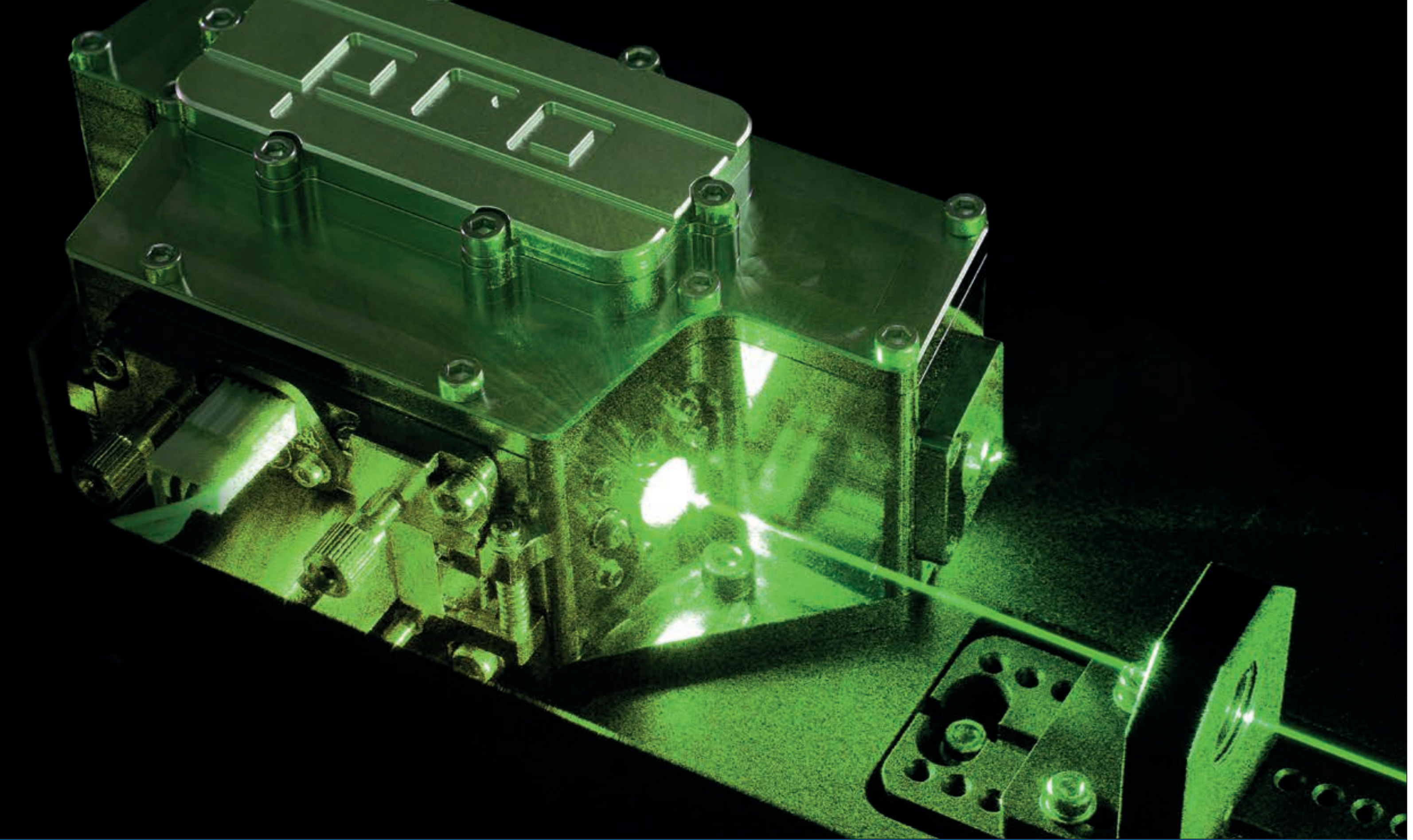
Wavelength [nm]	670	735	765	780	795	850	915	970	1010	1060	1100..1360	1480
Max. Power [W] **BoosTA pro**	0.5	0.5	2	3	3.5	3	1.5	3	2	2	1.5	0.3
Max. Power [W] **BoosTA**	0.5	0.5	1.3	1.5	1.2	1.3	1.2	0.75	-	1	-	0.25
Max. required Current [A]	1.1	1.5	3	4	4	5	3	5	5	4	7	3



Typical saturation behavior of tapered amplifier chips at different amplifier currents (seed power levels exceeding 40 mW are not recommended).

Specifications			
	DLC TA pro	**BoosTA pro**	**BoosTA**
Configuration	MOPA	Amplifier	
Master laser	DL pro (integrated), DL DFB on request	External	
Wavelengths	660 .. 1495 nm*		
Max. power	3.5 W		1.5 W
Coarse tuning	10 .. 50 nm		
Typical mode-hop-free tuning	20 - 50 GHz	Depends on master laser	
Typical linewidth (5 µs)	10 kHz .. 300 kHz	Depends on master laser	
Polarization	Linear > 100 : 1		
ASE background, typ.	< -40 dB	Depends on master laser	
Beam quality M²	< 1.5 (< 2.0 for some higher-power chips)	< 1.5 (< 2.0 for some higher-power chips)**	
Divergence	< 1 mrad		
Beam height	50 ± 1 mm		53.9 mm
Optical isolators	Internal: 60 dB included, Output: optional 30 or 60 dB	Input: none, Output: optional 30 or 60 dB	
Fiber-coupling	Output and probe beam: optional	Input*** and Output: optional	
Fiber-coupling efficiency****: min. (typ.)	50 % (60 %)	50 % (60 %)**	
Monitor photo diodes	For seed and output	-	
Intensity modulation option	TA-Mod included		-
Control electronics	DLC pro, digital	DC HP	Integrated + power supply
Maximum TA current (HP)	5 A (10 A)	7 A	2.5 A
Frequency modulation option	Included	-	
Locking options	DLC pro Lock, DLC ext	Depends on master laser	
Environment temperature / humidity	operating: 15 - 30 °C, transport: 0 - 40 °C / Non condensing		
Operating voltage	100 - 120 V / 220 - 240 V AC, 50 - 60 Hz (auto detect)		
Power consumption	Typ. 70 W	Typ. 40 W	Typ. 35 W
Size head (H x W x D)	90 x 192 x 400 mm³	90 x 115 x 275 mm³	85 x 100 x 312 mm³
Size electronics (H x W x D)	154 x 450 x 348 mm³	85 x 105 x 200 mm³	70 x 175 x 179 mm³
Weight head / electronics	9.5 kg / 8.5 kg	3.9 kg / 2.3 kg	4.5 kg / 2.4 kg

*With gaps **With TOPTICA master laser ***Requires PM fiber FC/APC ****With TOPTICA's FiberDock, isolation required.

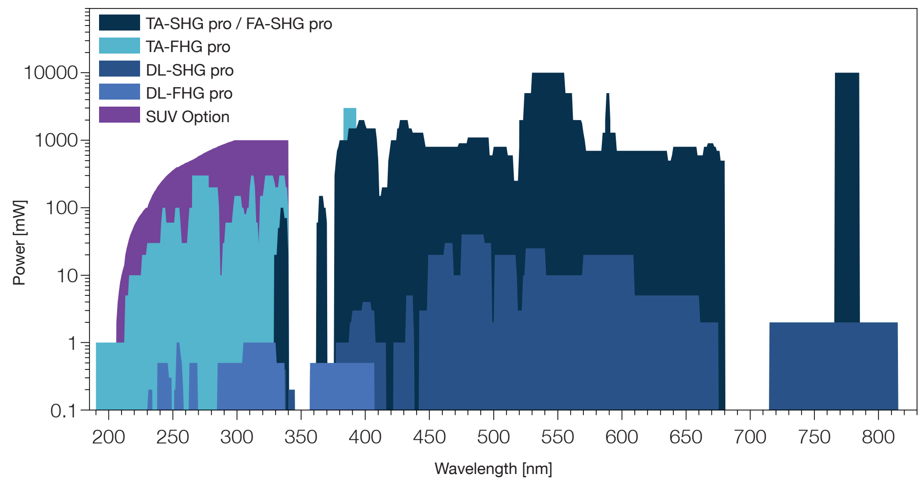


FREQUENCY-CONVERTED LASERS

Tunable Diode Lasers for Visible and UV Wavelengths

Standard systems and customized solutions
By combining comprehension of diode laser technology and extensive experience in frequency conversion, TOPTICA's lasers achieve the highest output power levels and the best performance on the market. Frequency converted lasers are available at wavelengths between 205 nm and 680 nm, with only few spectral gaps, and special solutions down to 190 nm. Novel developments like the digital controller DLC pro, AutoAlign functionality, or the Super-UV option allow for the easiest possible operation.

Together with our customers, TOPTICA's experts will identify the best product and tailor it according to specific requirements in terms of output power, wavelength and tunability. For dedicated applications, we provide pre-configured TOPSeller systems. But if our standard product families do not match your needs, we will go one step further - do not hesitate to challenge us!



***pro* philosophy in frequency-converted systems**
The laser head of TOPTICA's *pro* design lasers is machined from one solid metal block for enhanced robustness against vibrations, acoustic noise and temperature fluctuations. Integrated flexure-based mirror mounts provide an unmatched long-term stability. The "bow-tie" resonator SHG pro comes in a closed design with entrance and exit windows, and can be adjusted without opening the cover lid, allowing for a typical residual leak rate at the 10^{-5} mbar l /s level.

The SHG wavelength is tuned by altering the fundamental laser color. Mode-hop-free tuning of tens of gigahertz is realized by scanning the fundamental laser while the SHG resonator follows automatically. Coarse tuning over several nanometers is achieved by manually changing the wavelength of the fundamental laser. Only if phase matching has to be optimized a realignment of the SHG resonator may be necessary.

Diode laser advantages
The diode laser systems are most compact in size, extremely reliable, conveniently operated, with low running costs and available without water cooling.

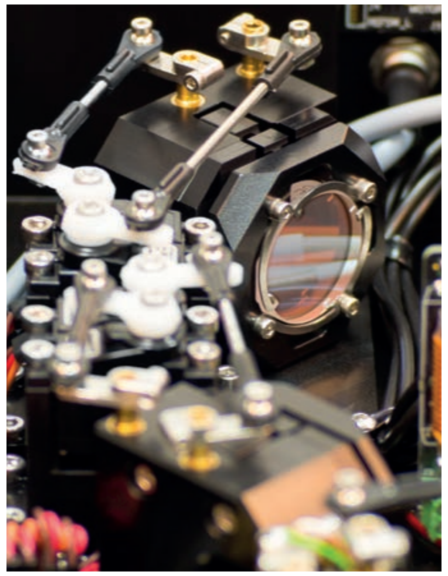
Based on almost 20 years of experience in building frequency converted diode laser systems, and several hundreds of units installed in the field, TOPTICA's frequency-converted lasers are now entering an unprecedented level of stability, functionality and performance. They go digital!

SUV
The Super-UV functionality is a major technological leap, significantly boosting output powers and lifetimes of DUV lasers. The redesign of the FHG stage includes complete sealing of the DUV optics, developed exclusively for DLC pro-controlled systems. The option includes a lifetime warranty, and the projected total lifetime exceeds 10,000 hours.

AutoAlign
In the past, the sturdy design of TOPTICA's frequency-converted lasers has set standards in the entire field. Today, using digital electronics, we push even further. Thanks to the AutoAlign option, the time-consuming task of laser system realignment belongs to the past. With built-in intelligence and servo-controlled flexure mirror mounts, the system optimizes the coupling of the beams into TA and SHG cavity, and even the output fiber. Optimize your SHG power with one simple click!

PowerLock
During their experimental runs, many of our users rely on constant output power. The excellent stability of our current systems was improved further with PowerLock. Residual power excursions are cancelled automatically by controlling the TA power. Users benefit from stable SHG output powers, without having to compensate for drifts externally.

Fiber Mon
With the FiberMon option, one can directly monitor the optical power coupled to the SHG output fiber. AutoAlign and Power-Lock are ready to be used with FiberMon, so the user has both optimization and stabilization of the fiber output at hand. Consequently, you get the best fiber pigtailed SHG system ever!



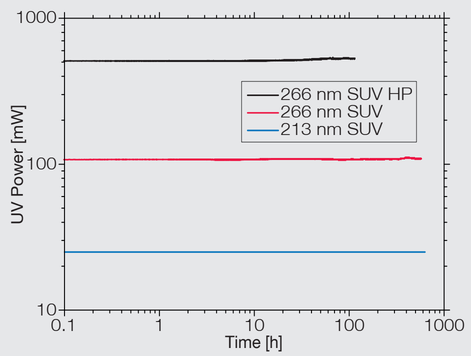
With AutoAlign, the user starts optimization of the beam alignment with one simple click. Built-in servos and digital intelligence do the rest of the job.

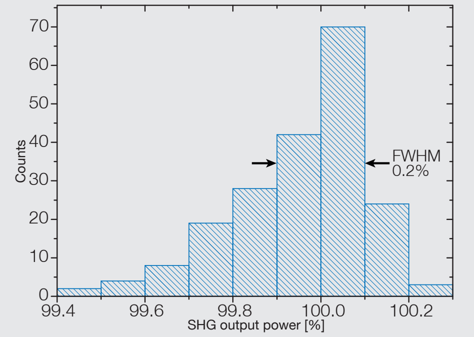
Convenience & precision
The DLC pro control rack allows for full stand-off remote control and operation of the laser system. For working in the lab, the touch display allows direct control. For independent and remote control, a computer interface provides full access to all laser parameters. Just switch on your laser and start the experiment!

Furthermore, the users benefit from our lowest-noise digital control electronics. Since the master laser is based on TOPTICA's DL pro technology, narrowest linewidths are routinely achieved, and sensitivity to environmental perturbations is minimized to an extreme level.

Features

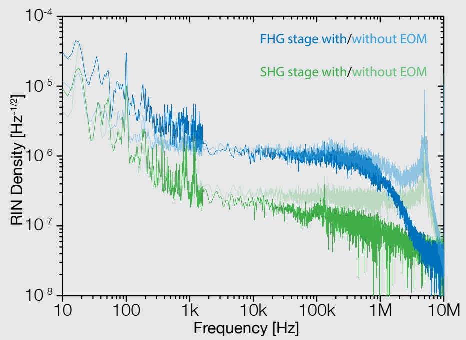
- SUV: Unprecedented DUV power and lifetime
- AutoAlign option: Hands-off coupling into TA, doubling cavity and fiber (with FiberMon)
- PowerLock for applications demanding constant powers during longterm operation
- FiberMon: Measure, control and optimize your fiber-coupled laser!
- Every system customized with respect to experimental needs

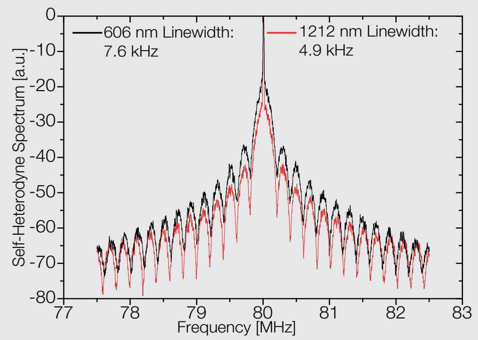




Top left: SUV long-term output power stability measurements for a selection of wavelengths and output power levels, with a projected lifetime exceeding 10,000 hours. 213 nm (266 nm) measurements are shown with PowerLock on (Off).

Top right: AutoAlign performance after intentional misalignment, showing a residual scattering at the per mille level.





Bottom left: RIN benefit from the EOM option in the DLC TA-FHG pro. Integrated RIN of the FHG light RIN is 0.09% (0.23% without EOM), and PDH sidebands are suppressed.

Bottom right: Owing to the superior noise performance of our new DLC pro electronics, we routinely achieve narrowest linewidths.

TA-SHG pro — High-power, cw, tunable UV, blue, green, yellow or red laser source.

Key Features

- TA pro diode laser + SHG pro second-harmonic generator in one box
- UV, blue, green, yellow or red wavelengths: 330 - 680 nm
- 10 mW - 2000 mW output power (wavelength dependent)
- PowerLock: Active output power stabilization
- Up to 15 nm coarse tuning (wavelength dependent)
- Tunable single-frequency emission, typ. linewidth < 200 kHz
- Probe-beam output of fundamental laser and SHG beam
- SHG pro key features see page 36

High-power, tunable UV, blue, green laser, yellow or red laser light
The DLC TA-SHG pro, a frequency-doubled amplified diode laser, is the system of choice if narrow-band, tunable laser radiation with up to 2000 mW output power in the UV to visible wavelength range is required. Typical applications are laser cooling or trapping of atoms and ions, metrology, spectroscopy, holography and interferometry.

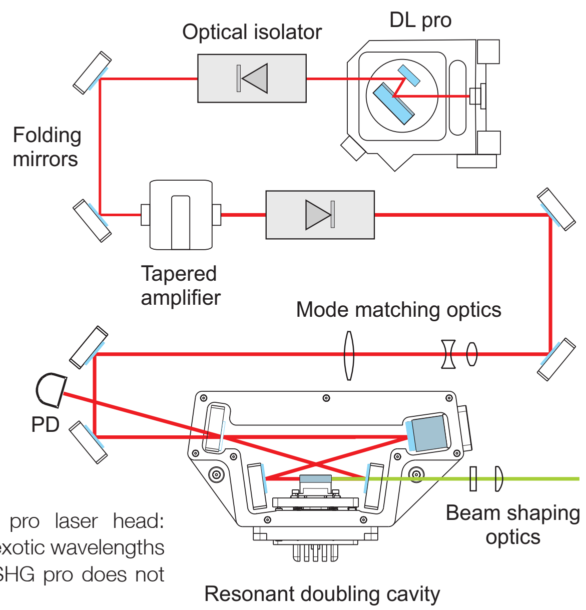
The system comprises a solid laser head and a DLC pro digital electronics rack, including all modules needed to operate the fundamental diode laser, to stabilize the SHG resonator with respect to the laser wavelength, and to thermally control the nonlinear crystal. Ultra-low noise sensitivity, best long-term stability of the laser frequency and output power, as well as ease of use are the cornerstones of the design. Frequency locking of the master laser is available with the Lock option, and further linewidth narrowing is possible using fast lock modules (DigiLock 110, FALC 110) in combination with DLC ext.

TOPTICA's patented beam-steering mirror mounts guarantee best short and long-term stability of the output power. With the AutoAlign option, servo-controlled mirrors and built-in intelligence re-optimize the beam alignment into the TA chip and the SHG cavity at the push of a button. Active power stabilization of the output (PowerLock) is integrated. Both optimization and stabilization are available for fiber-coupled systems with the FiberMon option. A probe-beam output of the fundamental laser is also provided. The TA-SHG pro lasers are available within a wide wavelength range (currently available 320 .. 780 nm with only few spectral gaps). Specific laser characteristics are customized to the respective application requirements.

Depending on the design wavelength, typical output powers range from 10 mW to 2000 mW. A medium-power solution without tapered amplifier (DL-SHG pro) is also available.

Options

- AutoAlign for TA, SHG and FiberMon stages
- FiberMon option (for SHG wavelengths of 400 nm - 640 nm)
- Integrated EOM option: Independent low-noise error signal generation
- Fiber output of fundamental probe beam and SHG beam
- Fast analog modules for further linewidth narrowing
- SYST control electronics or medium-power version DL-SHG pro available upon request



Schematic of the TA-SHG pro laser head: High power at common and exotic wavelengths (Medium-power version DL-SHG pro does not include the TA section.).

UV meets high power
TOPTICA's TA-FHG pro unites a grating-stabilized diode laser and a tapered amplifier as a fundamental light source with two cascaded second-harmonic generation stages SHG pro – all integrated in one solid laser head to obtain stable, high-power UV laser light.

Options

- SUV for unprecedented DUV output power and stability
- AutoAlign for TA, SHG and FHG stages
- EOM option: Independent low-noise error signal generation
- Fiber output of fundamental probe beam and SHG probe beam
- Fast analog modules for further linewidth narrowing
- SYST control electronics or medium power version DL-SHG pro available upon request

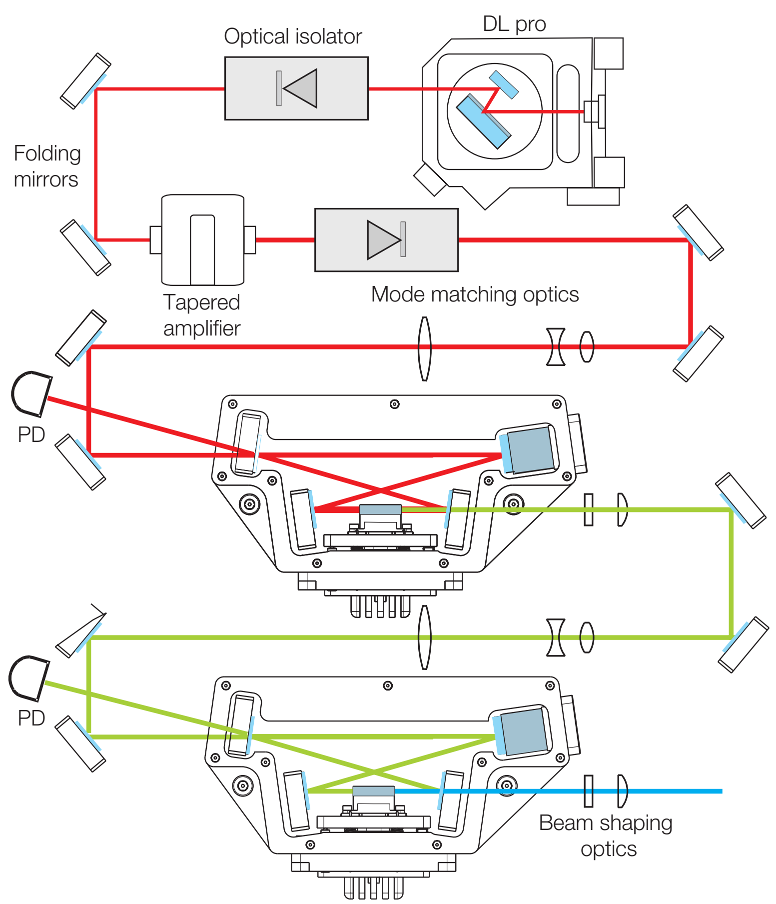
True cw single-frequency operation with linewidths below 500 kHz (coherence length > 200 m), output power levels up to 500 mW, 20-40 GHz of mode-hop-free tuning and coarse-tuning ranges of 1 - 4 nm make up the hero characteristics of this unique laser. It is equipped with state-of-the-art digital electronics to drive the laser diode and TA chip, to thermally control the two NLO crystals, and to stabilize the two SHG resonators.

The laser can be operated like a DL pro external-cavity diode laser. Typical applications of TA-FHG pro lasers are ultra-high-resolution spectroscopy, laser cooling of atoms (e.g. Hg, H, Mg), ions (e.g. Mg^{+}, Yb^{++}, Al^{+}, In^{+}, Cd^{+},...), molecules (NO) or condensed-matter studies via angle-resolved photoemission spectroscopy (ARPES), and parametric down-coversion to the visible range.

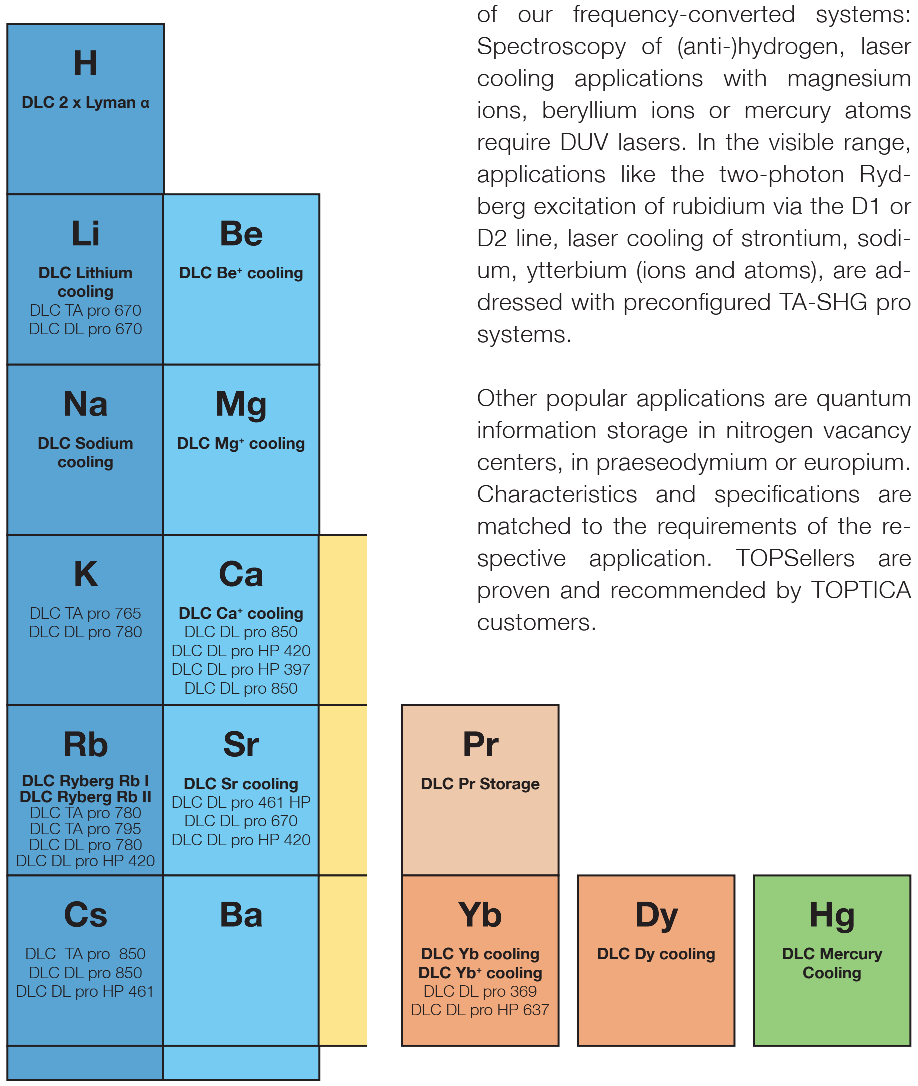
Close-up of open TA-FHG pro — Tunable single-frequency UV laser with high output power.

Key Features

- TA pro diode laser + two subsequent second-harmonic generators SHG pro in one box
- Available wavelengths: 205 nm .. 330 nm, below 205 nm upon request
- 1 mW - 500 mW output power (wavelength dependent)
- 1 nm - 4 nm coarse tuning (wavelength dependent)
- Tunable single-frequency emission, typ. linewidth < 500 kHz
- Probe-beam output of fundamental laser
- SHG pro key features see page 36



Schematic of the TA-FHG pro laser head: High-power tunable UV laser radiation is generated by two-fold frequency doubling of an amplified diode laser TA pro (Medium-power version DL-FHG pro does not include the TA section.).

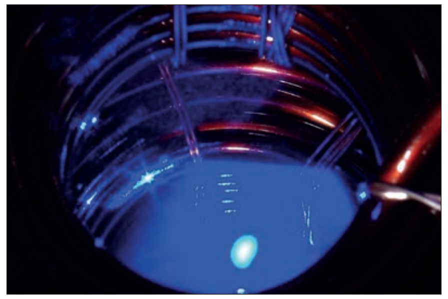


Pre-configured laser systems
TOPTICA's TOPSellers are designed for some of the most common applications of our frequency-converted systems: Spectroscopy of (anti-)hydrogen, laser cooling applications with magnesium ions, beryllium ions or mercury atoms require DUV lasers. In the visible range, applications like the two-photon Rydberg excitation of rubidium via the D1 or D2 line, laser cooling of strontium, sodium, ytterbium (ions and atoms), are addressed with preconfigured TA-SHG pro systems.

Other popular applications are quantum information storage in nitrogen vacancy centers, in praeseodymium or europium. Characteristics and specifications are matched to the requirements of the respective application. TOPSellers are proven and recommended by TOPTICA customers.

Key Features

- Specifications matched to experimental requirements
- One laser head (DL pro master laser + tapered amplifier + air-sealed SHG pro stage + 2nd SHG stage for FHG systems) and DLC pro rack
- Tunable single-frequency emission with < 500 kHz linewidth and 10 mW - 1500 mW output power (TOPSeller dependent)
- Excellent beam profile of all output beams
- Probe-beam output of fundamental laser beam (and SHG beam in FHG systems)
- SHG pro key features see page 36



Laser-cooled Sr atoms.
Ch. Lisdat, PTB Braunschweig, Germany.

A number of TOPSeller systems are available, e.g. for laser cooling or excitation of specific transitions. Listed in this cut-out of the periodic table are all TOPTICA TOPSeller solutions for each element. Frequency-converted diode lasers are marked in bold letters. TOPSellers based on direct diode lasers (see page 19) or amplified TA systems (see page 26) are mentioned for completeness.

TA-FHG pro TOPSeller TA-SHG pro TOPSeller

TOPSeller	2x Lyman alpha	Mercury cooling	Mg⁺ cooling	Be⁺ cooling	Yb⁺ Cooling	Ca⁺ Cooling	Strontium Cooling	Rydberg Rb I
Wavelength	243 nm	254 nm	280 nm	313 nm	369.5 nm	397 nm	461 nm	473-481 nm
Output power	60 mW	60 mW	30 mW	300 mW	40 mW	1500 mW	700 mW	800 mW
Coarse tuning	1 nm	1 nm	2 nm	2 nm	1 nm	2 nm	4 nm	8 nm

TOPSeller	Rydberg Rb II	Ytterbium Cooling	N-V centers	Sodium cooling	Praseodymium Storage	Dysprosium Cooling	Lithium Cooling
Wavelength	479-488 nm	556 nm	575 nm	589 nm	606 nm	626 nm	671 nm
Output power	1000 mW	400 mW	10 mW	1000 mW	800 mW	800 mW	800 mW
Coarse tuning	9 nm	5 nm	10 nm	4 nm	6 nm	10 nm	4 nm

SUV
A modified FHG cavity design allows for unprecedented DUV output power and stability. Warranty included.

AutoAlign
Automated alignment of beams coupled to TA, SHG and FHG cavities, and FiberMon. No compromising of passive stability - AutoAlign is 100% switched off during normal operation.

FiberMon
Allows measurement of the SHG output power propagating in a single-mode, polarization-maintaining (SM-PM) fiber for PowerLock and AutoAlign. Two wavelength regions are available.

FiberDock
Fiber coupling of various output beams: Fundamental probe beam, SHG probe beam, and SHG output beam.

High Power
At certain wavelengths, high power tapered amplifiers are available. The option includes high-current driving electronics and a high- power capable SHG stage.

EOM
An EOM before the doubling cavity allows to independently create the PDH signal for laser locking. Advantageous for nondisturbed DL pro operation and maximum mode-hop-free tuning range in case of SHG cavity, and significant RIN reduction and suppression of UV sidebands in case of FHG cavity.

Narrow Linewidth
The DL pro master laser is replaced by a narrow-linewidth version. Other master lasers (DFB/DBR) available upon request.

Advanced Locking
Various lock options from side-of fringe frequency stabilization to PDH linewidth narrowing available. Modules like PDD 110/F, FALC or DigiLock can be installed in the DLC ext extension rack, with shortest-possible cable length right next to the laser head (see chapter Laser Locking & Laser Driving).

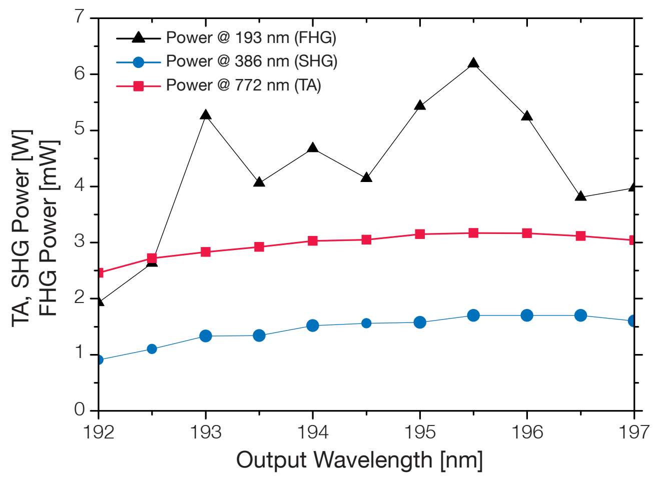
TOPTICA's frequency-converted systems are ready for a multitude of applications with their standard configuaration. For customers wanting to go one step further, the following customizations are available:

Exotic wavelengths
Exotic nonlinear crystals can be used to overcome the stringent limits on the lowest possible SHG wavelength imposed by standard materials. For example, the potassium fluoroboratoberyllate (KBBF) crystal enables us to reach wavelengths below 200 nm. Another option is sum-frequency generation from two different wavelengths in conventional crystals.

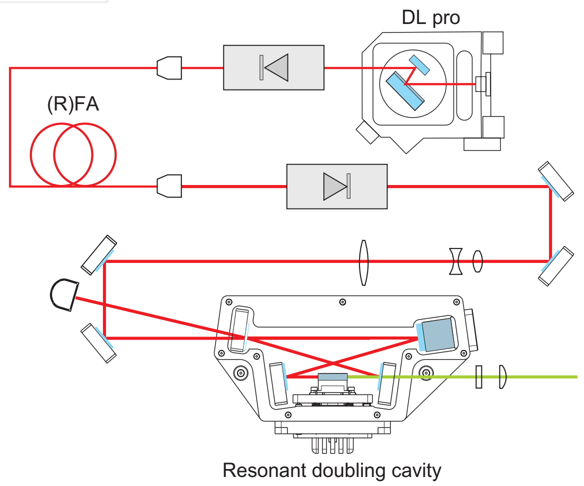
(Raman) Fiber amplified systems
Fiber amplifiers can provide higher output power than diode lasers or tapered amplifiers. Thus, output powers of DL-SHG pro or DL-FHG pro systems can be significantly increased by using such amplifiers.

TOPTICA has extensive experience and access to the world's leading single-frequency high power fiber amplifier manufacturers. For example, the laser guide star system uses a Raman fiber amplifier, and is capable of emitting 20 Watts of output power around 589 nm from a DL-RFA-SHG pro like system.

Similar systems are available at other wavelengths (above 250 nm for FHG and 500 nm for SHG systems) on request. Do not hesitate to challenge us!



The KBBF crystal enables frequency doubling to FHG wavelengths below 205 nm.



The versatility of TOPTICA's lasers allows for straight forward implementation of (Raman) fiber amplifiers.

Key Features

- Air-sealed bow-tie cavity with highest mechanical and thermal stability
- Customized optics and AR-coated NLO crystal selection
- Analog electronics for Pound-Drever-Hall locking with automatic relock and temperature control for NLO crystal included
- Adjustments with closed head / resonator

Professional unit for frequency doubling of cw lasers

The stand-alone Second-Harmonic Generator SHG pro is the device of choice for frequency-doubling of existing cw lasers. The SYST SHG pro package comprises mode-matching optics for the external laser, ultra-stable beam-steering mirrors, electronics for Pound-Drever-Hall stabilization with automatic relocking of the resonator length and temperature control of the NLO crystal, the bow-tie resonator in pro design, and beam-shaping optics for the frequency-doubled light.

The AR-coated NLO crystal and the mirror coatings are specially selected according to customer requirements. The Double-Piezo Lock – two integrated piezo-electric actuators for the stabilization of the resonator length – can be added to the SHG pro.

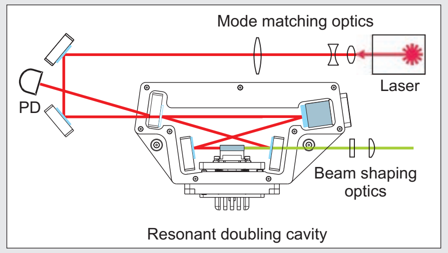
Options

- EOM option: Independent low-noise error signal generation
- Fiber input
- Fiber output of wavelengths above 350 nm
- Double-Piezo Lock with up to 30 kHz bandwidth

One actuator, driven by a FALC 110 module, accomplishes high-bandwidth locking while the other one is used in conjunction with a PID 110 for large-amplitude regulation. TOPTICA offers competent technical support to adapt the SHG pro to many varieties of existing laser systems. The SYST SHG pro will be installed and demonstrated on-site.

Specifications SHG pro	
Wavelength range*	410 nm - 1600 nm → 205 nm - 800 nm
Optical conversion efficiency*,**	
410 nm - 500 nm → 205 nm - 250 nm	5 - 10 %
500 nm - 700 nm → 250 nm - 350 nm	12 - 20 %
700 nm - 900 nm → 350 nm - 450 nm	20 - 30 %
900 nm - 1600 nm → 450 nm - 800 nm	30 - 60 %
General characteristics	
Beam quality	Nearly diffraction limited, single-mode fiber-coupling efficiency > 60 % @ 400 nm
Beam diameter	1 - 2 mm
Beam height	50 mm
Tuning range	> 60 GHz @ 400 nm output (continuous), 5-10 nm (coarse)
Polarization	Linear, > 100:1
Residual infrared	Typ. < 0.1 %
Locking scheme***	Pound-Drever-Hall with automatic relock, Double-Piezo Lock optional
Output power noise	Typ. < 1 % (depending on laboratory conditions and fundamental laser)
SHG cavity leak rate	cavity leak rate < 10^{-3} mbar l s^{-1}
Dimensions (H x W x D)	90 x 216 x 400 mm^3 (head) and 19“ control rack

*Full wavelength range coverage requires several NLO crystals and mirrors, other wavelengths upon request.
**Assuming 1 W single-frequency (< 1 MHz linewidth) cw laser input. Max. output power may be limited by crystal and optics lifetime.
***May require additional EOM (purchase and integration from TOPTICA recommended)

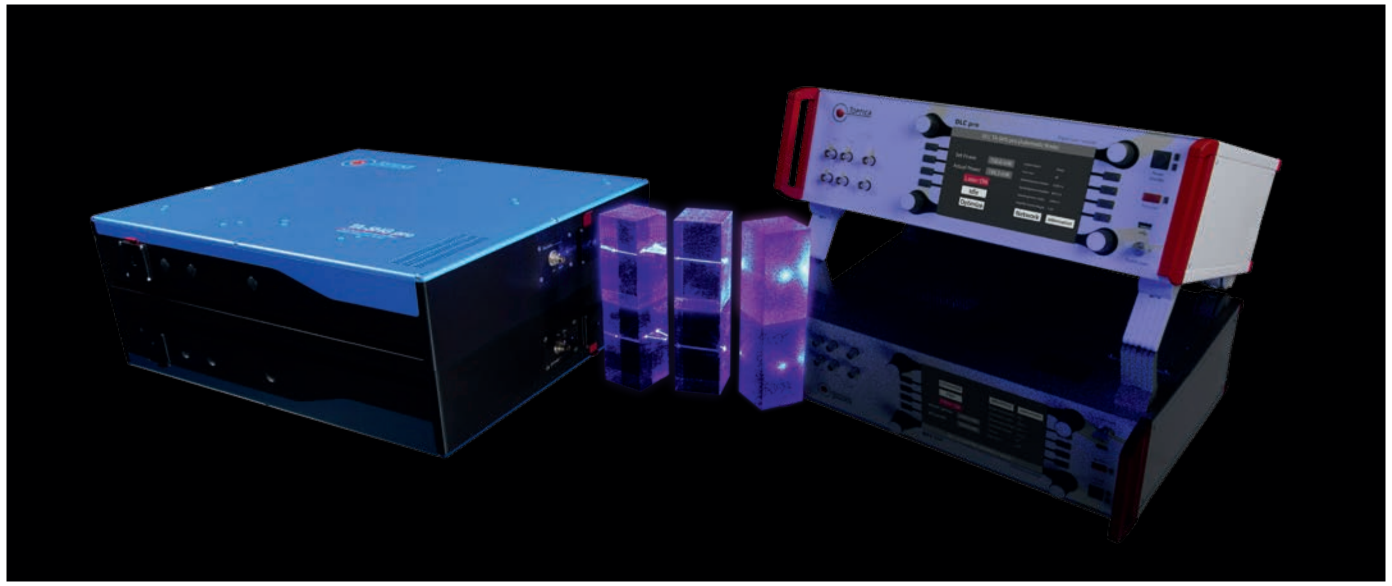


Schematic of SHG pro, stand-alone resonant frequency-doubling cavity.

SYST SHG pro – flexible stand-alone second-harmonic generator for single-frequency cw lasers.

Specifications	DL-SHG pro / TA-SHG pro	DL-FHG pro / TA-FHG pro
Center wavelengths	320 .. 680 nm* / 330 .. 780 nm*	225 .. 320 nm* / 190 .. 390 nm*
Typical power range	1 .. 40 mW / 10 .. 2000 mW	50 .. 1000 µW / 1 .. 500 mW
Typical tuning range	2 .. 20 nm	1 .. 4 nm
Typical mode-hop-free tuning range	~ 20 GHz	~ 30 GHz
Typ. linewidth (µs)	< 200 kHz	< 500 kHz
Long-term frequency change with room temperature**	< 200 MHz/K (typ. < 100 MHz/K)	< 400 MHz/K (typ. < 200 MHz/K)
Spatial mode	Nearly diffraction limited, collimated, M^2 < 1.2 typ.	
Beam height	50 mm	
Probe-beam output	Fundamental light with ~ mW power level	
Polarization	Linear, > 100:1	
RIN 10 Hz ... 10 MHz (typ.)	< 0.2 %	< 1 %
Residual infrared unfiltered	< 1 %	
SHG cavity leak rate	< 10^{-3} mbar l s^{-1}	
Warm-up time	Few minutes, depending on crystal temperature	
Environment temperature	Operation: 15 .. 30°C (non-condensing), transport: 0 .. 40°C	
Operating voltage	100 .. 120 V / 220 .. 240 V AC, 50 .. 60 Hz (auto detect)	
Power consumption	Typ. < 100 W, max. 300 W	
Size laser head (H x W x D)	90 x 410 x 485 mm^3	90 x 410 x 692 mm^3
Electronics	Single-stage 19“ rack DLC pro	

*Spectral coverage with gaps.
**Under stable laboratory conditions.



LASER LOCKING & LASER DRIVING

Electronic Control for Passive Stability and Active Locking

Apart from a well-engineered opto-mechanical design and the integrated laser diode, the most important part of a tunable diode laser system is its driving electronics, which is responsible for getting the most out of a laser system.

Wide mode-hop-free tuning with Littrow setups requires a well-defined interplay between piezo actuator and current driver. Drifts of the laser diode current, the temperature or the piezo voltage determine the drift of the laser frequency and the stability against mode-hopping.

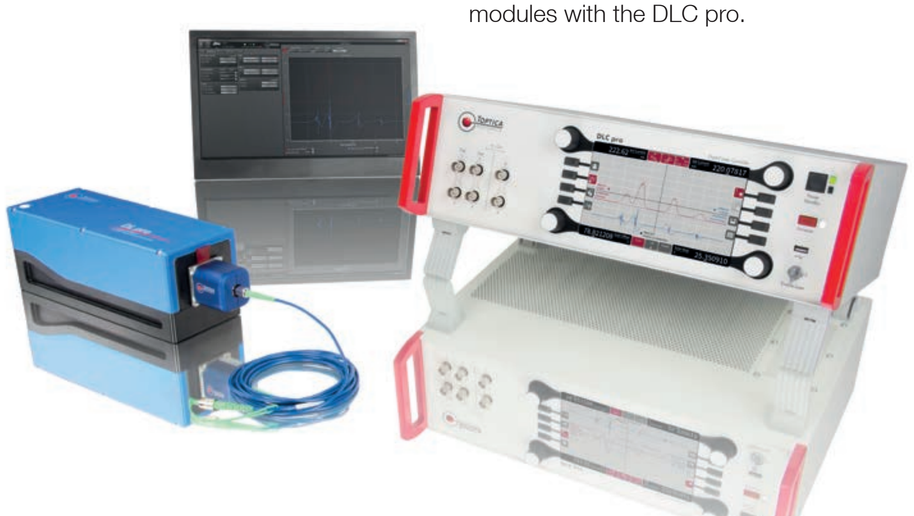
Noise on any of these outputs increases the laser linewidth. For laser frequency stabilization and linewidth narrowing, various locking schemes are used and require a variety of compatible options (see pages 10).

The digital DLC pro represents the latest stage of development of laser control electroncis. Its noise and drift properties are even better than the well established and widely used preceeding electronics SYS DC 110, which is still available as economic solution.

The DLC pro offers intuitive dial and multi-touch control on a 7" capacitive touch display. Remote control is possible via USB and Ethernet (TCP/IP), using either a graphical user interface on a standard PC, which is specifically developed for the DLC pro and included with the system, or through a vast set of software commands.

The DLC pro also offers laser-frequency locking enabled by a software license: A 30 day trail version is included. It has never been so easy to scan and lock a laser!

TOPTICA also provides a number of electronic modules for locking laser systems, e.g. DigiLock, the first digital laser locking solution or the analog FALC 110, the fastest locking electronic. The DLC ext allows to combine these electronic modules with the DLC pro.



Easy operation of lasers with either an included computer program or at the laser controller directly.

The DLC pro supports all lasers of TOPTICA's cw diode laser series: All laser systems in the lab may be operated via the same intuitive user interfaces or command language.

Features

- Current, temperature and piezo controller with lowest noise and drift
- No fans for cooling required: High reliability and low acoustic noise
- Signal display with hardware zoom (changes scan parameters to zoom into spectrum, etc.)
- Power Lock via control of current of laser diode or tapered amplifier current in kHz range
- Scan generator and X/Y, time- and frequency (FFT) display
- Side- and top-of-fringe locking*
- Two PIDs, lock-in signal generator*
- Lock detection and ReLock*
- Total remote control: PC GUI (included) and commands via TCP/IP and USB, e.g. for LabView or Python control programs
- Free software updates available on www.toptica.com

** These features are enabled with the DLC pro Lock software license.*

TOPTICA's DLC pro is a fully digital controller for tunable diode lasers, offering a new level of stability and lowest noise while allowing intuitive and comfortable control. Zooming into a Doppler-free line on a touch display and locking by tapping the desired peak opens up a completely new way of working with lasers.

A well-configured ReLock mechanism greatly increases an experiment's uptime, especially when it involves several lasers.

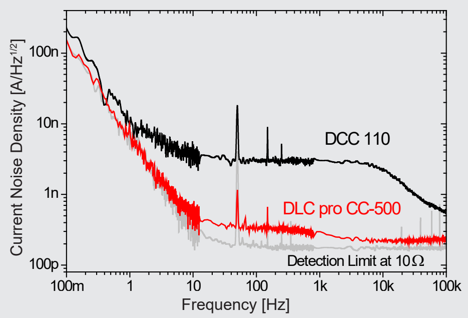
The advantages of using a digital control are starting to become available: A Power Lock allows for an active stabilization of the power, using an internal photodiode if available, to compensate for slow degradation of alignment or laser diode performance. Moreover, it is possible to use the included air pressure sensor to compensate for length changes in the laser cavity and hence improve the stability against mode-hopping even further.

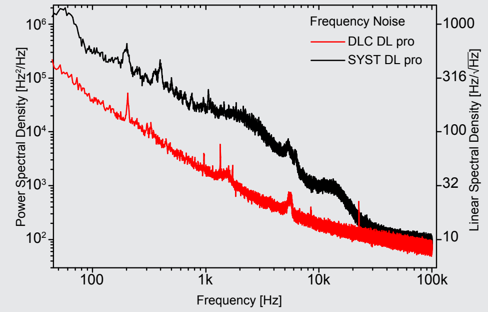
The DLC pro Lock is a software licence that enables the frequency lock of DLC pro controlled lasers at bandwidth of up to 30 kHz. Both, top-of-fringe and side-of-fringe locks are enabled - including the modulation of the laser frequency and the demodulation of the spectroscopic signal.

DLC pro — All-digital diode laser controller.

Options

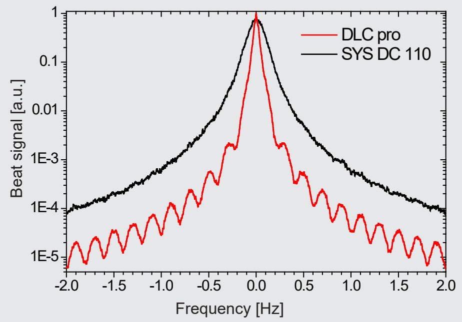
- The direct laser systems available with DLC pro control:
  - DLC DL pro
  - DLC DL pro HP
  - DLC DFB pro
  - DLC CTL
  - DLC TA pro
- Systems with frequency multiplexing available with DLC pro control:
  - DLC DL-SHG pro
  - DLC TA-SHG pro
  - DLC DL-FHG pro
  - DLC TA-FHG pro
- Break-out cable for digital lines
- DLC pro Lock: Enabling of frequency locking features via software key.

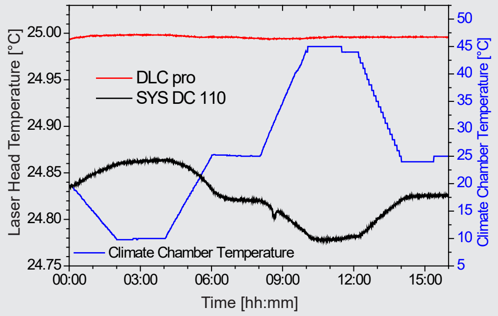




Left: Comparison of the current noise density of the current control modules.

Right: Frequency noise density of the laser light created with a DLC DL pro and a SYST DL pro.





Left: Delayed self-heterodyne linewidth measurement. Due to the long coherence length periodic modulation appears. The linewidth is obtained from the modulation depth (see page 9).

Right: Temperature of a DL pro laser head connected to a laser control electronics, which is located in a climate chamber and exposed to the temperature sequence shown by the blue line.

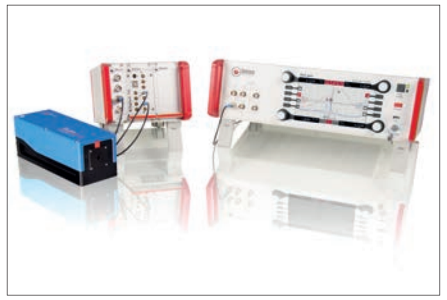
Specifications
DLC pro

DLC pro Specifications	
General / MC	
Operator controls	Touch display, 10 push buttons, 4 knobs, 1 key switch
Display	7 inch, 800 x 480 pixels, 262k colors
Touch panel	Projective capacitive (PCT) with multi-touch capability
Interfaces	Ethernet and USB
Inputs / Outputs	
Analog inputs (BNC)	2x (24 bit, DC .. 300 kHz) 2x (16 /10 bits, DC .. 300 kHz / 1.7 MHz)
Input range, impedance	-4 V .. + 4V, 10 kOhm
Analog outputs, BNC	2x (16 bit, DC .. 300 kHz)
Output range, impedance	-4 V .. + 4V (no load), 50 Ohm
Digital inputs**	4x TTL, 10 kOhm, Sub-HD 15-pin
Digital outputs**	4x TTL, 50 kOhm, Sub-HD 15-pin
Temperature Control TC	
Smallest set-temperature step	50 µK
Act. temperature noise (100 µHz ... 1 Hz)	< 300 µK p-p
Repeatability of actual temp.	< 0.001 K after >1h warm-up
Temperature coeff. of actual temperature	< 140 ppm K/K after >1h warm-up
Environment / Supply	
Voltage requirements	100 - 240 V~, 50/60 Hz
Power requirements	< 220 W, typ. 35 W, no active cooling fans
Size (H x W x D)	154 mm x 450 mm x 348 mm
Weight	8.0 kg (with MC, CC-500, PC, TC)

Specifications		
Current Control	**CC-500**	**CC-5000***
Max. laser current	2x 245 mA or 1x 490 mA (selectable)	5000 mA
Max. laser voltage	7 V @ 360 mA, 5 V @ 490 mA	3.5 V
Smallest current step	0.015 µA	5 µA
Current noise density	280 pA/√(Hz) @ 1 kHz	120 nA/√(Hz)
Low-frequency current noise (0.1 Hz ... 10 Hz)	< 50 nA p-p	10 µA p-p
Temperature coefficient of laser current	<3 ppm/K typ. after >1 h warm-up	100 Hz
Long-term stability of laser current	< 100 ppm/√(khrs) after >1 h warm-up	
Modulation bandwidth	DC to 15 kHz .. 30 kHz (depending on laser diode)	100 Hz
Piezo Control PC		
Piezo voltage range	-1 V .. +140 V	
Max. piezo current (charge/decharge)	25 mA	
Smallest piezo voltage step	0.01 mV	
Voltage noise density	140 nV/√(Hz) @ 1 kHz	
Temperature coefficient of piezo voltage	< 40 ppm/K	
Small-signal bandwidth	3 kHz (0 load)	

*For TA pro systems. Two CC-5000 can be combined to drive one amplifier chip at up to 10 A.
**Optional break-out cable with 8 SMB connectors available.

DLC ext
Combination of DLC pro with fast locking modules



Laser system DLC DL pro extended by a DLC ext equipped with a DigiLock.

The DLC ext allows extending the DLC pro with TOPTICA's well-established fast locking modules. These modules DigiLock and FALC (see next page) provide high performance laser locking if a faster feedback than available with the DLC pro Lock option is needed.

Features

· Supports up to two modules, any two PDD 110, FALC 110, mFALC 110 and DigiLock 110

· 4 BNC signal outputs for access to backplane signals

· External power supply with automatic mains voltage detection

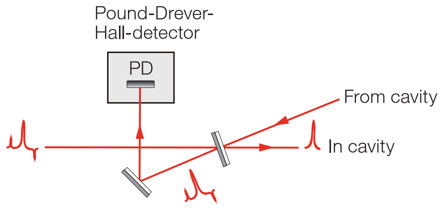
PDD 110/F, FALC 110 and mFALC 110
High-Bandwidth Linewidth Control with Optional Analog Mixer

PDD 110/F – fast Pound-Drever-Hall detector module

The Pound-Drever-Hall Detector PDD 110/F serves to lock a diode laser to the maximum of an absorption, reflection or transmission feature, such as an optical resonator or an atomic line. The module generates an HF modulation signal that acts either on the laser current, or on an electro- or acousto-optic modulator (EOM, AOM). A phase-sensitive detector unit demodulates the spectroscopic signal[1] and produces an error signal, which, in turn, serves as input for a PID regulator (e.g. FALC 110).

FALC 110 - highest bandwidth for frequency locking

The Fast Analog Linewidth Controller FALC 110, a high-speed control amplifier, performs advanced frequency stabilizations tasks, such as laser linewidth reduction or high-bandwidth frequency locking. The module is compatible with any of TOPTICA's tunable diode lasers such as the DL pro, DL 100 and DL DFB.



Pound-Drever-Hall detection scheme.

Researchers using the FALC 110 highly benefit from a fast circuit layout. At 10 MHz there is a phase delay of less than 45 degrees, and the bandwidth of the fastest signal path reaches 100 MHz.

In a typical setup, the fast output of the FALC 110 controls the current of an ECDL or DFB laser. Additionally, a slow integrator cancels out long-term frequency drifts, by acting either on the grating piezo of an ECDL, or on the temperature of a DFB laser.

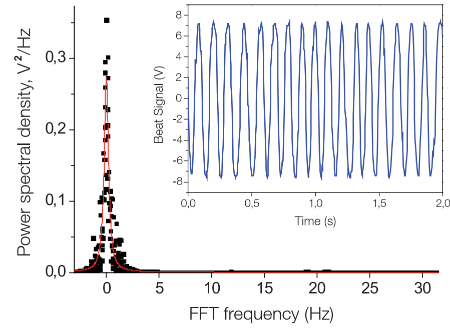
mFALC 110 – the solution for phase locking

The mixing FALC (mFALC 110) extends the functionality of the FALC 110 by integrating an additional analog mixer. The module accomplishes fast phase-locking of two diode lasers to a local RF oscillator: The beat signal of the two lasers is mixed with and phase-stabilized to the external RF source.

Sub-Hertz linewidths

The design works: Researchers at MPQ Garching locked two diode lasers to two high-finesse cavities with a resulting beat width of less than 0.5 Hz[1]. Sub-Hertz frequency stabilization of a DL pro with FALC was shown at the MPL Erlangen[2]. And scientists at the University of Frankfurt used the mFALC to maintain a stable phase lock of two DL DFB lasers to a local RF oscillator, and employed this setup for coherent terahertz imaging[3].

PDD 110/F — Pound-Drever-Hall detectors.
FALC 110 — Fast Analog Linewidth Controller.
mFALC 110 — FALC with integrated mixer.



Beat measurement of two independent ECDLs locked to two high-finesse ULE cavities, one of them using FALC 110. The beat width was less than 0.5 Hz over 8 s. The inset shows the phase stability of the beat note filtered with a 100 Hz low-pass filter (J. Alnis, MPQ Garching).

PDD 100/F	
Input section	
Error signal generated	Dispersive error signal for top-of-fringe locking
Modulation frequency	20 MHz (default), adjustable from 12 .. 35 MHz
Output section	
HF output amplitude	1 V pp (+4 dBm) @ 50 Ω
Second-harmonic suppression	> 30 dB typ.
General specifications	
Adjustable LO phase at mixer	0° - 190°, inversion +/- 180°
Total signal delay	< 12 ns (100 MHz bandwidth)
Number of detection channels	1 (2 possible with PDD 110/F DUAL)

FALC 110, mFALC 110	
Input section	
Inputs	Two high-speed differential inputs, adjustable input offset
Fast circuit branch	
PID regulator	Signal delay < 15 ns, Phase delay < 45° @ 10 MHz
DC gain	15 dB .. 80 dB
Output voltage range	Max. ± 2 V @ 50 Ω
Slow integrator	
Bandwidth	10 kHz, for grating piezo or laser temperature control
DC gain	Typ. 110 dB
Output voltage range	Max. ± 5 V, high-impedance load
RF input (beat signal of two lasers, mFALC only)	
Frequency range	10 MHz .. 200 MHz
Max. input voltage	5 V DC, 4.5 V pp AC
LO input (local oscillator, to be mixed with RF input, mFALC only)	
Frequency range	10 MHz .. 200 MHz, sine wave preferred
Max. input voltage	2 V DC, 2.8 V pp AC

[1] J. Alnis et al., Phys. Rev. A 77, 53809, (2008). [2] Y. N. Zhao et al., Opt. Commun. 283, 4696, (2010). [3] F. Friederich et al., Opt. Express 18:8, 8621, (2010).

DigiLock 110 — A versatile, digital locking module for DLC ext or SYS DC 110 electronics.

Features

- Scan generator
- Laser control
- Multi-channel Oscilloscope
- Controller Design
- Dual PID + P
- Click & Lock
- Pound-Drever-Hall
- AutoLock & ReLock
- Lock-in
- Computer control
- Spectrum analysis
- Network analysis

Laser stabilization easier than ever

Selfmade solutions for stabilization tasks often involved a heap of electronics, soldering, trial and error, and frustration. The DigiLock 110 is TOPTICA's versatile solution: a digital locking module, flexible to solve locking tasks with perfection, and yet easy to use thanks to intelligent software control with a clear and comfortable graphical user interface.

In addition to standard functions like side-of-fringe and top-of-fringe locking, the DigiLock 110 offers computer control over the laser, signal visualization, and signal analysis. In AutoLock mode, the user can modify the scan parameters of the laser by dragging the mouse, and zoom into a feature of a spectrum on the software oscilloscope screen.

With the feature displayed on the screen, one can then simply “Click & Lock” to any peak or slope. For optimizing lock parameters, spectral analysis of error signals can be performed, as well as measurements of actuator transfer functions.

DigiLock 110 – flexibility and perfection

Flexibility and perfection both originate from the underlying technology: The hardware is based on a fast FPGA (Field Programmable Gate Array). Together with numerous high-speed and high-precision AD and DA converters, the FPGA provides the needed flexibility with sufficient bandwidth. The large bandwidth, in fact, allows for substantially reducing diode laser linewidths: using two DigiLocks 110 to lock two DL pro to one FPI 100, a beat width of less than 300 Hz was measured.

As shown with FALC 110, it was possible to also achieve sub-Hz linewidths with the DigiLock 110, utilizing the high-bandwidth analog bypass.

Intelligence in laser stabilization

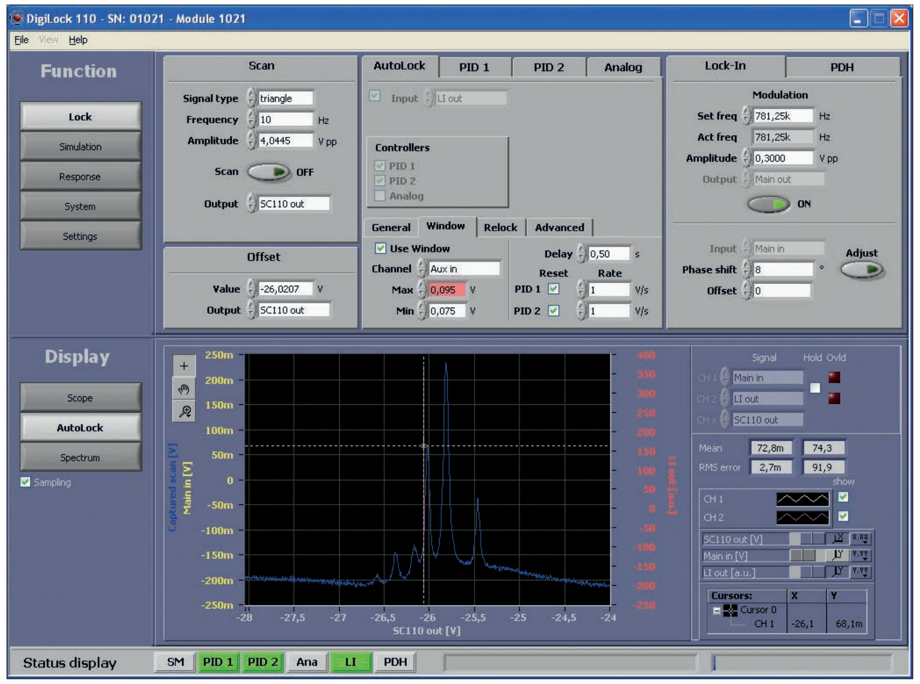
The DigiLock 110 tries to support the laser user wherever possible. In addition to the aforementioned features, the DigiLock can be configured to detect whether the frequency is locked – locked in general – or even whether the laser is locked to the right position.

It is for example possible to define a voltage window in a Doppler-broadened spectroscopy signal, that contains only one transition of the corresponding Doppler-free signal, thus allowing the laser to only lock to this particular peak (see AutoLock & ReLock example, page 43).

Once out of lock, the DigiLock can start searching, at pre-set speed, over a configurable width, until the voltage lies within the locking window again and the laser is tightly locked. The automatic relock makes frequent manual readjustments obsolete.

Multiple DigiLocks and remote control

The latest software version of the DigiLock 110 offers control of up to four DigiLocks from one computer. Also, remote control via TCP/IP is now available, so the DigiLock can be integrated in automated experiments and controlled by other hard- and software.



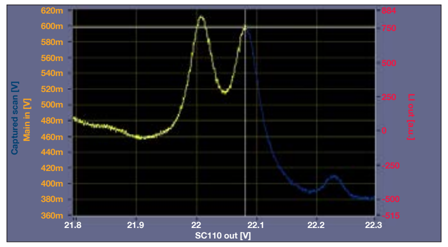
DigiLock's graphical user interface.

DigiLock 110
Digital Feedback Controlyzer for Laser Locking and Analysis

Functionality	Value	Unit	Comment
Scan frequency	0.1 - 33 x 10^6	Hz	Bandwidth limited on some channels
Waveform types	Sine, triangle, square, sawtooth		
PID function 1			
Signal latency	200	ns	ADC and DAC latency included
Parameters	P, I, D, I cut-off		
PID function 2			
Signal latency	200	ns	ADC and DAC latency included
Parameters	P, I, D		
Analog P function			
Bandwidth	21 MHz (-3 dB, 200° phase)		
Lock-In function			
Modulation frequency	0.012 – 781	kHz	
Pound-Drever-Hall function			
Modulation frequency	1.56, 3.13, 6.25, 12.5, 25	MHz	

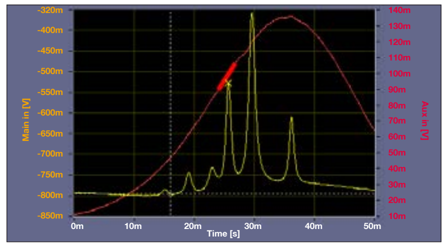
Input channels	Resolution (bit)	Sample rate (Hz)	Bandwidth (-3 dB) (Hz)	Range (V)	Impedance (Ohm)	Comment
Main in	14	100 M	14 M	± 2.1	50	Input signal <Main in> has to be between ± 3.5 V, <Input Offset> and amplification can be controlled from DigiLock Software
Aux in	14	100 M	15 M	± 2.1	50	
Precise in	16	200 k	50 k	± 2.0	10 k	
DCC I_{act}	16	100 k	15 k	± 13.1	40 k	SYS DC 110 backplane
DTC T_{act}	16	100 k	15 k	± 13.1	40 k	SYS DC 110 backplane
AIO 1 in	16	100 k	15 k	± 12.5	47 k	Normally used as output
AIO 2 in	16	100 k	15 k	± 12.5	47 k	
Sum in			27 M	± 1.0	50	Bandwidth between <Sum in> and <Main out>

Output channels	Resolution (bit)	Sample rate (Hz)	Bandwidth (-3 dB) (Hz)	Range (V)	50 Ohm driver	Comment
Main in	14	100 M	19 M	± 1.0	Yes	Sum of <Sum in> and analog P branch
Aux in	14	100 M	19 M	± 1.0	Yes	
SC 110 out	21	100 k	18 k	± 6.5	No	SYS DC 110 backplane; amplification by 15 with SC 110
DCC Iset	21	100 k	18 k	± 6.5	No	SYS DC 110 backplane
DTC Iset	16	100 k	18 k	± 6.5	No	SYS DC 110 backplane
AIO 1 out	16	100 k	16 k	± 6.5	No	
AIO 2 out	16	100 k	16 k	± 6.5	No	Normally used as input
Sum in			27 M	± 1.0	50	Bandwidth between <Sum in> and <Main out>
Error out			20 M	± 1.7	Yes	Error out = (<Main in> + <Input Offset>) x Gain/2; bandwidth between <Main in> and <Error out>
TRIG				0, 2.6	Yes	



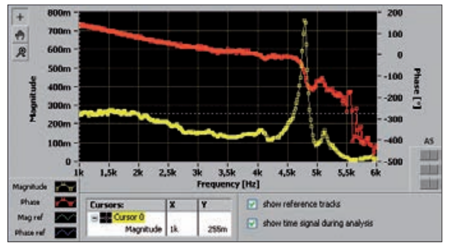
“Click & Lock”:

The user can click on the slope position or on any maximum or minumum. The laser scans to this position, and the DigiLock activates the lock.



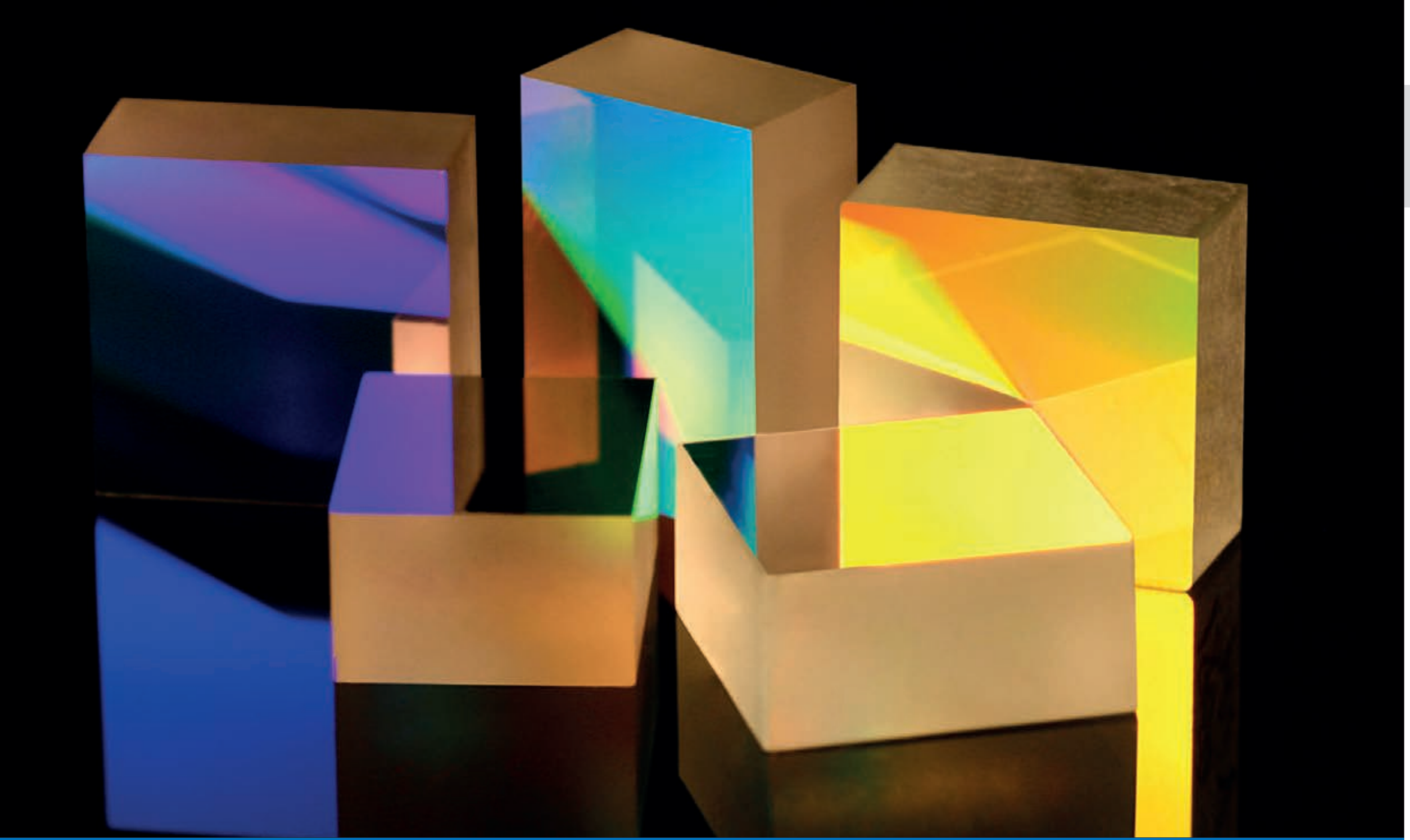
“AutoLock & ReLock”:

The DigiLock enables/disables multiple PIDs and an analog P component simultaneously. Once in lock, the error signal is plotted against the scan voltage for monitoring. The user can define voltage windows to allow the DigiLock to lock to certain features only, and initiate a search if the voltage lies outside the window.



“Spectrum and Network analysis”:

The DigiLock can show the spectrum of an error signal, for example to reveal oscillations. Actuator transfer functions and bandwidth can be measured by sweeping a modulation to an actuator and measuring the response in amplitude and phase. The picture shows a measurement of the DL pro piezo resonance frequency.



PHOTONICALS

Laser Diodes and Accessories

Photonic accessories and laboratory tools are just as important as the laser itself.

Researchers in modern optical laboratories need to prepare their laser beams in the requested shape, separate them from undesired feedback, control the spectral performance and monitor the wavelength, to name just a few everyday tasks.

TOPTICA offers a variety of Photonicals – instruments and components that upgrade, refine or characterize lasers.

We focus on a "selection of the best": Unique components and top-grade instruments that are extremely useful in the daily operation of diode lasers.

For detailed product specifications, please refer to our website www.toptica.com.

Laser Diodes

- Unique selection of FP, AR and DFB diodes, 369 .. 3500 nm
- Tapered amplifier chips, 660...1495 nm with up to 3.5 W
- All diodes and amplifiers extensively tested and qualified
- Check our regularly updated diode and TA chip stock list:

www.laser-diodes.com

FiberDock – Patented ultra-stable precise 6-axes mount for convenient single-mode fiber coupling.

Free Space Optical Isolators

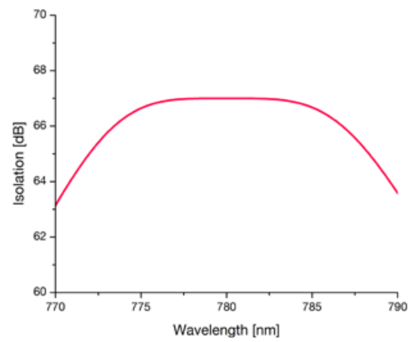
High Power Tunable Single and Dual Stage Performance

TOPTICA's product line of Faraday optical isolators are specially designed and manufactured in-house by the laser experts of TOPTICA to give industry leading performance in single and dual stage configurations. Single stage devices provide at least 38 dB isolation and 85 % transmission (>43 dB and >92 % average) over individual wavelength ranges in total spanning 395 - 425 nm and 630 - 1400 nm. Dual stage models provide at least 60 dB isolation and 80 % transmission (> 67 dB and >90 % average) over individual wavelength ranges in total spanning 640 - 1100 nm. All models are wavelength adjustable and can handle power densities up to 4 kW / cm².

High isolation, transmission, and power densities are achieved with precision polarizers and precisely designed Faradayrotator elements. Most isolators have magnetically locked and removable protective endcaps and mounting fixtures. All internal optical components are angled to eliminate collinear back reflections. Extensive individual, wavelength-specific testing guarantees performance of each isolator. All optical sub-components are inspected upon receipt, and all assembled devices are tested for transmission and isolation over their design wavelength ranges before shipment.

TOPTICA's isolators enable state of the art protection for the most stable lasers in the world. These are the same components already used by TOPTICA in the industry-leading DL pro, DL 100, TA-SHG pro, and TA-FHG pro product lines. They have been demonstrated to effectively reduce feedback in external cavity diode laser systems, block reflections from free-space fiber coupling, increase power stabilization in optical systems, and eliminate feedback-induced damage to sensitive optical components. The same superior isolators that make TOPTICA lasers the industry standard are now offered individually.

Other wavelengths and broadband isolators as well as OEM customizations are available upon request. Additional wavelengths spanning the UV to NIR regions are also available for integration into our scientific laser systems.



TOPTICA offers single-stage and dual-stage optical isolators.

Key Features

- High power damage threshold (4 kW / cm²)
- Highest guaranteed isolation in industry
  - > 38 dB (single stage)
  - > 60 dB (dual stage)
- High transmission
- Wavelength coverage 395-425 nm, 630-1400 nm
- All internal components angled 1° to eliminate back reflections
- 4.7 mm clear aperture
- All isolators are wavelength adjustable

Single Stage Isolators

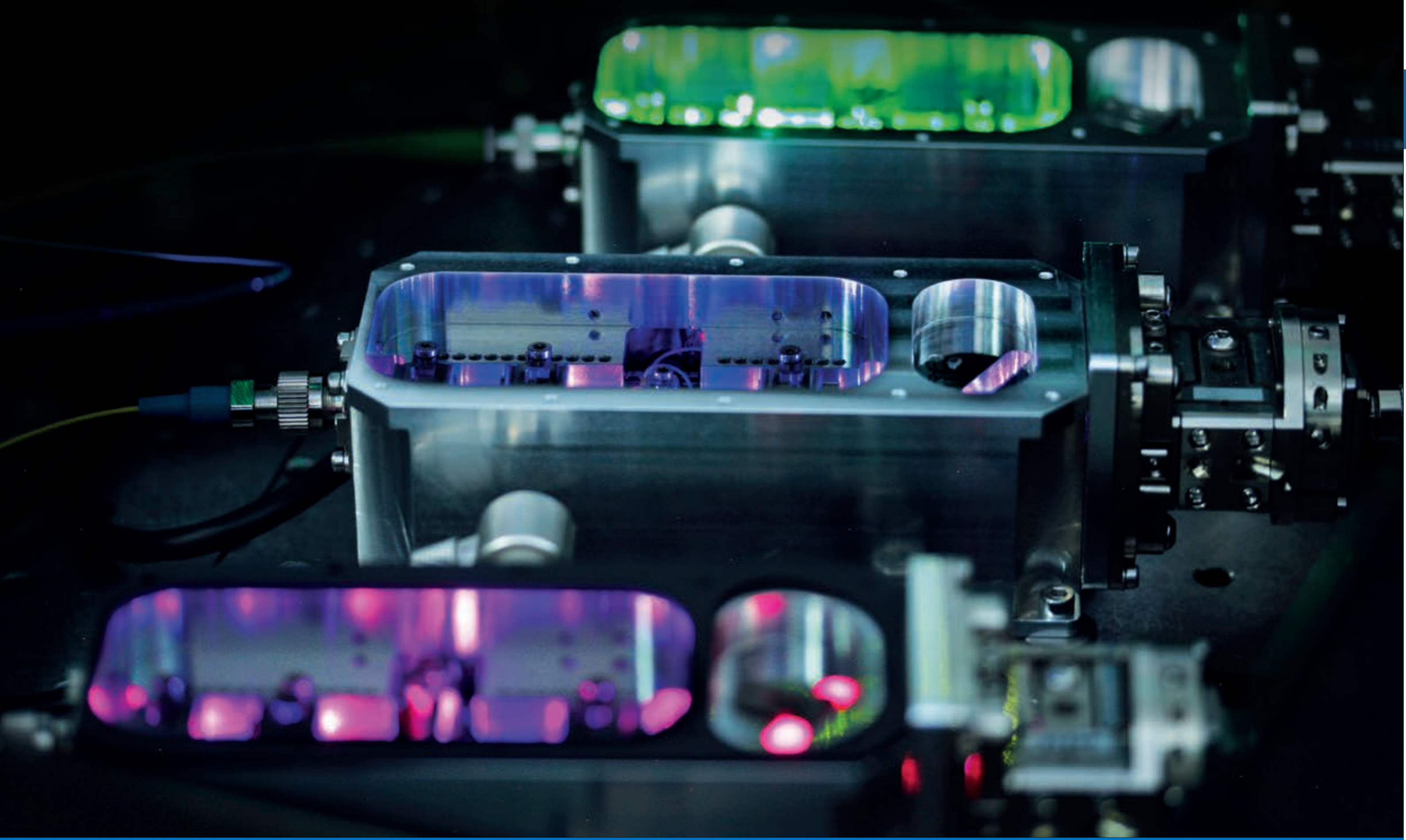
Model	SSR405	SSR650	SSR690	SSR730	SSR780	SSR835	SSR885	SSR945	SSR1150	SSR1250	SSR1350
Design Wavelength [nm]	405	650	690	730	780	835	885	945	1150	1250	1350
Tunable Wavelength Range [nm]	395-425	630-670	670-710	710-750	750-810	810-860	860-910	905-985	1100-1200	1200-1300	1300-1400
Fixed Operation Range* [+/- nm]	2.5	5	6	6.5	7	7.5	8	9	10	10	10
Clear Aperture	4.7 mm										
Isolation at Design Wavelength (Min/Ave)	38/43 dB										
Operating Temperature Range	15 °C to 40 °C, non-condensing										
Storage & Transport	Shock 25 g / 10 ms., Vibration 3 g (15-100 Hz), 0 °C to 60 °C non-condensing										

with respect to design wavelength >35 dB and >85 %

Dual Stage Isolators

Model	DSR660	DSR700	DSR740	DSR780	DSR820	DSR880	DSR950	DSR1020	DSR1070
Design Wavelength [nm]	660	700	740	780	820	880	950	1020	1070
Tunable Wavelength Range [nm]	640-680	680-720	720-760	760-805	800-865	860-930	930-995	995-1050	1050-1100
Fixed Operation Range* [+/- nm]	6	6.5	7	7.5	8	10	11.5	12	12
Clear Aperture	4.7 mm								
Isolation at Design Wavelength (Min/Ave)	60/67 dB								
Operating Temperature Range	15 °C to 40 °C, non-condensing								
Storage & Transport	Shock 25 g / 10 ms., Vibration 3 g (15-100 Hz), 0 °C to 60 °C non-condensing								

with respect to design wavelength >60 dB and >80 %



TOPTICA PRODUCT PORTFOLIO

Completed Overview

TOPTICA develops and manufactures high-end laser systems for scientific and industrial applications. Our product portfolio includes diode lasers, ultrafast fiber lasers, terahertz systems and frequency combs for markets such as quantum technologies, biophotonics or materials test & measurement.

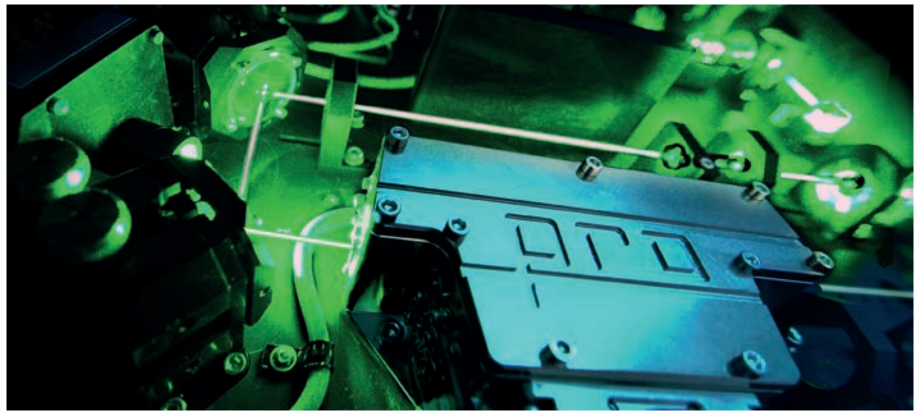
Scientists – including over a dozen Nobel laureates – and OEM customers acknowledge the world-class specifications of TOPTICA's lasers, as well as their reliability, longevity and their ease of use. With about 230 employees, TOPTICA takes always pride in developing new products to continuously push their limits or in specifically designing customized systems.

From several places in Germany, USA and Japan and including a global distribution network we provide exceptional service and application consulting worldwide. Founded in 1998 near Munich (Germany), TOPTICA became one of the leading laser photonics companies by consistently delivering high-end products.

TOPTICA's tunable diode lasers are appreciated for excellent coherence, wide tuning range and unique power/wavelength coverage. Our non-tunable single-mode diode lasers are also available in single-frequency versions or multi-laser engines.

Already since 2004, we provide ultrafast fiber lasers which quickly matured from merely scientific products to fully hands-off and reliable OEM instruments while maintaining required characteristics like high power, short pulses and appropriate repetition rate. Both, tunable diode laser as well as ultrafast fiber lasers, are the basis of our THZ product line which is world-wide unique in performance and versatility.

Thanks to our experience and a unique, patented technology, we were able to transfer the reliability of our OEM-type ultrafast fiber lasers to ultimately coherent, phase-stable and repetition rate controlled high-end systems. As culmination of our portfolio, we can even combine frequency combs with tunable and phase-locked single-frequency diode lasers to deliver optical frequencies as a package.



Difference Frequency Comb (DFC)

Inherently CEP-stable modular frequency combs

The operating principle of the offset-free Difference Frequency Comb relies on generating a broadband supercontinuum from the output of a low noise Er-fiber mode-locked oscillator and subsequent optical Difference Frequency Generation (DFG) between the low- and high-frequency parts of the octave spanning spectrum in a nonlinear crystal. The most important features are an improved stability and a more simple and reliable, all passive frequency offset stabilization. The comb is free from fluctuations of the offset-phase and offset-frequency due to the common mode suppression of the two parts of the original spectrum. Additionally, the carrier envelope offset frequency f_{CEO} of the DFC is fixed to zero.

TOPTICA's frequency comb product line is a modular system that supports a broad variety of applications. Three basic versions of the DFC are available: DFC CORE, DFC CORE+ and DFC SEED. All models use TOPTICA proprietary CERO-technology to achieve an unprecedented low-noise performance.

The DFC CORE and its high performance version DFC CORE+ come with a digital oscilloscope for beat monitoring and a GPS disciplined RF reference included. They both provide 4 or optionally 8 phase-stable outputs at 1560 nm.

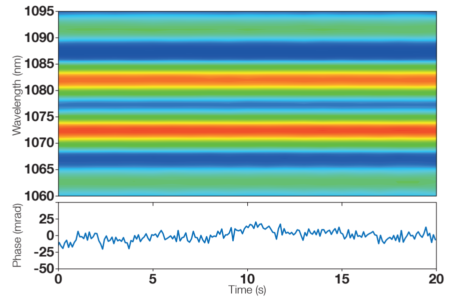
Several extension modules are available that can convert the DFC CORE / DFC CORE+ outputs to any wavelength between 420 nm and 2200 nm. The extension modules can be upgraded at any time after purchase of the DFC CORE and are interchangeable between outputs. In addition, beam combiner (DFC BC) and beat detector (DFC MD) units are available to provide RF beats between the DFC comb lines and cw lasers. The RF output signal of the DFC MD can be counted to determine the frequency of the cw laser. It also enables phase or frequency stabilization of the cw laser to the DFC using e.g. TOPTICA's locking modules mFALC or DigiLock. In the DFC CORE+ version, the RF output signal can also be used to stabilize the DFC to the cw laser which serves as optical reference.

Such a DFC system can be combined with any of TOPTICA's tunable diode lasers to achieve a complete, frequency-referenced laser system including wavelength meter and counter all from one source.

Spectral Interferometry

The performance of the CERO-technology is best characterized by means of spectral interferometry. The dedicated setup consists of an f-2f interferometer with optical spectrum analyzer which records optical fringes at the output. It measures the absolute phase stability of the f_{CEO} cancelation with respect to an independent reference. The figure shows a spectrogram of the interference fringes recorded over a time of 20 seconds. The high interference contrast is stable over the full time span and no offset phase drift is observed. The measurement shows a RMS phase stability of 8 mrad over 20 s, which is limited by the stability of the f-2f interferometer. The real phase stability of the DFC is expected to be below this value.

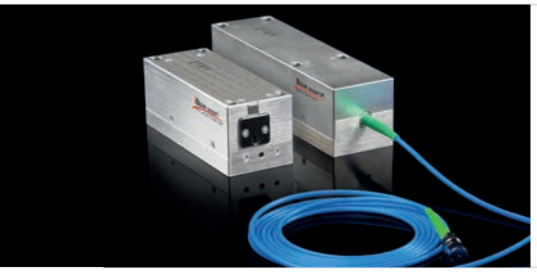
Find out more about TOPTICA's Difference Frequency Comb in our dedicated frequency comb brochure.



Typical result of spectral interferometry for out-of-loop measurement of the CEP stability.

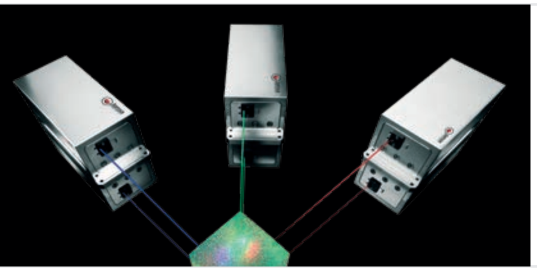
Key Features

- Patented CERO-technology („zero-f_{CEO}") with intrinsic CEP stability
- RMS phase stability < 35 mrad
- Frequency stability < $8 \cdot 10^{-14}$ @ 1s (measured with RF reference), or same as reference
- < 0.04 % RMS power fluctuations
- One free parameter f_{rep} with up to 3 control elements (oscillator temperature, piezo, pump current) and > 400 kHz bandwidth



iBeam smart

- Single-mode diode lasers
- TEM_{00}, $M^2 < 1.2$
- 375 nm .. 785 nm
- 50 mW .. 300 mW
- cw and pulsed operation
- Optional fiber output



TopMode

- 405 nm, 445 nm, 488 nm, 515 nm, 633 nm, 685 nm, 785 nm
- 20 mW .. 500 mW
- < 25 MHz linewidth, > 5 m coherence length
- Charm coherence control (TopMode)

iChrome

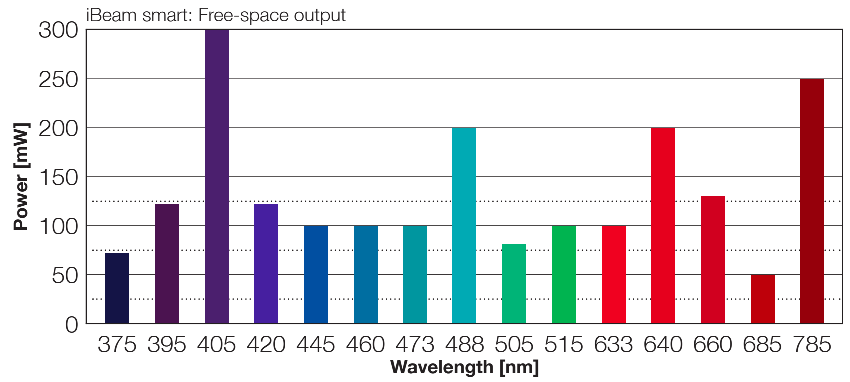
- Multi-laser engines
- 4 to 8 laser lines in one box
- Various power/wavelength options
- PM fiber output
- Direct modulation up to 20 MHz
- COOL^AC – hands-off, self-aligning system

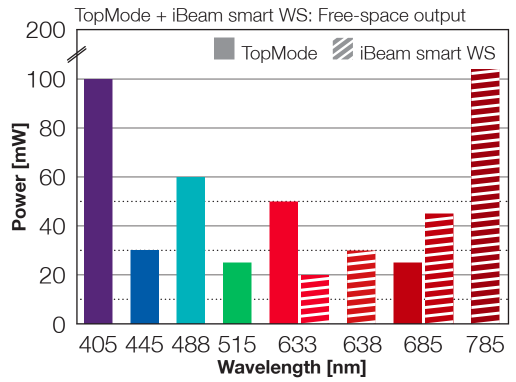
TOPTICA's single-mode diode lasers set new standards in terms of power, low noise and convenient OEM integration. They come with diffraction limited TEM_{00} output and reliable spectral properties, as well as optional robust fiber coupling. Compact design and low power consumption make them superior to old-fashioned, bulky and inefficient gas lasers. Multi-laser engines seamlessly integrate several wavelengths into true one-box laser systems – switching between colors has never been easier. The systems' flexibility and ease of use enable straightforward deep integration into any customer's system design.

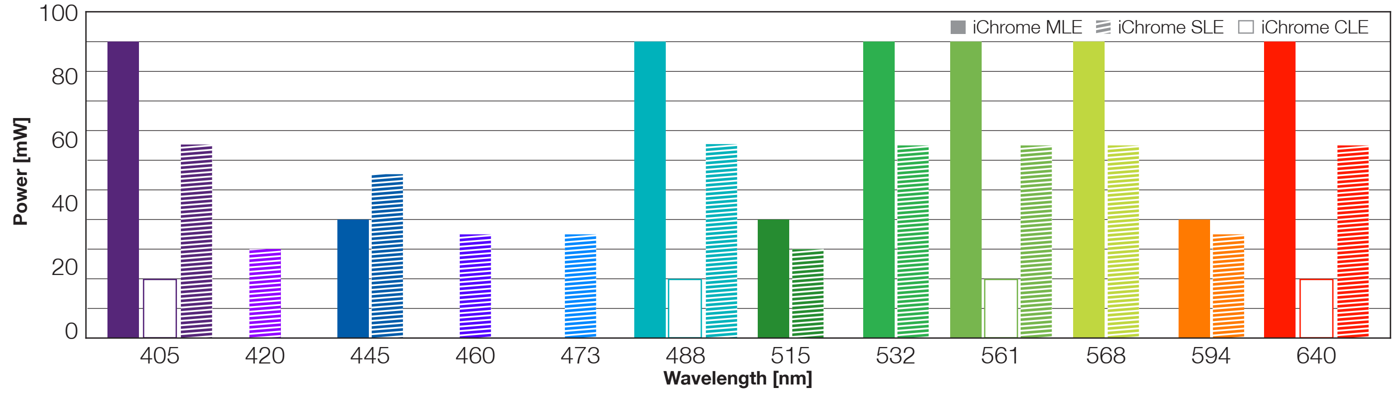
Visit www.toptica.com/products to find out more details. OEM and research inquiries welcome.

Ideal for

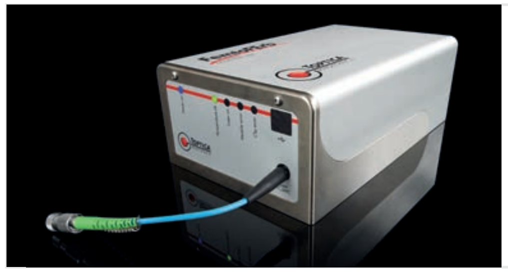
- Confocal microscopy
- Live-cell imaging
- Ellipsometry
- Flow cytometry
- Interferometry
- Microlithography
- Microplate readout
- Retina scanning





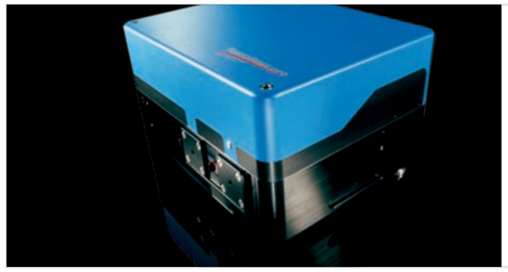


Output power/wavelength chart of TOPTICA's single-mode (top left) and single-frequency (top right) diode lasers as well as multi-laser engines (bottom).



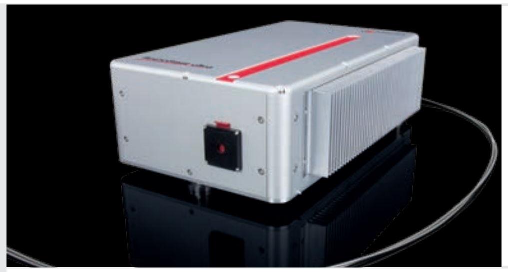
FemtoFiber smart

- Compact ultrafast fiber laser
- OEM one-box design
- All PM fiber setup
- 2000 nm, 1560 nm, 1064 nm, 1030 nm, 780 nm
- Pulse duration < 60 fs .. 10 ps



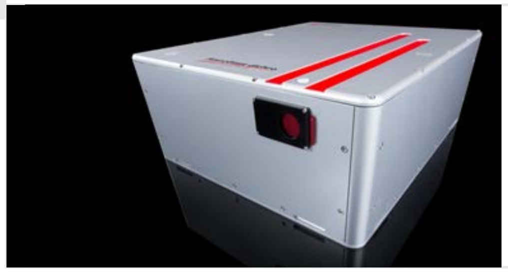
FemtoFiber pro

- Versatile ultrafast fiber laser
- 1560 nm, 1030 nm, 780 nm, 980-2200 nm, 830-1100 nm, 488-640 nm
- Pulse duration 25 fs .. 1 ps
- Multi-arm synchronized



FemtoFiber ultra

- High-power ultrafast fiber laser
- 0.5 W @ 780 nm
- 5 W @ 1050 nm
- < 150 fs pulse duration
- TEM_{00}, M2 < 1.2



FemtoFiber dichro

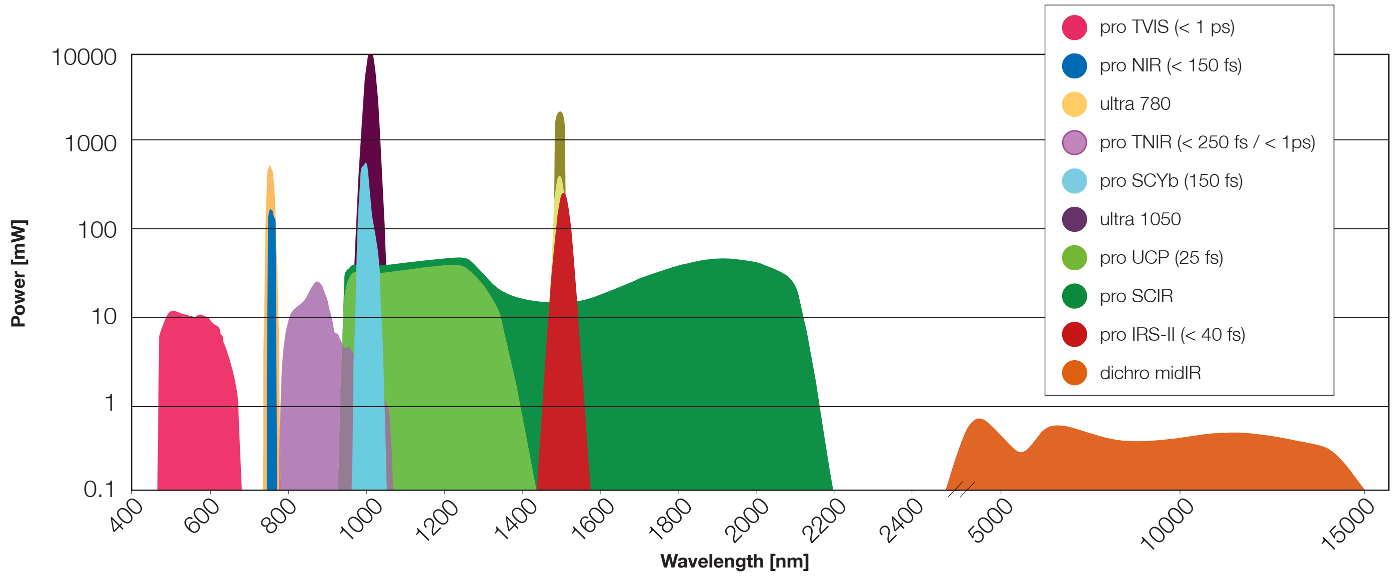
- "Two-color" ultrafast fiber laser
- Broadband mid-IR source
- 5 - 15 µm (20 - 60 THz)
- Output power > 0.5 mW

Ultrafast technology has seen a tremendous success since it was introduced. Many promising applications have emerged, benefiting mainly from the high peak power and ultrashort pulse duration, which give rise to nonlinear effects and open new paths in engineering and scientific research.

The key for successful use or integration of ultrafast technology is a robust system with simple push-button operation. TOPTICA offers cost-effective optimized products fulfilling these requirements: Ultrafast fiber lasers based on erbium- and ytterbium-doped active fibers. All systems use TOPTICA's FemtoFiber technology, incorporating polarization-maintaining fibers, saturable absorber mirror mode-locking, and reliable telecom components. Visit www.toptica.com/products/psfs-fiber-lasers to learn more about our products.

Ideal for

- Multiphoton / SHG microscopy
- Supercontinuum generation
- Material processing (seeder)
- Semicon inspection
- Two-photon polymerization
- Time-domain terahertz
- Pump-probe spectroscopy
- Optical coherence tomography
- Attosecond science



Output power/wavelength chart of TOPTICA's ultrafast fiber lasers.

Terahertz Systems

TeraFlash pro

- Time-domain THz system
- Up to 90 dB dynamic range
- 5 THz bandwidth
- Highest measurement speed

TeraScan

- Frequency-domain THz system
- Up to 90 dB dynamic range
- Up to 2.75 THz bandwidth
- < 10 MHz frequency resolution

Terahertz Accessories

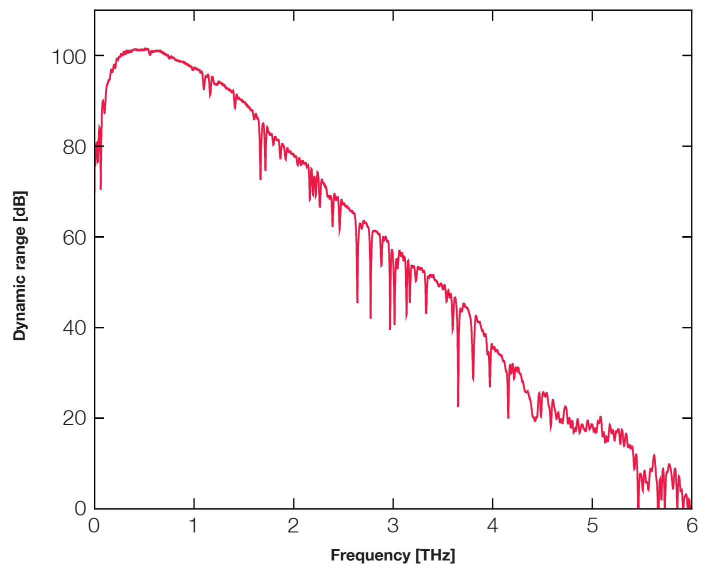
- Schottky Detectors (high sensitivity & high speed models)
- Optomechanics (2-mirror & 4-mirror assemblies)
- Reflection head

TOPTICA provides best-in-class systems for both time-domain and frequency-domain terahertz generation. The TeraFlash combines TOPTICA's FemtoFiber smart lasers with state-of-the-art InGaAs antennas and sets new standards in terms of dynamic range, bandwidth and measurement speed for time-domain applications.

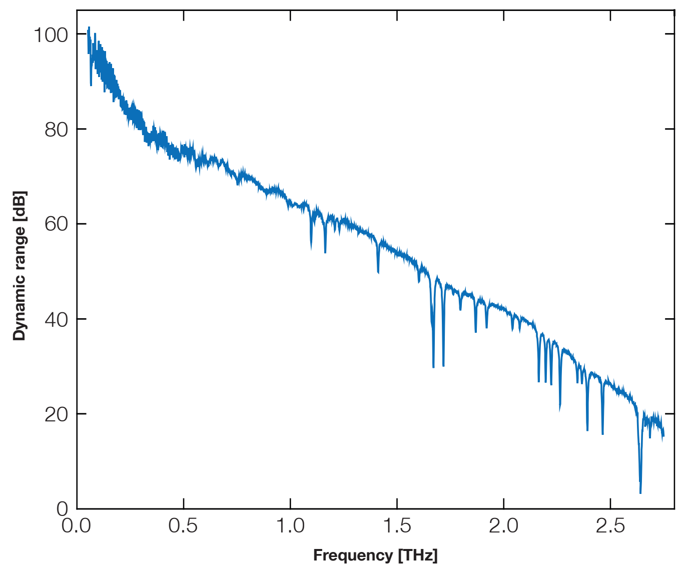
For frequency-domain terahertz spectroscopy, TOPTICA's TeraScan systems – which are based on precisely tunable DFB lasers, digital control electronics, and latest GaAs or InGaAs photomixer technology – provide sub-10 MHz frequency resolution and ultimate ease-of-use. More details on terahertz technology and related products can be found on www.toptica.com/technology/technical-tutorials/terahertz.

Ideal for

- Terahertz spectroscopy
- Trace gas sensing
- Non-destructive testing
- Hydration monitoring
- Material research
- Industrial quality control

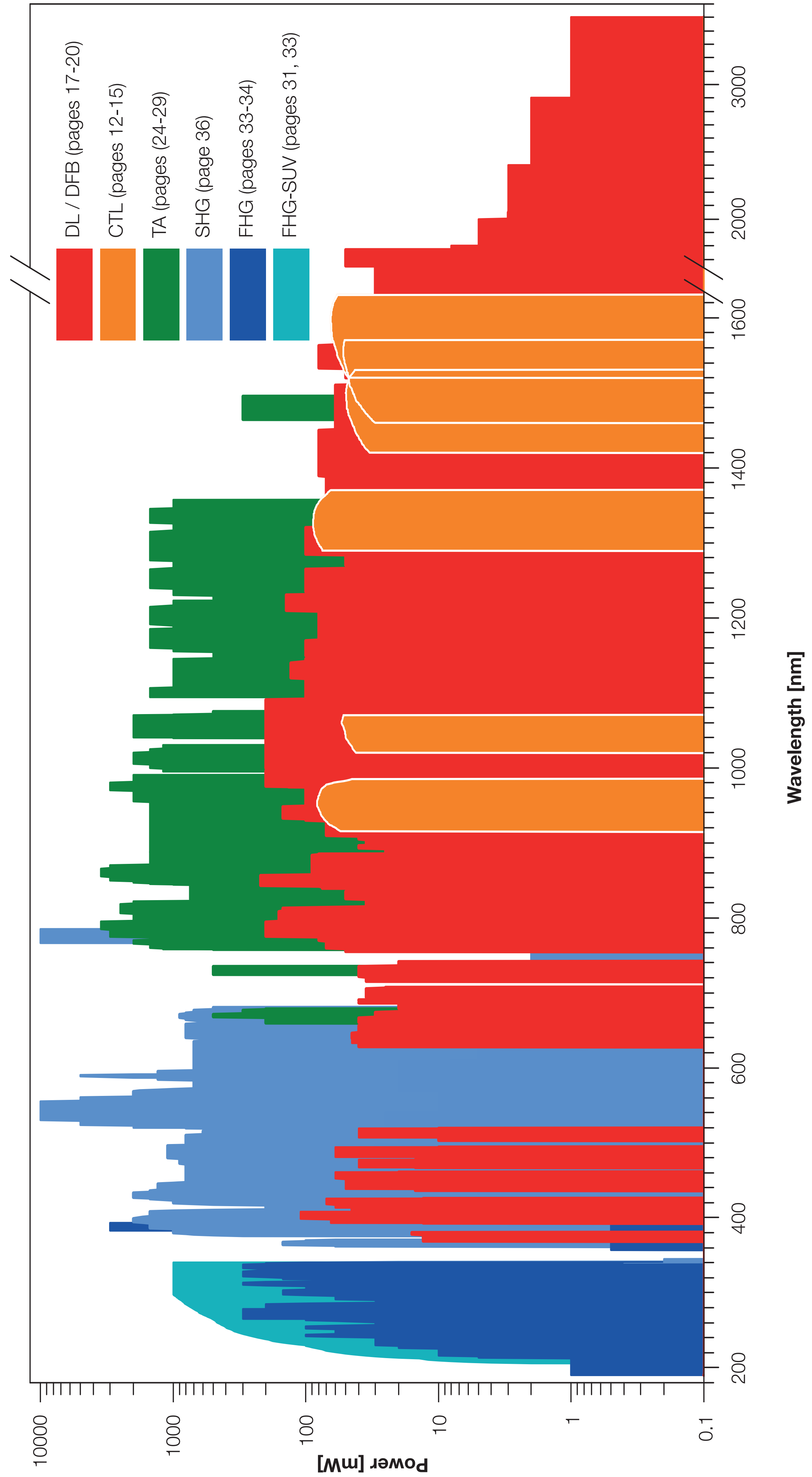


Typical THz spectrum as obtained with time-domain system TeraFlash.



Typical THz spectrum as obtained with frequency-domain system TeraScan.

Tunable Diode Lasers Wavelength Coverage



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