Demand-tailored laser systems

Integrated multi-color laser solutions for quantum optics and biophotonics.

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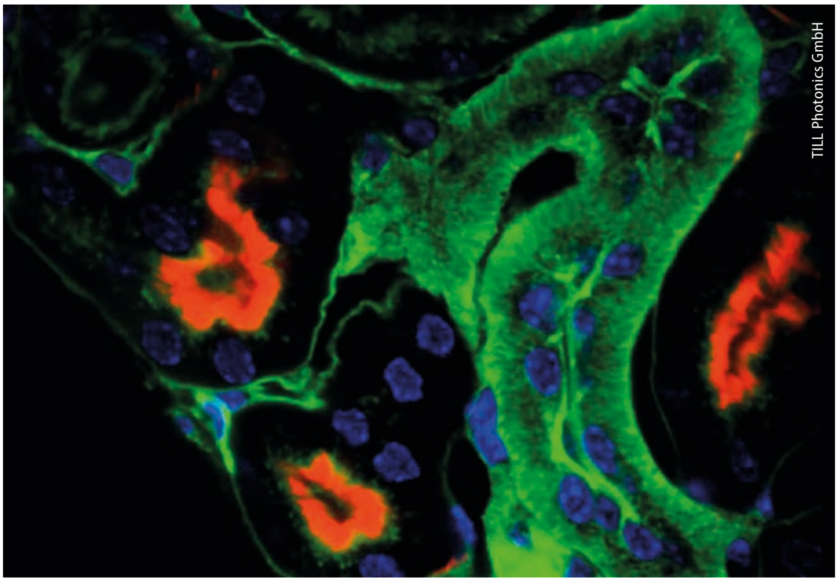
Ongoing development of laser systems not only serves to improve physical parameters of the laser light. Parameters as polarization stability, power stability or linewidth are important, but there are also soft factors, such as increased robustness, extended service life, and ease of use which can make a difference. These soft factors often open up new applications for lasers and devices integrating lasers. The step from an experiment in the laboratory to a standard use of a new concept in everyday life requires reliable and durable laser systems which are easy to integrate.

Many scientific experiments require several wavelengths. For example, in experiments with laser-cooled atoms or ions, resonant laser fields are used in addition to the cooling lasers for ionization, for optical traps, for re-pumping, for controlled driving and adjustment of quantum states and many more. The resonance condition results in a need for different, high-precision laser wavelengths. Biological and chemical experiments incorporate multiple laser wavelengths in many of their measurement techniques as well. In medicine and basic cell biological research, laser-based flow cytometers are standard tools for examining and quantitatively evaluating blood samples. In flow cytometers various laser wavelengths are used to activate different marker fluorophores. Fluorescence microscopy, another typical field of application in biological research, benefits from the multitude of fluorophores and fluorescent proteins made accessible by the available laser wavelengths.



Spinning disk confocal recording of a mouse kidney section: cytoskeleton (Alexa 568 fluorophore excited at 561 nm), DNA/cell nucleus (DAPI fluorophore excited at 405 nm), and endosomes (Alexa 488 fluorophore excited at 488 nm).

TOPTICA has over 20 years of experience in the development, manufacture and installation of laser systems. This expertise has successfully driven the development of highly integrated multi-color laser solutions. This innovation relieves customers of the time consuming task of setting up and maintaining their own beam guiding systems.

This article presents two systems that provide laser light from modules via fiber optics. The different user requirements for the laser light led to the development of two completely different product approaches: first, a 19-inch sub-rack with tunable diode lasers (DLC MDL pro, MDL = Multi Diode Laser System), to be used and integrated in many quantum optics experiments and, second, a highly integrated laser light source for biophotonics and microscopy (iChrome CLE, CLE = Compact Laser Engine).

Fig. 1 DLC MDL pro with four laser modules mounted in a 19-inch rack

DLC MDL pro

The availability of laser diodes at relevant wavelengths has strongly influ-

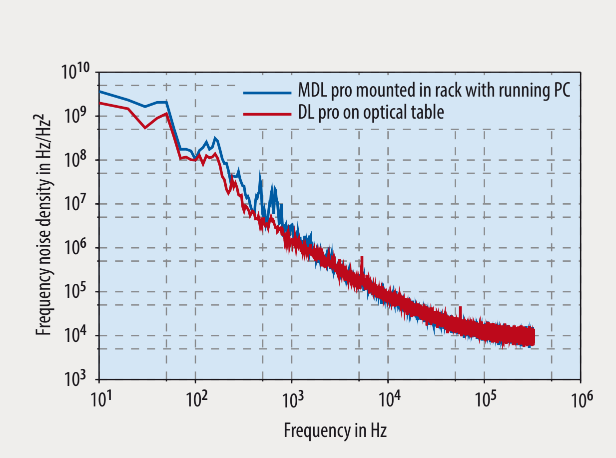


Fig. 2 Comparison of frequency noise density: a DLC MDL pro installed in a rack along with an air-cooled computer compared to a DL pro mounted on an optical table. The increased noise is at low frequencies so that feedback for correcting these requires only little effort.

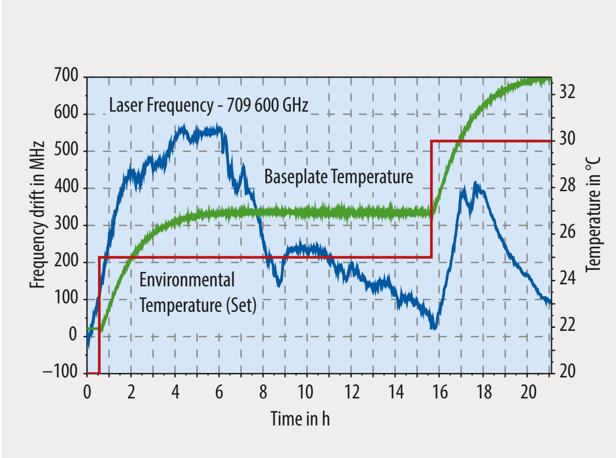


Fig. 3 Frequency of a DLC MDL pro laser at 423 nm exposed to two temperature steps of 5 °C. The measured frequency drift of 550 MHz is significantly lower than the mode-hop-free tuning range of 30 GHz. Even under these conditions, active feedback will keep the laser on resonance.

enced quantum optics over the past twenty years. Diode lasers transform these laser diodes into spectroscopic tools by means of an optical grating. They are omnipresent, e. g., in laser cooling of atoms and ions. Often there are several diode lasers in use and many optical tables lose a significant amount of space due to the setup of the lasers alone. The increasing complexity of optical laboratory setups led to an interest in relocating these lasers to less precious areas, i. e., away from the optical tables. In addition, it is increasingly the goal of quantum optical experiments to build transportable measuring instruments. Technologically, diode lasers are so advanced (due to patented mechanical structures of the laser resonators and improved control and monitoring electronics) that an optical table is no longer necessary for the operation of diode lasers.

The DLC MDL pro was developed based on these requirements and possibilities (**Fig. 1**). Four diode lasers can be mounted in a 19-inch sub-rack: Just two height units allow for operating any combination of up to four External-Cavity Diode Lasers (ECDL, known as DL pro) or DFB (DFB = distributed feedback) or DBR (DBR = distributed Bragg reflector) lasers. For each individual laser, there is a single mode optical fiber that either directs the light to an optical table –which is now free of lasers – or feeds it directly into an experiment that has been set up as a transportable system. Thus, the system maintains flexibility regarding wavelength selection to reflect the variety of quantum optics experiments as well as the requirements regarding laser linewidths (MHz or lower) and tuneability (e. g., needed to stabilize the laser frequency).

The performance of these ECDLs, now being ready for integration into standard rack systems, is shown in the frequency noise spectrum of a laser on an optical table compared to that of a laser of a DLC MDL pro (**Fig. 2**) and in climatic chamber tests of the new rack-mounted lasers (**Fig. 3**). Even with temperature variations of 10 degrees, the lasers are still a quantum-optical tool of the very highest quality. These extreme conditions do not cause mode hops which would lead to a sudden, strong change of the laser wavelength. Here, the advantages of the modern, digital laser control electronics DLC pro impress again. It was introduced five years ago. E. g., using the TOPTICA Python Laser SDK, it enables remote control via network.[1)]

Different customer requests

The product design of the DLC MDL pro takes flexibility to select different wavelengths and their tuneability into account. In the field of microscopy, some standard wavelengths are already established. On the basis of these standard wavelength, it was possible

Fig. 4 iChrome CLE, standard configuration 405, 488, 561, 640 nm with 20 mW per wavelength delivered via a single-mode fiber optic

1) www.toptica.com/laser-sdk

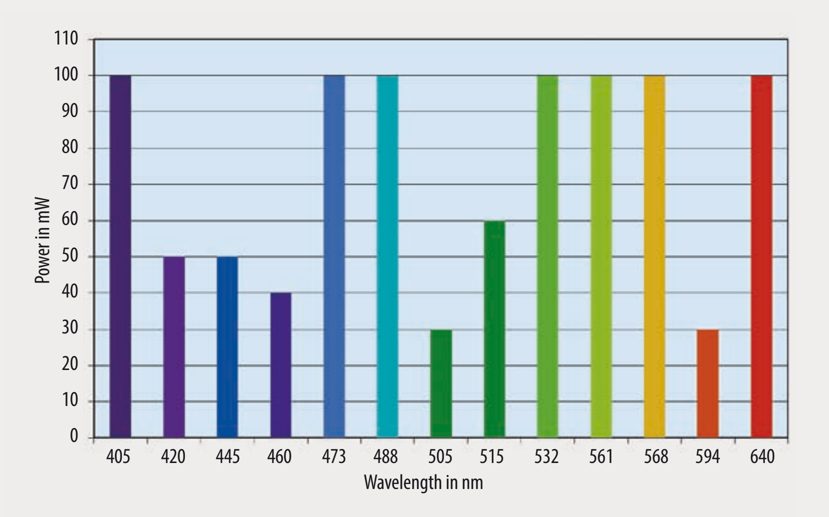


Fig. 5 Wavelength and power selection for the iChrome xLE family, including the iChrome CLE and the more flexible iChrome MLE.

to develop the iChrome CLE, a standard module which covers the basic needs in large parts of the biophotonics field. This standardization allows the product design to be even more compact and robust. As a second result of standardization, the production processes can be optimized and streamlined in order to offer the highest quality at attractive conditions.

iChrome CLE

The iChrome CLE multi-color laser source is a dedicated device for microscopy and biophotonics (**Fig. 4**). Similar to the DLC MDL pro, the areas of application can be found in the scientific area but the field of microscopy is already more "industrialized", i. e., a few large companies currently serve the majority of the scientific microscopy customer market. This leads to a higher level of competition. An adequate laser light source for this market must therefore meet both the financial and the critical technical specifications. The iChrome CLE utilizes new technology, to achieve the contradictory requirements of price, stability, durability and outstanding modulation.

The constantly increasing scanning and imaging speeds in laser-based microscopy require laser sources that can be modulated quickly. On the other hand, the acousto-optical modulators (AOM or AOTF = acousto optic tunable filter) used for modulation so far are quite expensive. The elimination of these components is therefore accompanied by a welcomed price reduction. For the typically required "standard" wavelengths of 405, 488, 561, and 640 nm, however, the problem arises that 561 nm cannot be covered by a standard laser diode. Laser diodes are inherently easy to modulate. However, the DPSS (Diode Pumped Solid State) or OPS (Optically Pumped Semiconductor) lasers used at 561 nm can only be modulated to a very limited speed. For these laser sources, an external modulator was still necessary. TOPTICA has developed the so-called FDDL (Frequency Doubled Diode Laser) as a solution which has been specially optimized for the scanning parameters important for microscopy, i. e., low overshoot, and undershoot in combination with low intensity noise.

This approach based on the frequency doubling of 1122 nm laser light also results in an advantage for the lifetime of the 561 nm laser line since an FDDL only emits light when required by the application. On the other hand, standard laser sources combined with an AOM/AOTF must emit light permanently which is then switched "on and off" by the modulator. This results in very long operating times for these laser lines which lead to premature "burnout" or failure of the laser line.

In microscopy, the fiber coupling of illumination lasers has established itself as the standard. The advantages for the application are obvious: On the one hand, a standardized interface is available with the fiber connector (typically FC/APC or FC/AFC). On the other hand, the single-mode fibers in use offer an almost perfect beam quality which is required for many applications ($M^2 < 1.1$). For the laser manufacturer, fiber coupling in single-mode fibers with core diameters of approximately 4 µm (in the visible

Product lines in comparison

	DLC MDL pro	iChrome CLE
Typical applications	Quantum optics: Laser cooling of ions and atoms	Biophotonics and microscopy
Wavelengths	Configurable, up to four wavelengths from 369 nm to 1625 nm	405, 488, 561, and 640 nm
Linewidth / Coherence length	Typ. 100 kHz / approx. 1 km	~0,5 nm / < 1 mm
Tuneability	Coarse tuning 2 to 100 nm, fine tuning typ. 30 GHz	Pre-defined wavelengths
Light delivery	Each laser module via SM/PM fiber with FC/APC connector	One single broadband SM/PM fiber for all wavelengths
Control electronics	Digital Diode Laser Controller DLC pro	Dedicated, fully integrated electronics
Method of operation	Touch screen or Ethernet-connection: PC-GUI, TOPTICA Python Laser-SDK, computer commands	RS-232, Ethernet or analog and digital inputs, PC-GUI
Mechanical design	19-inch sub-racks 2 HE with 1 or 2 DLC pro à 3 HE	248 x 201 x 110 mm^3 (L x W x H)
Superhero-skills	Frequency locks	COOL^{AC}

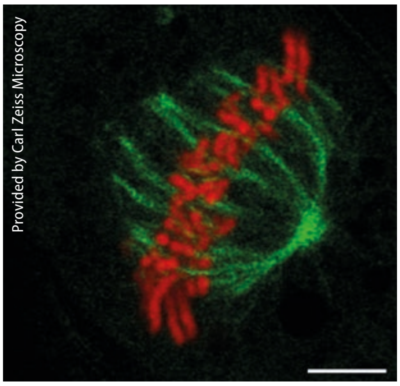


Fig. 6 Kidney cell imaged with an Airyscan confocal microscope (with 488 and 561 nm)

wavelength range) represents an additional challenge.

The requirement is therefore to create a fiber-coupled laser light source for an "industry-like" application. In order to achieve adequate stability, the complete laser-head unit was deliberately kept very compact. In addition to the stability provided by the compact design, this laser-head unit is temperature-stabilized as a whole to ensure the greatest possible stability even changing ambient conditions. This approach prevents or minimizes the effects of thermal expansion and, thus, leads to a truly long-term stable, fiber-coupled system.

An additional requirement to the passive stability during operation is to avoid the alignment after transport or during installation of the device at the customer site. To fulfill this requirement, the iChrome CLE is equipped with an automatic fiber coupling. The system called COOLAC (Constant Optical Output Level – Auto Calibration) can realign each individual laser line automatically via a simple command. This unique feature enables integration, installation and operation of the multi-color laser without any user intervention and renders the entire device series into true "hands off" systems.

Conclusion

The development of the two product lines DLC MDL pro and iChrome CLE illustrates how specific requirements of different user groups influence product design (**Table**). While the DLC MDL pro focuses on the flexibility of the wavelength configuration, a standard configuration is suitable for the iChrome CLE which allows a broader scientific use due to a very attractive price. Constant market observation and determination for our customers' needs will continue to influence and drive future development of our products.

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