Mode-Hop-Free Quantum Explorations

Continuously tunable diode lasers explore the micro, nano and quantum world.

Rudolf Neuhaus and Tim Paasch-Colberg

The continuously tunable laser CTL enables mode-hop-free wavelength tuning up to 100 nm with narrow linewidth and highest accuracy. It will improve measurements on small structures and in the quantum regime that rely on mode-hop-free laser operation.

Continuously tunable, single frequency lasers are now available with ultrawide mode-hop-free tuning, unprecedented low noise levels, as well as convenient digital control electronics. Active control with the new digital electronics is a key element that enables such wide mode-hop-free tuning and hands-off operation. The new lasers facilitate sophisticated measurements on the quantum level, reaching from observation and manipulation of quantum oscillations in microcavities or detecting single molecules in solution towards QED studies with single quantum dots. Other important applications are optical component testing and molecular spectroscopy.

Quantum dots as well as microcavities have become increasingly important for numerous applications, for example single photon sources, qubits for quantum computers, telecommunication devices, frequency combs or nonlinear optics. Many of these applications approach quantum limits and depend on light sources that fulfill demanding requirements in terms of linewidth, noise, high resolution tuning, flexibility and control. Usually, narrow-bandwidth lasers that are tunable without mode-hopping are utilized to detect, study and use resonance frequencies of quantum dots and microcavities.

Obviously, spectroscopic applications are limited when the mode-hop-free tuning range of the laser is smaller than the spectral width of the studied feature(s). Patching numerous independent narrow mode-hop-free scans is tedious and involves the risk of missing important details. Only wide and mode-hop-free tuning safely enables applications that study individual broad spectral features, or several lines that are widely separated. Searching for resonance frequencies over a large wavelength range and following lines when they shift without unpredictable mode-hopping is possible only with such tunable lasers.

Fig. 1 The widely tunable laser CTL enables mode-hop-free wavelength tuning of 100 nm with a narrow linewidth and supreme accuracy. Operated with the digital controller DLC pro it provides high flexibility, low noise and drift values, as well as fantastic convenience.

In general, mode-hopping can be caused by unsteady external conditions or instable laser parameters. For example, a temperature variation of the gain medium shifts the wavelength of highest gain, whereas the frequencies of the resonator modes are not affected in exactly the same manner. Therefore the previous lasing mode may no longer be the mode of highest gain and the system may start lasing at another mode. Likewise, a drift of the resonator length shifts its frequency modes and causes mode-hopping if the change is not compensated in the gain medium. Additionally, other influences like moving or vibrating optical elements can disturb the smooth single-mode operation.

As a consequence, a sophisticated laser design is required to prevent mode-hopping of single-frequency lasers. Mode-hop-free tuning of a few tens of nanometers can be achieved using a good mechanical and well isolated laser setup, i. e. perfect synchronization of tuning elements, in combination with low drift and noise of the diode current. For guaranteeing even wider tuning, TOPTICA has integrated active control into their

Dr. Rudolf Neuhaus and **Dr. Tim Paasch-Colberg**, TOPTICA Photonics AG, Lochhamer Schlag 19, 82166 Gräfelfing

CTLs (**Fig. 1**). It enables mode-hop-free scans of more than 100 nm across the full gain spectrum of the integrated laser diode.

Active Stabilization

The active control in TOPTICA's CTL is called SMILE (Single Mode Intelligent Loop Engine). It ensures mode-hop-free operation by analyzing signals in the laser head and synchronizing the involved tuning elements by active feedback while the laser is running – even during wavelength scans (**Fig. 2a**).

The wavelength can be tuned in several ways: Motorized coarse tuning with a step size of approx. 1 pm and a speed of up to 10 nm/s, as well as piezo-based fine tuning. The piezo can scan the wavelength across more than 30 motor steps with an extremely high resolution of less than 5 – 10 kHz. In addition, extremely fast wavelength changes and therefore fast laser stabilization are enabled by controlling the laser diode current.

The CTL is now available with two specified wavelength ranges: 915 nm to 985 nm or 1530 nm to 1620 nm with up to 80 mW output power. Other wavelengths will follow soon. Despite the incredibly large tuning range, the CTL has a notably narrow linewidth, which has been measured to be ~5 kHz on short timescales (5 µs) in a self-heterodyne beat measurement (**Fig. 2c**) and ~100 kHz in a beat experiment with two individual identical lasers and a sweep time of 50 ms. The narrow linewidth and low drift values make it ideal for measurements involving quantum dots or microcavities.

Light for Quantum Measurements

Quantum properties are usually not observable in macroscopic objects due to environmental decoherence unless specific sample geometries and cooling are utilized. Employing microcavities, for example, is one possibility to observe quantum effects in a relatively large, micrometer-scaled structure. **Fig. 3a** illustrates an isolated, donut-shaped glass microcavity of about 30 microns in diameter. With this geometry, it is a macroscopic mechanical oscillator and a ring-shaped high Q optical cavity at the same time: light of certain wavelengths can be coupled into the cavity via evanescent wave coupling. The oscillating light bounces off the walls of the donut by total internal reflection and thus transfers a small force on the structure by radiation pressure.

In this way, the coupled light can influence the vibrational behavior of the structure and vice versa. This turns microcavities into interesting objects for quantum research. For example, in [1] such parametric coupling between light and mechanical oscillations was observed. In [2] a sensor that is based on opto-mechanical coupling was used for active feedback cooling of such a microcavity.

Because of their small size, the free spectral range of microcavities is relatively large, and tiny size deviations cause large spectral shifts. Hence, a widely mode-hop-free tunable laser is an invaluable tool to find and study the resonance frequencies of microcavities.

The spectral dependence on size and other environmental parameters of microcavities can be exploited for a promising application: label-free detection of single biological molecules in solution. This is enabled using a microtoroid optical resonator in combination with a widely tunable mode-hop-free laser like CTL. In [3] it is described how such a laser is stabilized to a microtoroid optical resonator and how shifts of the optical resonance frequency caused by molecules binding to the resonator are observed. The laser follows the frequency change and by examining the shift in laser frequency, particles of radius between 2 nm and 100 nm can be detected and distinguished.

This application can strongly benefit from DLC pro's optional locking functions: Feeding a signal from the experiment back into the controller, the scanning of the laser across a cavity resonance can be optimized by simple pinch, swipe and spread gestures on the touch display. After selecting a cavity resonance frequency on the display, the laser can then easily be stabilized to this resonance by the push of a button. The results were further extended towards creating a non-invasive tumor biopsy assay, and

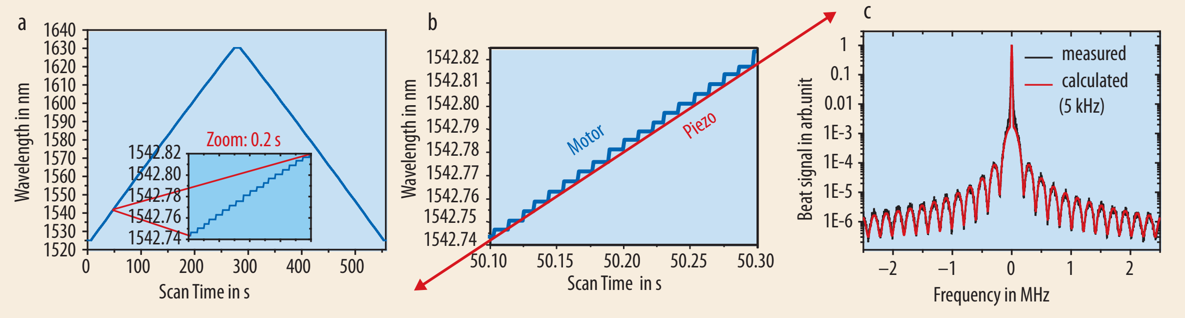
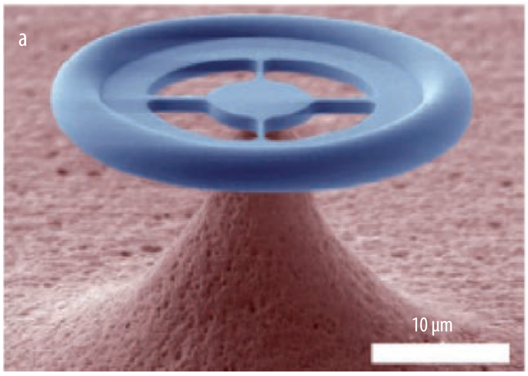


Fig. 2 a) Mode-hop-free wavelength tuning over 100 nm is enabled with the active SMILE stabilization of the CTL 1550. b) Motorized wavelength tuning can be performed with step sizes of approx. 1 pm, higher accuracy is achieved by a piezo driver. c) A self-heterodyne beat measurement with the CTL 950 using a fiber of 1 km length (according to 5 µs delay) reveals a linewidth of approximately 5 kHz. The linewidth is determined by reproducing the interference pattern of the beat measurement with a parameterized model.



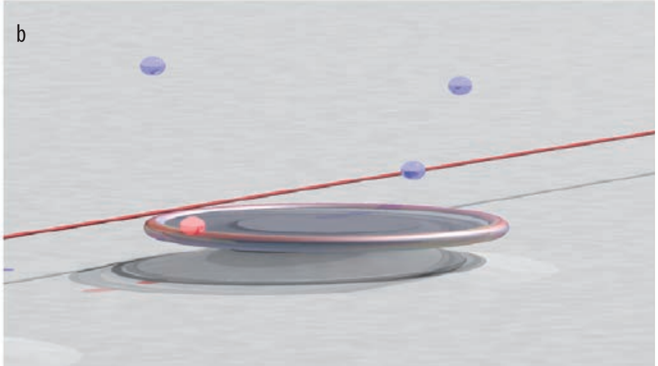


Fig. 3 a) Electron microscopy image of a microcavity that was used to demonstrate parametric coupling between light and this mechanical oscillator [1]. b) Microtoroid optical resonator for detecting molecules in solution. By stabilizing a widely mode-hop-free tunable laser to the resonator, molecules binding to the resonator can be detected by analyzing shifts of its optical resonance frequency [3].

provide a basis for an "optical mass spectrometer" in solution.

Coupled Double Quantum Dot

Semiconductor quantum dots are exciting nanostructures that show atom-like behavior because of their small size and three-dimensional confinement. Due to the confinement, electronic states in quantum dots are quantized and such structures are often referred to as artificial atoms. Atom-like properties have been verified by demonstrating strong photon antibunching and near lifetime-limited linewidths. Quantum dots in general are interesting systems to realize qubits, and especially semiconductor quantum dots are promising candidates for scalable quantum computers since semiconductor processing is well studied and understood: Unlike real atoms, semiconductor quantum dots can be grown and placed in a controlled fashion. By integrating quantum dots into other semiconductor structures like waveguides or photonic crystal structures (e. g. cavities), even cavity QED experiments are possible without the need for trapping atoms.

En route to scalable qubit arrays, coupled quantum dots have recently raised a lot of interest. Electron transport measurements on coupled quantum dots have demonstrated spin-sensitive coupling and manipulation of electron and nuclear spins, and optical spectra of coupled excitons have been measured and calculated in self-assembled coupled quantum dots.

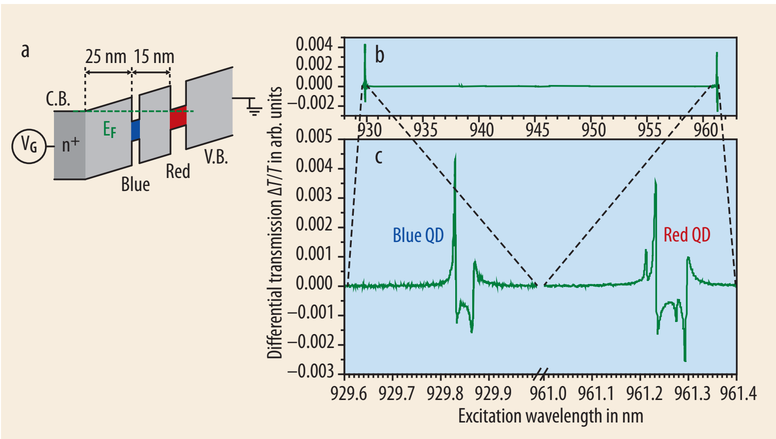


Fig. 4 a) Schematic band-edge diagram of a coupled double quantum dot. The wavelength-dependent differential transmission signal $\Delta T/T$ of such a system is shown in b). It was recorded by a single mode-hop-free scan over a wavelength-range of more than 30 nm. c) shows a zoom into the resonances of both quantum dots.

Resonant optical excitation of quantum dot states is crucial in particular for coherent state manipulation and detection. However, due to the intrinsically random growth process, all quantum dots are slightly different in size and hence feature different optical resonance frequencies. To find and resonantly excite the optical transitions of a single quantum dot, a widely mode-hop-free tunable, narrow band laser is an ideal tool.

A first series of quantum dot measurements with CTL was carried out at ETH Zürich [4]. A single GaAs quantum dot was resonantly excited using a DLC CTL 950 and its resonance fluorescence signal was detected. By changing the gate voltage, the quantum dot was charged with a single electron and transferred from the neutral state to a negatively charged state. This change resulted in a spectral shift of the excitonic transition. The new resonance frequency could be easily found by tuning the laser mode-hop-free by approximately 4 nm.

In another experiment, the differential transmission of both quantum dots in a coupled double quantum dot system was measured. In this structure, two quantum dots are grown on top of each other (**Fig. 4a**). Both quantum dots can be brought into resonance by changing their common gate voltage which is a means to control their coupling strength. The variable coupling strength makes these double quantum dots interesting for qubits and quantum computing applications.

Their optical resonances differ by several tens of nanometers (approximately 10 THz).

The differential transmission signal $\Delta T/T$ of the double quantum dot system for one common gate voltage is shown in **Fig. 4b**: The resonance frequencies of both quantum dots are more than 30 nm apart. The presented spectrum was achieved in one single mode-hop-free scan across the resonance frequencies of both quantum dots. Because such wide scans are tedious without a mode-hop-free laser, the blue quantum dot was not studied with this type of measurement before.

Improved Light Sources

These examples show how well quantum dot and microcavity properties can be studied with powerful optical tools like the CTL. Further investigations with even more sophisticated structures of different geometry, size and material are necessary to reveal deeper insight into the interaction between light and matter on the quantum level. These experiments require reliable light sources and will benefit from the unique stability, accuracy, narrow linewidth and mode-hop-free tuning range that is provided by the widely tunable laser CTL.

CTL's versatile digital controller DLC pro enables easy access to all relevant laser parameters via touchscreen and additional knobs. Since the controller is digital, it ensures highest flexibility and future compatibility, as well as lowest noise and drift values. Intelligent features like SMILE and FLOW (see below) are enabled with the DLC pro only. Furthermore, remote control of the laser is possible via USB or TCP/IP using a preconfigured PC GUI or a powerful command language.

In the unlikely event of a laser cavity misalignment, for example after mechanical shock or large temperature changes, the integrated FLOW (Feedback Light Optimization Wizard) of the CTL re-optimizes the cavity upon the push of a button. This re-establishes stable and mode-hop-free operation. Since this optimization can be performed "in the field", shipping of the laser system back to the manufacturer is not required.

The outstanding parameters of the CTL in combination with its highly convenient and elaborated digital controller DLC pro represent state-of-the-art laser technology – making it a great tool to explore the micro, nano and quantum world.

[1] *E. Verhagen* et al., Nature **482**,63 (2012)

[2] *D. J. Wilson* et al., arXiv:1410.6191v2 (2015)

[3] *Tsu-Te Judith Su*, Label-Free Detection of Single Biological Molecules Using Microtoroid Optical Resonators. Dissertation (Ph.D.), California Institute of Technology, USA (2014)

[4] Measurements carried out by Dr. *Martin Kroner* and *Yves Delley*, Quantum Photonics Group of Prof. Imamoglu, ETH Zürich.