12 Orders of Coherence Control

Tailoring the coherence length of diode lasers

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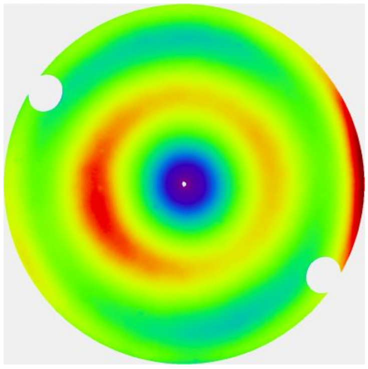
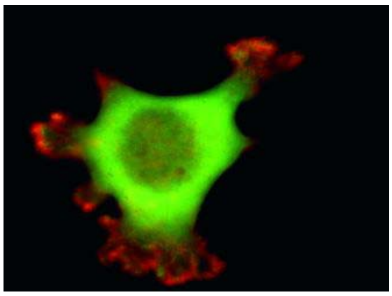
The control of the coherence properties of laser light is a major success factor in many photonic applications – in areas as diverse as spectroscopy and optical pumping of atoms, nonlinear frequency conversion, interferometry, or laser-based imaging. Established diode laser technology has however only covered individual points of the "coherence length spectrum". Recently developed electronic techniques for laser coherence control help to fill the remaining gaps, enabling a controlled manipulation of the linewidth and thus, coherence length of diode lasers – from the micron range to hundreds of thousands of kilometres.



Interferometry and holography demand long coherence lengths (wavefront image of a lens).

Linewidth and coherence

The term "coherence" is derived from the Latin verb cohaerere – to join together. A light wave is considered to be coherent if two joint parts of the wave exhibit interference. In laser physics, one distinguishes between two different aspects of coherence, namely temporal and spatial coherence. Spatial coherence denotes the distance between two points of the wave, over which they still interfere with one another. Spatial coherence governs focusability of the laser beam. Temporal coherence, on the other hand, describes the ability of a wave to interfere with a time-shifted copy of itself. The time during which the phase of the wave changes by a significant amount (reducing the interference) is referred to as *coherence time*. The propagation length during this time is called *coherence length*. In this report, "coherence" only refers to the temporal coherence properties.



Some laser imaging methods like confocal microscopy require a low spatial coherence, in order to avoid speckle patterns.

The larger the range of frequencies in any given wave, the faster the phase correlation is lost. In mathematical terms, linewidth and coherence length are linked via an inverse proportionality, with a numerical factor depending on the spectral profile of the laser. In case of a rectangular emission spectrum, the coherence length l_c is simply given by

$$l_c = c \,/\, \Delta\nu \,, \qquad (1)$$

with c = speed of light and $\Delta\nu$ = full width half maximum linewidth.

In the more realistic scenario of a Gaussian spectral distribution, the coherence length is

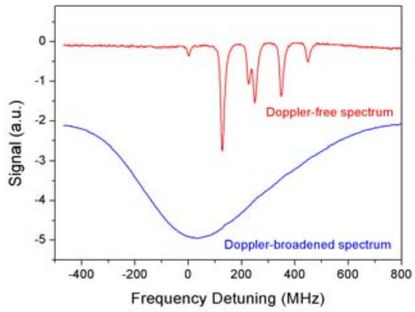
$$l_c = (2 \ln(2)\, c) / (\pi\, \Delta\nu) \,. \qquad (2)$$

In practical units, this translates into approx. 132 m / (linewidth in MHz). Note that eq. (2) is independent of the absolute wavelength.

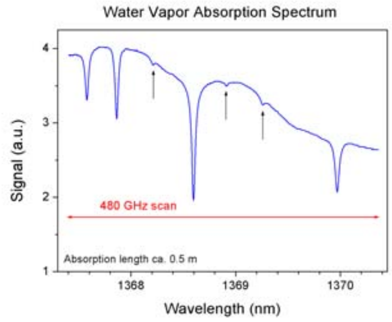
Consider for example the emission spectrum of a violet diode laser emitting at 405 nm. Without any frequency stabilization, the spectrum has a halfwidth of approximately 0.5 nm or 900 GHz. The coherence length is thus calculated to be around 150 µm, which is indeed observed.

If the diode laser is used in an external-cavity configuration, a diffraction grating narrows the diode's spectrum and the effect is dramatic: the typical linewidth is now 0.0005 pm or 1 MHz, and the coherence length is greater than 100 m. The grating effectively changes the coherence properties by almost six orders of magnitude.

Unfortunately, this simple trick cannot be adopted universally and the intermediate range has long been considered a gap in the coherence length spectrum of diode lasers. In particular, the realization of coherence lengths on the order of millimetres through to 50 m has been very difficult, much as it would have been desirable for a variety of applications. In this article, we will present technologies to close this gap and extend the coherence length spectrum to even longer – and shorter – values.

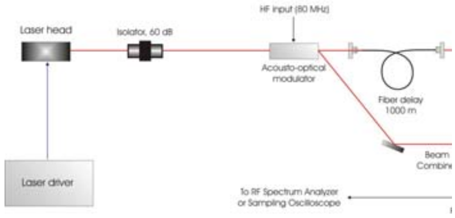


Doppler-broadened and Doppler-free atomic transition lines (Cesium, 852 nm). Doppler-free spectroscopy requires a laser linewidth in the 1 MHz range (coherence length > 100 m).



Molecular absorption lines have a typical width of 5 GHz (water vapor, 1368 nm).

Coherence length measurements



Delayed self-heterodyne linewidth measurement.

There is not a single universal technique to measure laser linewidths or coherence lengths. Different setups are employed for different linewidth regimes. One method that is particularly attractive for narrow laser lines (100 kHz .. 100 MHz) is a so-called delayed self-heterodyne measurement. Here, the output beam of the laser under scrutiny is split into two probe beams, one of which is frequency-shifted by an acousto-optical modulator and coupled into a fiber delay. Subsequently, the beams are re-combined and the beat signal is detected by a fast photo diode, the output of which is connected to an RF spectrum analyzer. Frequency fluctuations within the delay time contribute to the beat note, the width of which is approximately twice the laser's linewidth. Advantages of this method are short measurement times and easy implementation – neither moving parts nor laser stabilization means are required. At TOPTICA, we use two set-ups with single-mode fiber delays of 1 km and 20 km, respectively. This allows us to assess the linewidth on time scales of 5 µs and 100 µs.

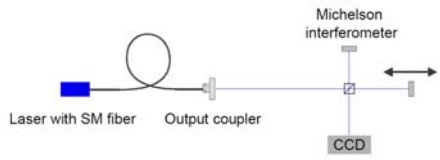
The method does not provide any information about the long-term linewidth. A second limitation is the requirement that the coherence length be shorter than the fiber delay. Measurements are still possible if this is demand is not met, but the interpretation of the beat signal becomes more difficult and requires intricate data post-processing routines.

Measurements on longer time scales, or of even narrower laser lineshapes (down to 1 Hz or less) are accomplished by detecting the beat signal of two identical lasers. This usually requires careful stabilization of the lasers' emission frequencies – an issue to which we will return later.

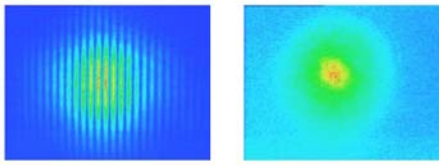
Scanning Fabry-Perot interferometer (FPI).

Broader spectral profiles are readily characterized with a scanning Fabry-Perot interferometer (FPI). The resolution of such a measurement is given by the finesse of the interferometer, whilst the largest quantifiable linewidth depends on the free spectral range of the instrument. Commercially available FPIs have a finesse between 100 and 1000, and free spectral ranges between a few 100 MHz and 10 GHz. Hence, FPIs are suitable for laser linewidth measurements from MHz to few GHz.

The FPI, too, has its limitations: When the laser line starts to fragment into several longitudinal modes – an effect often observed with semiconductor lasers at linewidths beyond a few GHz – the FPI usually does not mirror the correct spacing of the different modes, which may even appear superimposed. Under these circumstances, it is preferable to directly measure the coherence length, using e.g. a Michelson interferometer with variable arm length. The coherence length then corresponds to the path length difference, at which the fringe visibility contrast decreases to one-half of its initial value. Range and resolution of the measurement are governed by the design of the interferometer. Even with a simple lab setup, one can readily assess coherence lengths between 100 µm and 100 cm (linewidth ranges 100 MHz .. 1000 GHz). This technique also works for (spectrally) multi-mode lasers, even though the fringe contrast does not exhibit a monotonous decrease any longer.

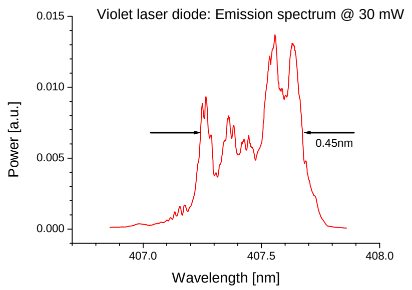


Michelson interferometer.



Interference patterns with high (left) and low (right) fringe contrast.

Finally, lasers with a spectral width in the 50 to 100 pm (10-100 GHz) region are easily examined with a grating spectrometer.

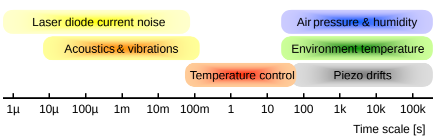


Typical emission spectrum of a violet laser diode, recorded with a grating spectrometer.

For any laser linewidth specification, one should always state the time scale of the measurement. Frequency fluctuations faster than the actual measurement add to the laser's linewidth (sometimes referred to as *technical linewidth* to acknowledge the influence of current noise or acoustics), while slower processes will cause a frequency drift between successive measurements. Obviously, fast measurement techniques do not reveal slower drift effects of the laser line.

What influences the coherence length?

The coherence length of an ideal (theoretical) laser can be derived from the Schawlow-Townes formula and is proportional to the output power divided by the square of the cavity round-trip time. In reality, this limit is usually not achieved due to the influence of various noise sources. If this noise is due primarily to spontaneous emission (quantum noise), then high intracavity power, long resonator length and low resonator losses will all increase the coherence length and, consequently, reduce the laser's linewidth.



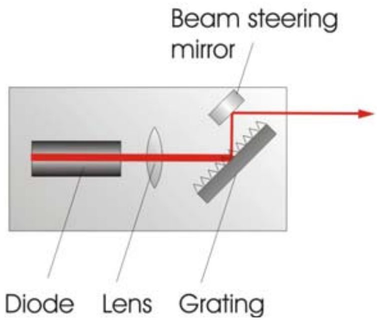
Influences on the coherence of an external-cavity diode laser and their respective time scale.

In a real-world diode laser, the coherence is further influenced by coupling between intensity and phase noise (so-called Henry factor or linewidth enhancement factor α), drift factors and technical excess noise. Temperature drifts, environmental factors such as air pressure and humidity, and, in the case of external-cavity lasers, piezo creep, all cause long-term drifts on time scales of seconds to hours. On the other hand, current noise and acoustic perturbations influence the linewidth on a time scale of ms or µs.

Efficient coherence control must be performed on the correct timescale, or in other words, bandwidth is the key to linewidth narrowing and broadening concepts. The ability to apply high-frequency electric fields directly to the laser chip distinguishes diode lasers from other laser types, where a controlled coherence variation usually involves intricate external modulation schemes, e.g. with acousto-optic or electro-optic modulators.

Laser Type	Typical coherence length
Lamp pumped Nd:YAG	1 cm
HeNe (non-stabilized)	20 cm
HeNe (stabilized)	1 km
Argon/Krypton	1 cm
Argon/Krypton + Etalon	1 m
Dye Laser	5 .. 250 m
Fiber Laser (non-stabilized)	50 µm
Fiber Laser (stabilized)	100 km
Free running diode laser	< 1mm
External-cavity diode laser	100 .. 1000 m

Table: Typical examples of laser coherence lengths.



External-cavity diode laser with Littrow resonator geometry.

Coherence control of diode lasers

Diode lasers can be operated in a variety of different configurations. Free-running diodes without any spectrally selective means are used in applications where spectral control is either not necessary at all, or comes second to a high-class beam profile. Examples include laser microscopy, flow cytometry, disc mastering, and microlithography.


iBeam smart 405 – ultra-compact diode laser with 120 mW output and 100 µm coherence length.

Interestingly, despite their short coherence length, these lasers are susceptible to a phenomenon dubbed “fringe revival”, that is related to the non-monotonous fringe visibility decrease of laser light composed of a plurality of longitudinal modes. After a certain distance (several millimetres, depending on the mode spacing), constructive interference between the individual modes makes the fringes reappear and gives rise to unwanted interference and speckle effects. TOPTICA's answer to this challenge is an electronic "speckle killer" that is optionally available for the industrial diode laser modules of the iBeam smart series.

"Speckle killer": the speckle pattern in the left image is eliminated by electronic means (right).

Grating-stabilized external-cavity geometries are used if single-frequency emission and spectral tunability are required. As outlined above, the coherence gain due to spectral filtering by a grating spans up to six orders of magnitude.

For many years, this increase in coherence had to be paid for in terms of output power. A recent achievement by TOPTICA's engineers is the BlueMode technology, which provides up to 50 mW output from a direct blue-violet diode laser – with single-line emission and a coherence length in excess of 25 m.

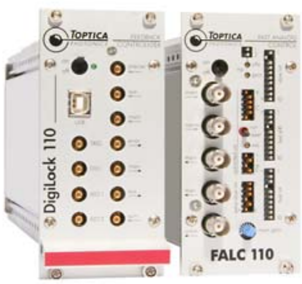
BlueMode: High-power diode laser with high coherence (405 nm, 50 mW, > 25 m).

Laser	**Linewidth**	**Coh. Length**	**Power**
iBeam	900 GHz	150 µm	110 mW
iWave	50 GHz	3 mm @ 20 mW 1 mm @ 50 mW	50 mW
BlueMode	< 5 MHz	> 25 m	50 mW
TA-SHG pro	2 MHz	65 m	100 mW

Table: Typical linewidth, coherence length and output power of TOPTICA's blue-violet diode lasers.

Application example: Ultra-precise spectroscopy

Narrow laser linewidths are required in precision spectroscopy, quantum optics and metrology. So-called "forbidden" transitions between long-lived atomic energy levels have halfwidths between a few ten kHz and a few Hz. One noteworthy example is the 243 nm 1s – 2s intercombination transition of hydrogen, which has a natural linewidth of 1.3 Hz. In order to match these narrow lineshapes, the laser linewidth must be several decades smaller than that of common external-cavity systems. Narrowing a diode laser's output to these levels requires both ultra-stable high-finesse reference cavities and extremely fast locking circuitry. TOPTICA's latest innovations are the fast analogue linewidth control module FALC 110 and its digital counterpart Digilock 110. These modules comprise a PID regulator with 10 MHz bandwidth, which controls the driver current of an external-cavity diode laser. A second, slower loop also cancels out long-term frequency drifts by acting on



DigiLock 110 and FALC 110: modules for linewidth narrowing.

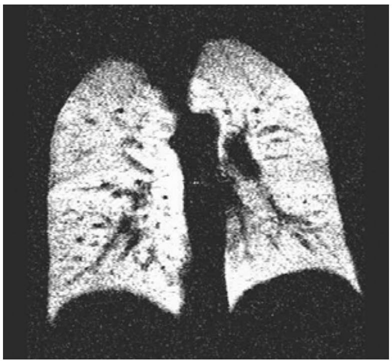
the grating piezo of the laser cavity. Researchers at the Max-Planck Institute for Quantum Optics in Garching, Germany, have reduced the linewidth of a 972 nm diode laser to 0.5 Hz using the FALC 110. This is a coherence length of 264 000 kilometers – two-thirds the distance to the moon.

Application example: Optical pumping of Helium-3

Whilst modules for linewidth narrowing have traditionally been the backbone of TOPTICA's laser electronics, a growing number of applications demand just the opposite: increasing the laser linewidth in a stable and reproducible way. Tasks like molecular spectroscopy or optical pumping of Doppler-broadened gases, are faced with absorption signatures several 100 MHz wide. Here, one prefers an artificially broadened laser linewidth, which has been virtually impossible to achieve with diode lasers: external-cavity systems are spectrally too narrow but free-running diodes are far too broad.

Laser coherence control unit LCC: linewidth broadening up to GHz ranges.

Recently, dedicated modulation sources such as TOPTICA's laser coherence control (LCC) unit have brought about the long searched-for solution. The LCC employs a proprietary high-bandwidth current modulation scheme to increase the spectral line profile of an external-cavity or distributed feedback diode laser. Changing the amplitude of the modulation permits a precise adjustment of the laser linewidth. Whilst the minimum output (-33 dBm) hardly causes any measurable broadening at all, the maximum output (+28 dBm) yields a laser linewidth well in the GHz range. The spectral profile of a diode laser can therefore be matched to a given absorption profile while the laser remains tuned to the resonance frequency.



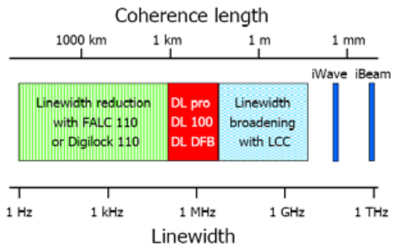
In vivo image of a human lung, recorded with magnetic resonance tomography using spin-polarized Helium-3 (courtesy University of Mainz).

One intriguing application is magnetic resonance imaging of human lungs using spin-polarized Helium-3 gas (see figure). Helium-3, a stable isotope a million times rarer than common Helium-4, has a nuclear spin of ½, which carries a magnetic moment. Aligning the tiny nuclear magnets renders the gas magnetic, and enables in-vivo imaging of human lungs and airways. This technique has been used to identify ventilation defects caused by smoking; to visualize gas inflow through the trachea and bronchi; and to measure oxygen concentrations within the lungs. Optical pumping is used to magnetize the gas and this process is most efficient when the laser linewidth matches the Doppler-broadened absorption profile of the gas. Here, the LCC module broadens the output of a 1083 nm distributed feedback laser to approximately 2 GHz.

Lowest coherence

At the far end of the scale, the spectral width of a diode laser is limited only by its gain profile. The spectrally broadest diodes – though admittedly not true lasers – are superluminescent LEDs (SLEDs). These sources offer a spectral width of up to 50 nm, which corresponds to a coherence length on the 10 µm scale. SLEDs are used in applications such as optical coherence tomography (OCT), where an increase in spatial resolution is obtained by means of a low temporal coherence (and high spatial coherence). If this spectral width is still not sufficient, a supercontinuum can be generated by ultrafast pulsed lasers. Their spectral bandwidth of several hundred nanometers brings the coherence down to the 1 micron level.

The attainable coherence spectrum of semiconductor lasers now covers more than 12 orders of magnitude – from spectrally broad violet diodes to new records in frequency resolution. Applications ranging from laser-based imaging to precision studies of hydrogen transitions are now a reality. Optical and electronic feedback, short signal processing times and high operating bandwidths are the main tools that laser engineers resort to.



12 orders of coherence control for diode lasers.