Digital Revolution in Laser Control

The tunable diode laser DL pro is now complemented by a modern, digital control concept (DLC pro) that also offers improved noise levels.

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With a newly-developed generation of control electronics for diode lasers, modern concepts such as intuitive multi-touch operation or computer-supported remote control are conquering laser laboratories worldwide. Simultaneously, the reduction of laser noise and drift has reached new records.

Over the last years, narrow-band tunable diode lasers have exerted a strong influence, especially in the field of cold atoms and ions. In quantum-information technology or high-precision spectroscopy, for example, diode lasers are an essential tool for investigating the internal structure of atoms and the exact determination of fundamental constants. In another important field, optical atomic clocks enable time measurements with higher precision compared to the conventional cesium standard, due to the higher frequency of the involved narrow linewidth clock transitions [1].

The first diode lasers were developed after semiconductor laser diodes became commercially available in the late 1970s. Today, external-cavity diode lasers (ECDLs) offer wavelengths from deep UV to mid-IR (external cavity quantum cascade lasers) with narrow linewidths and wide tuning ranges. The wavelengths are generated either directly from the semiconductor or through efficient non-linear frequency conversion.

Within the last few years, external-cavity diode lasers have seen a tremendous improvement. Since its introduction in 2007, the DL pro has lead the field of tunable diode lasers, thanks to its optimized opto-mechanical setup which provides the highest stability against vibrations and temperature changes.

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Fig. 1 The new digital laser controller DLC pro combines interactive touch-screen operation with excellent noise characteristics.

Laser control at your fingertips

With a new generation of electronic control systems, the outstanding opto-mechanical properties of the DL pro are now complemented by a modern, digital control concept that also offers improved noise levels. The new laser driver DLC pro (**Fig. 1**) combines a modern look and feel with additional degrees of freedom from the digital world (e. g., computer and network compatibility, storage of important system parameters, an easy integration into digital experiment controls; and new features or configurations can be realized with software- and firmware-updates and do not require redesign or even soldering). The DLC pro includes current and temperature regulators for the laser diode, and a piezo driver for the ECDL grating. A main unit enclosing processor and FPGAs, generates scan signals for mode-hop free tuning and lock-in modulation of the laser frequency. Furthermore, the main unit processes input signals from external devices.

In addition to traditional tactile buttons for "blind" operation, the DLC pro also offers a capacitive multi-touch screen and the possibility of remote computer-control. The DLC pro is also capable of directly displaying signals from the experiment, alleviating the need for additional external oscilloscopes. All relevant laser parameters such as diode current, scan amplitude and scan offset, can be changed by simple and intuitive touch gestures.

Feedback processing from the experiment is particularly easy. For example, a spectroscopic signal can be displayed directly on the touch screen, and the laser frequency can be set to any feature of interest with just the touch of a finger. Fast analog outputs (16-bit resolution, 200 kHz bandwidth) and analog inputs (24-bit, 200 kHz) guarantee a smooth communication between the electronics, the laser and the experiment. (High-resolution AD and DA converters facilitate the precise digitization of photo diode signals and other control and error signals from the application as well as the

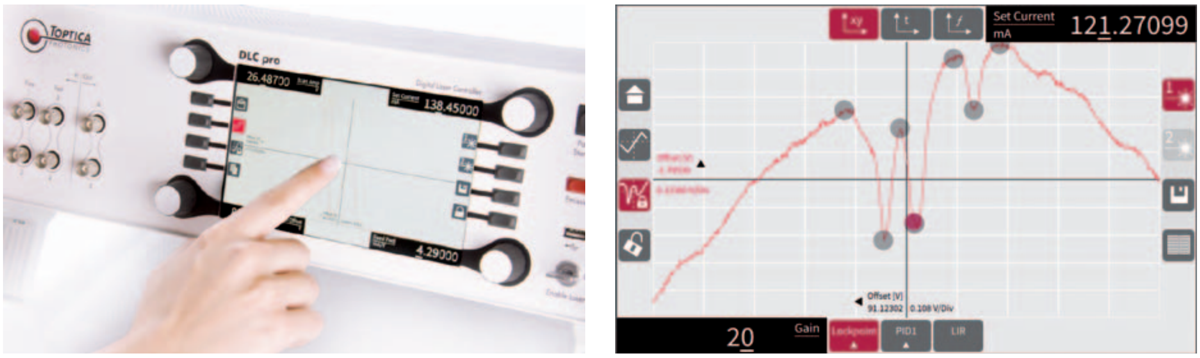

Fig. 2 The touch-screen of the DLC pro displays measurement data and facilitates the interactive adjustment of scan offset, scan amplitude or locking parameters (left). With a simple click, automatically-detected lock points (right, indicated by circles in the spectrum) can be addressed and the laser is stabilized to the selected feature.

exact output of analog signals for laser current and piezo voltage.)

The new operating philosophy revolutionizes the most common application: the active stabilization of the laser frequency to a spectroscopic signal. To this end, the DLC pro is equipped with a digital lock-in amplifier (up to 30 kHz modulation frequency) and two digital proportional-integral regulators. These are operated via the touch monitor or via remote control from the computer. The control electronics automatically detects appropriate lock points (either side-of-fringe or top-of-fringe features, depending on the pre-selection) that are highlighted by circles in the spectrum (**Fig. 2**, right). Touching one of these features on the display (or via mouse click in the supplied PC software) activates the frequency stabilization of the laser. The scan is automatically terminated, and the laser frequency is actively stabilized to the selected spectral feature.

The consistent digital concept also allows remote operation of the laser. A graphical computer software communicates with the electronics via a built-in USB or Ethernet interface. Thus, the laser can be easily tuned or locked even if the actual experiment takes place thousands of kilometers away.

Improved technical properties

The step into the "digital world" not only offers convenient laser handling, but also improves the laser's noise and stability properties, compared to all previously available commercial systems.

The integrated current driver delivers currents up to 500 mA with a maximum resolution of 16 nA (24 bits) and a modulation bandwidth of 30 kHz. **Fig. 3a** shows the current noise density of the new current driver compared with the second-best, analog 500 mA driver. (At low frequencies as well as at 50 Hz and multiples, the measuring equipment sets the limit.) The new digital driver exhibits lower noise levels throughout the entire frequency range. Potential digital artifacts are below the detection limit. The current-noise density amounts to only 280 pA/√Hz @ 1 kHz, and the low-frequency current-noise amplitude is less than 50 nA peak-to-peak in the range from 0.1 to 10 Hz. Equally important for the fine-tuning and frequency stability of an ECDL is the quality of the piezo controller. The integrated piezo driver has a smallest step size of < 10 μV (24 bits) and a voltage-noise density of less than 150 nV/√Hz @1 kHz. Due to these improvements, users can now take full advantage of the DL pro's opto-mechanical qualities. **Fig. 3b** illustrates the frequency-noise density of a DL pro with the new control electronics.

The reduced frequency noise results in a narrower linewidth (**Fig. 4a**). For measuring the line-

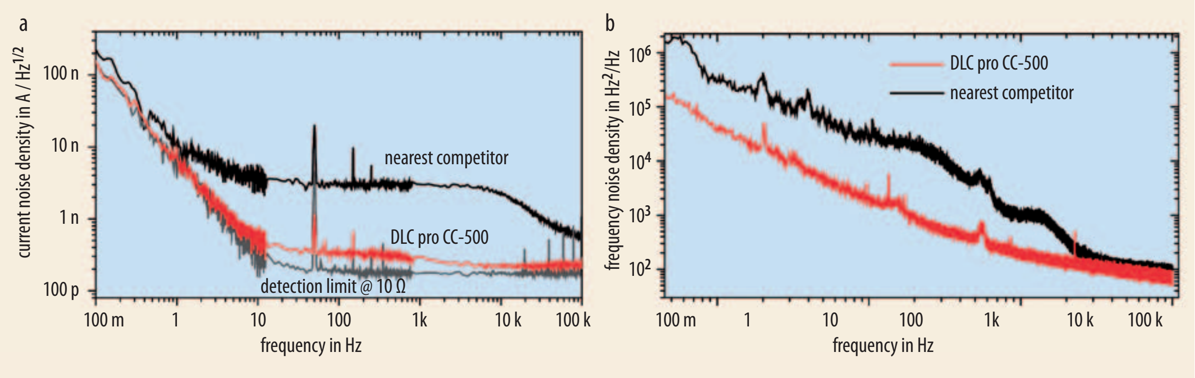

Fig. 3 Current-noise density of the new digital laser driver compared to analog control electronics (a). Throughout the entire frequency range, the new electronics (red) exhibit lower noise levels than previous devices (black). Laser frequency-noise spectrum [2] of a DL pro with digital and analog driver electronics in comparison (b). Improved current and voltage-noise values of current and piezo driver lead to a significantly reduced frequency noise.

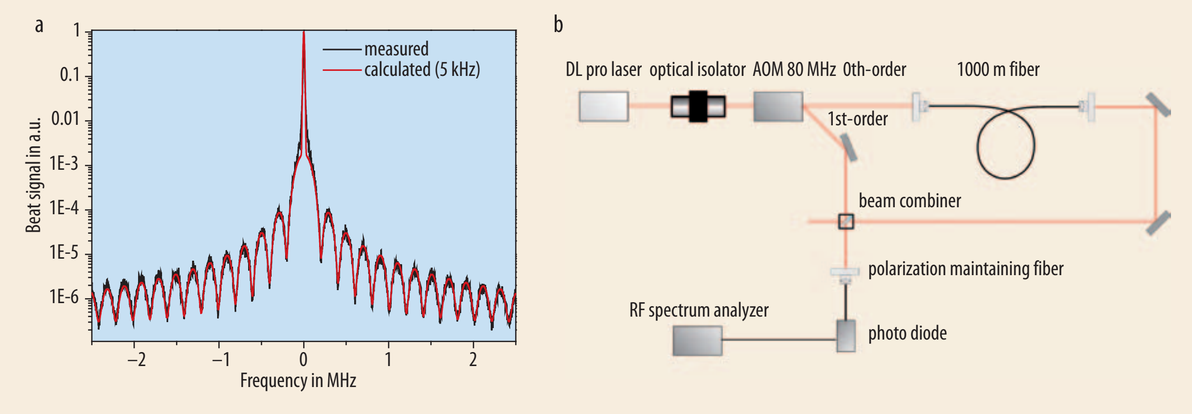

Fig. 4 The linewidth of an unstabilized DL pro laser at 1200 nm goes down to 5 kHz with the new digital electronics (a, black) in a delayed self-heterodyne linewidth measurement with a 1 km fiber delay (b). The setup assesses the laser linewidth on a time scale of 5 µs.

width of the free-running laser, a delayed self-heterodyne setup [3] was employed: the laser beam was split by an acousto-optical modulator (AOM), which shifted the frequency of the first-order diffracted beam by 80 MHz. The zero-order beam propagated through a glass fiber of 1 km length and underwent a delay of 5 µs. The two beams were recombined and the beat signal was measured with a fast photo diode connected to an RF spectrum analyzer (**Fig. 4b**). Since the coherence length of the laser exceeded the fiber length, the line shape of the beat signal showed a delta peak with side fringes, rather than a single Lorentzian peak. With proper fit algorithms, the linewidth can be calculated nonetheless [4]. In the example of **Fig. 4**, the new electronics reduced the short-term linewidth of a DL pro down to 5 kHz.

No less important than the fast linewidth is the long-term stability of the laser. This stability is influenced by slow drifts of the temperature, piezo and current drivers which can result from ambient temperature changes. The new digital electronics shows impressively low drift values of < 140 ppm/K (temperature), < 40 ppm/K (piezo voltage) and < 3 ppm/K (current). **Fig. 5** depicts the stability of the laser temperature with the electronics exposed to thermal cycling in a climate chamber.

As an ultimate test of the digital control electronics, a beat measurement of two independent, free-running DL pro lasers at 1160 nm was recorded (**Fig. 6**). Given that both lasers are identical, the beat linewidth equals two times the individual laser linewidth. A 2.5 s sweep revealed a laser linewidth of less than 20 kHz. The frequency difference of both lasers varied by only 350 kHz peak-peak per laser over more than 5 minutes.

Summary and outlook: Applications

In addition to convenient and intuitive operation in the lab, the new digital electronics lends itself to remote usage (e.g., from remote computers in a control center). In connection with the excellent long-term stability, this enables high-precision laser applications in hard-to-reach places. One example is a LIDAR (Light Detection and Ranging) measurement of the temperature profiles and composition of different atmospheric layers in the Arctic [5]. For this purpose, narrow-band ECDLs are frequency-locked to Fabry-Perot interferometers or atomic transitions and serve as seed lasers for pulsed amplifiers. With the new digital electronics, the seed laser can be operated from around the world.

Other fields that will benefit from the outstanding characteris-

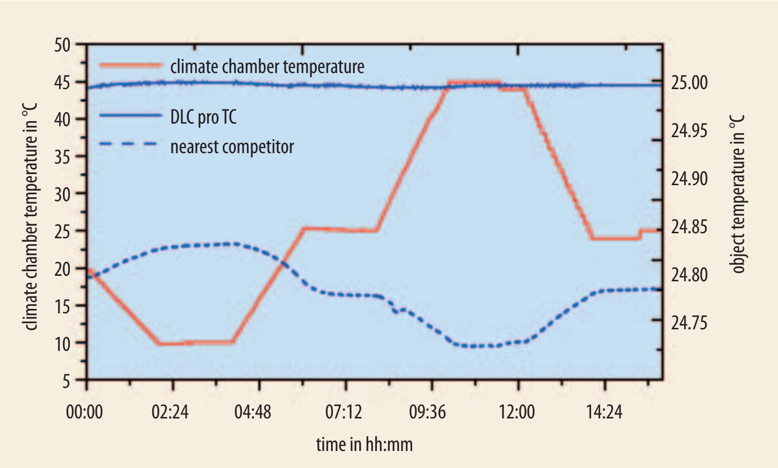

Fig. 5 Temperature (right y-axis), measured at the laser resonator (outside of the climate chamber), while the control electronics was exposed to temperature changes from 10 °C to 45 °C (red, left y-axis) in the climate chamber. The comparative analog electronics (blue broken line) achieves a stability of < 0.1 K peak-peak. The digital control electronics (blue solid line, DLC pro) outperforms its analog counterpart by a factor of 20.

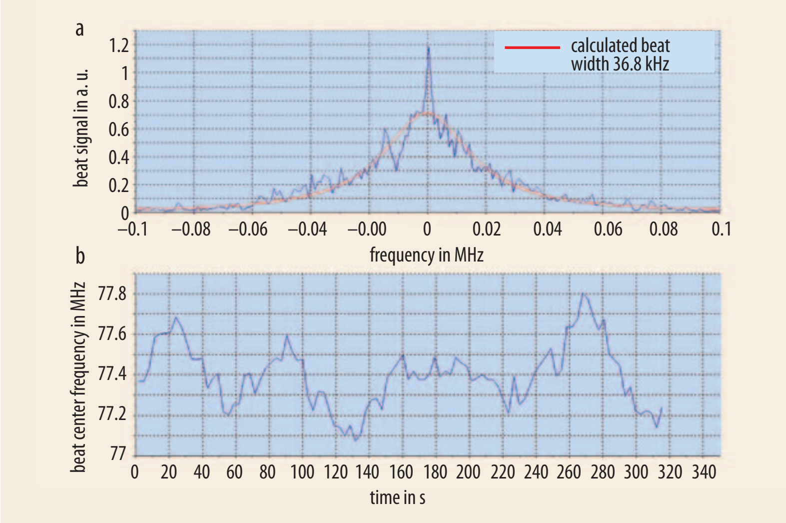

Fig. 6 Beat frequency measurement of two free-running DL pro lasers at 1160 nm with new digital control electronics (a) and variation of the frequency difference over time (b).

tics of the new digital electronics are setups with more than just one laser. The more lasers an experiment uses, the more important the performance and stability of each individual source. In applications such as optical atomic clocks [6], lasers are required to function reliably over long periods, with linewidths in the single-Hertz or even sub-Hertz range. The new low-noise electronics facilitate the stabilization of these lasers while the low drifts enable a best-in-class long-term stability.

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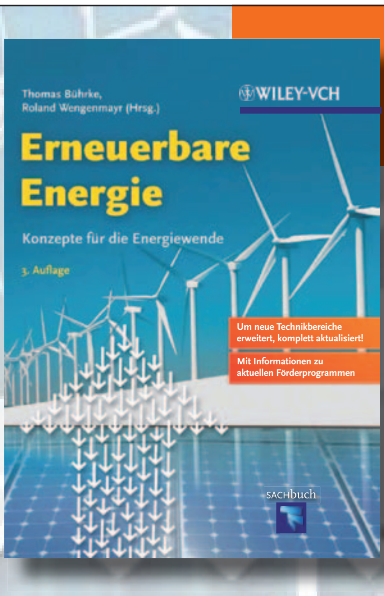

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