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Tuneable, stabilised diode lasers for compact atomic frequency standards and precision wavelength references

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Abstract

We describe the ongoing activities in Observatoire Cantonal de Neuchâtel in the fields of precision laser spectroscopy and metrology of Rb atomic vapours. The work is motivated by the potentials of highly stable and narrowband laser light sources for a variety of technical and scientific applications. We describe the use of extended-cavity diode lasers for the realisation of such narrowband light sources and the basic schemes under study for their stabilisation, with focus on Doppler and sub-Doppler laser spectroscopy. The resulting laser systems offer good frequency stabilities and can be effectively miniaturised. This makes them interesting for direct applications of these techniques, as well as the presently developed precision instruments: compact atomic frequency standards for ground and space applications (GALILEO satellite positioning system), secondary optical frequency standards, transportable extended cavity diode lasers as seeding lasers, and others.

Keywords: Laser spectroscopy; Laser stabilisation; Atomic frequency standards; Wavelength references; High spectral resolution LIDAR

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1. Introduction

The past years have shown tremendous advancements in the field of compact and spectrally well-controlled diode laser sources, concerning both spectral narrowing of the laser emission and frequency control. These developments make it interesting to exploit the availability of such compact lasers sources for, e.g. secondary wavelength references [1,2], or for performance improvements of precision instruments like, e.g. compact atomic frequency standards [3,4] or atomic magnetometers [5,6].

Here we will discuss the realisation of a compact single-mode laser source, a quantitative comparison of different schemes for frequency stabilisation of the laser to an atomic Rb reference, and application examples of the resulting compact and stabilised laser heads. Applications to secondary wavelength standards, laser-pumped Rubidium gas-cell atomic clocks and high spectral resolution LIDAR (light detection and ranging) instruments will be considered.

2. Frequency-stabilised laser modules

Many applications not only require well-controlled laser emission spectra, but also small size and low power consumption of the laser source. Here semiconductor diode lasers are an excellent choice, being available in a huge variety of types spanning large ranges of emission wavelengths, output powers, and spectral characteristics. Promising advances have been made towards intrinsically single-mode and narrowband diode lasers like, e.g. distributed feed-back (DFB), distributed Bragg reflector (DBR) or vertical-cavity (VCSEL) lasers, but still these devices are not always commercially available at the desired wavelength or are compromised by spectral linewidths of a few MHz or more, too large for applications aiming for ultimate performance in optical instrumentation and spectroscopy. Here we therefore focus on the realisation of compact external-cavity grating stabilisation of standard Fabry–Perot type laser diodes [7], whose linewidth is spectrally narrowed by the optical feedback [8] and where there is usually a large choice of diodes commercially available.

2.1. Compact diode laser modules

We have built two types of extended-cavity diode lasers (ECDL) using the Littrow configuration [9], which can be realised very compact [10,11] and still offer the good frequency tuning behaviour and spectral linewidths around 300 kHz required for subsequent stabilisation to atomic or molecular resonances: Fig. 1 shows the CAD design and the final realisation of an ECDL for laboratory use. Coarse adjustment of the external cavity is achieved by aligning manually a modified commercial mirror mount supporting the diffraction grating, while fine tuning and frequency scanning is realised using a piezo actuator acting on the grating support (see Fig. 2b for a schematic view of the ECDL). The laser implements two separate temperature controls which allow independent stabilisation of the external cavity and

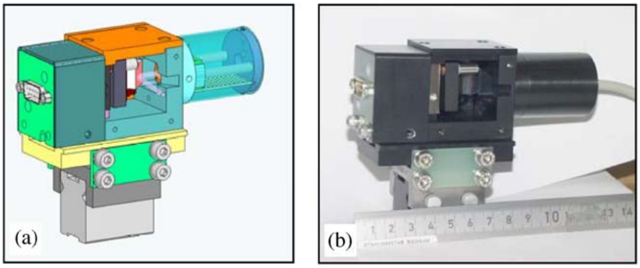

Fig. 1. Compact extended-cavity diode laser for laboratory use. (a) CAD design. (b) realised device.

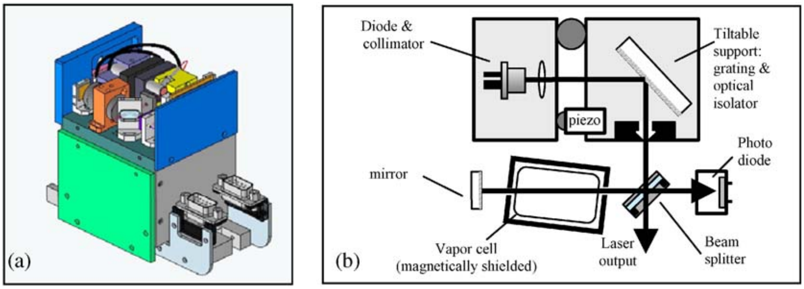

Fig. 2. Compact laser head with integrated stabilisation to a Rb reference cell. (a) CAD design. The upper part constitutes the physics package, the lower part will house the control electronics. (b) Schematic diagram of the physics package, consisting of the grating-stabilised laser (upper part) and the vapour cell reference spectroscopy (lower part).

temperature tuning of the laser diode. With this design, ECDLs emitting at 780, 795, 852, 894, and 935 nm have been successfully realised so far.

Fig. 2a shows the design of a compact laser head module which in addition to an ECDL described above also includes frequency stabilisation to a Rb vapour reference cell using a compact saturated absorption setup [12,13]. The physics package of this laser head has an overall volume of only 200 cm^3, 45 cm^3 of which are occupied by the ECDL itself, and to our knowledge this constitutes the most compact unit containing both an ECDL and frequency stabilisation. The laser head typically delivers 3 mW of output power, by far sufficient for instruments like atomic magnetometers or Rb atomic clocks (cf. Section 3.2).

Fig. 2b gives a schematic view of this compact laser head's physics package. The ECDL (upper part of Fig. 2b) is tuned by controlling the external cavity via a piezo actuator. A miniature optical isolator — mounted to the same support as the grating — suppresses optical feedback from the reference spectroscopy setup, which would otherwise cause frequency instabilities of the laser diode. The saturated absorption setup (lower part of Fig. 2b) consists of a simple retro-reflected beam scheme without subtraction of the Doppler background in order to keep the setup simple and compact. The reference cell is contained in a two-fold magnetic

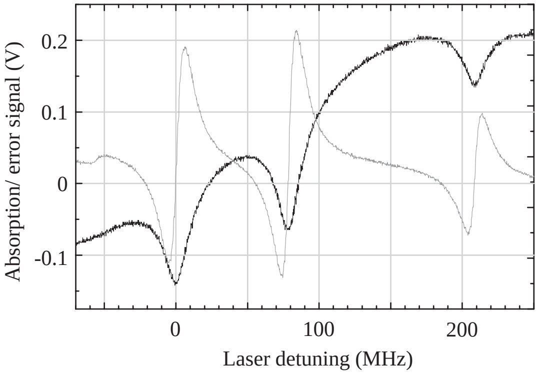

Fig. 3. Absorption (black trace) and error signal (grey trace) from the reference cell included in the laser head. The absorption signal shows three narrow sub-Doppler resonances of Rb superimposed on the significantly broader Doppler background (manifested as the mounting slope here). In the error signal the slope of this background is largely reduced due to the FM modulation technique.

shield in order to suppress distortions on the reference signal due to magnetic fields originating, for example from the optical isolator. Fig. 3 shows an example of the sub-Doppler absorption signals obtained from the integrated reference cell, along with the error signal for frequency stabilisation, which is derived by FM modulation of the laser frequency and synchronous detection. The width of the Doppler-free resonance lines is limited to about 10 MHz here by the still strong pump light in the simple spectroscopic scheme implemented. A more detailed characterisation of spectral characteristics is in progress. We also evaluate the possibilities to replace the ECDL by other laser diodes like, e.g. DBR, DFB, or VCSELs, which would make obsolete the mechanically moving grating, further reduce the laser head size, and due to their modulation capabilities facilitate light shift reduction methods in optical pumping applications [14].

2.2. Frequency stabilisation

While the short-term frequency stability of free-running diode laser modules may be sufficient in some cases, high-precision applications in metrology demand improved frequency stability over an extended range of time. Thus stabilisation of the laser to a stable atomic or molecular reference line is required.

For the frequency stabilisation of our laser module to the D_2 line of ^{87}Rb we have studied in detail two selected schemes that offer the potential to realize compact and robust instruments: sub-Doppler stabilisation by the so-called saturated absorption spectroscopy (cf. the three narrow lines in Fig. 3) and stabilisation to simple Doppler-broadened absorption resonances (broad background in Fig. 3). While the sub-Doppler scheme has the advantage of resonance linewidths up to a factor 100 narrower than the Doppler absorption, the Doppler scheme may be nevertheless suitable for instruments where a somewhat reduced frequency stability can be tolerated, but the physics package needs to remain the simplest possible. Furthermore, automated identification of the correct line to lock to is much simpler in the Doppler case.

For a systematic and quantitative comparison of the two schemes, we have performed relative frequency stability measurements of two extended-cavity diode lasers, stabilised independently to different reference cells using frequency modulation. The first laser was stabilised to a sub-Doppler absorption signal of the ^{87}Rb D_2 transition from a Rb vapour cell and thus provided a stable frequency reference. The physical parameters of this stabilisation setup like, e.g. cell temperature and the magnetic field, were well-controlled and held fixed at their respective values. The second laser could be stabilised using either a second sub-Doppler or a Doppler stabilisation setup, and provided the stabilisation scheme under test. The frequency difference between the two laser frequencies was measured by the heterodyne signal from a fast photodetector and compared to a hydrogen maser using a frequency counter. Both laser stabilisation setups remained routinely locked over several days and thus allowed long-term studies of the frequency stability.

Table 1 summarises the main results for the frequency shift of the stabilised lasers due to variations of different experimental parameters [15]. In order to estimate the long-term limit of the achievable laser frequency stability, we have combined the obtained values with the stability of the experimental parameters over 10^4 s. For both the Doppler and sub-Doppler stabilisation the cell temperature is identified as the most the critical parameter for the long-term stability, although being controlled to better than 100 mK. In spite of the much higher numerical value, shifts induced by

Table 1
Shift rates of the stabilised laser frequency due to changes of environmental parameters of the sub-Doppler and Doppler stabilisation schemes

Parameter	Unit	Doppler	Sub-Doppler[a]
Magnetic field	kHz/mG	0.035	0.03–0.12
Laser beam power	kHz/μW	8	1.3–10
Cell temperature	kHz/K	*300*	*4–33*
Angular sensitivity	kHz/deg	100	450–1400
FM modulation amplitude	kHz/kHz	1.4	0.14
Short-term stability (1–100 s)			
Theoretical limit (S/N)	$\tau^{-1/2}$	$1-3 \times 10^{-11}$	$1-4 \times 10^{-12}$
Experimental	$\tau^{-1/2}$	2×10^{-11}	2×10^{-12}
Long-term stability (10^4 s)			
Theoretical limit (drifts)	$\tau^{-1/2}$	1×10^{-10}	$0.3-1 \times 10^{-12}$
Experimental	$\tau^{-1/2}$	2×10^{-10}	2×10^{-12}

The experimentally found stabilities are compared to the theoretical limits calculated from the long-term parameter variations and signal-to-noise limited short-term stabilities. Values given in italics mark the most critical parameters for each scheme.

[a] Values depend on the sub-Doppler resonance chosen for stabilisation.

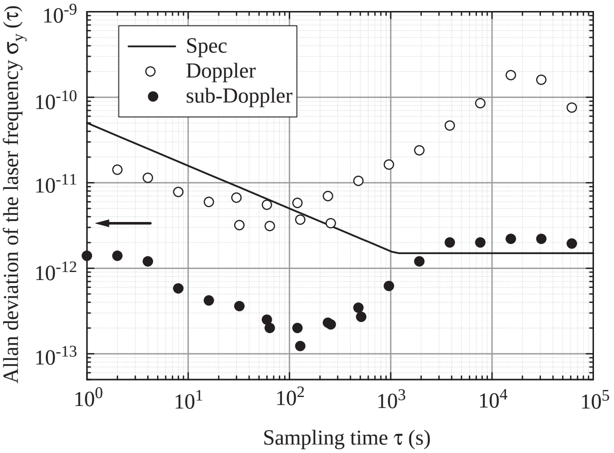

Fig. 4. Measured laser frequency stabilities for the Doppler and sub-Doppler stabilisation schemes. The solid line gives the frequency stability required for application in a laser-pumped Rubidium atomic clock. The arrow indicates the level of 1 kHz frequency change.

drifts of the beam angle are of minor importance, due to their smaller variation over time (less than 10^{-4} deg). Amplitude variations of the FM modulation source on the per cent level due to thermal drifts in the laser electronics only give smaller contributions to the stability budget. As the reference cells were mounted in magnetic shields, fluctuations of the laboratory magnetic field cause insignificant frequency shifts only, as do variations of the laser beam power. Table 1 also gives the theoretical limit for the long-term stability of both schemes calculated from this analysis of experimental parameters, as well as the short-term stability limit determined from the signal-to-noise ratio of the resonance error signals.

Fig. 4 summarises the experimentally measured laser frequency stabilities in terms of the Allan standard deviation for the two schemes studied. As can be seen, the sub-Doppler scheme offers about one order of magnitude better stabilities, but even the Doppler scheme meets the requirements for the application example of an atomic clock at short integration time up to 100 s (solid lines, cf. Section 3.2). A comparison with the theoretical values given in Table 1 shows that both the measured short-term and long-term stabilities coincide well with the calculated stability limits. Note also that the measurements using the sub-Doppler scheme show improved stability on the short-term time scales up to 300 s compared to previous results [16], but with a considerably simpler and more compact setup.

3. Application examples

In the following we discuss some applications of narrow-band frequency stabilised lasers that can benefit from the realisation of compact devices, where the volume of the stabilised laser module is around or well below 1 l for a single-wavelength source.

While ultimate state-of-the-art performance of much larger laboratory devices will in most cases be superior to the stability and precision of the laser modules discussed here, a compact device offers the potential for, e.g. mobile applications with volume restrictions or applications requiring large unit numbers but moderate price. Depending on the specific application the implemented atomic or molecular reference line will differ and also the laser type used might change.

3.1. *Secondary wavelength references*

A laser module stabilised to a suitable reference line can serve as a secondary wavelength reference and find applications in fields like telecommunication or the experimental realisation of the meter unit [1]. Using diode lasers stabilised to the D_2 line of ^{87}Rb, frequency stabilities of $4 \times 10^{-12}\ \tau^{-1/2}$ were previously demonstrated using laboratory setups [16], validating the feasibility of this approach. Our compact stabilised laser module reaches similar stabilities and can be easily adopted to meet wavelength stabilisation to other alkali atomic resonance lines at 795, 852, or 894 nm. We also envisage a modification of the module to meet the Rb 2-photon transition at 778 nm, which is recommended as a metrology reference wavelength [1].

The implementation of frequency doubling techniques allows to extend the wavelength range met by the laser module to 1556 or 1560 nm, and thus into one of the standard wavelength ranges used in telecommunications. A simple system for frequency doubling in this wavelength range was recently demonstrated using compact and standard commercial components only [17].

3.2. *Laser-pumped atomic clocks*

We have implemented the stabilised laser head for optical pumping in a Rb gas-cell atomic clock that is being developed in collaboration with Temex Neuchâtel Time as industrial partner within the frame of a project funded by the European Space Agency ESA. The aim of this activity is the realisation of a high-performance laser-pumped Rb clock as a secondary frequency standard as a possible upgrade candidate for future generations of the GALILEO satellite communication system, as well as to meet high-performance demands in space science missions and telecommunications. Project goals for the laser-pumped clock performance are frequency stabilities of $10^{-12}\ \tau^{-1/2}$ up to 10^4 s and a flicker floor of 10^{-14} at longer timescales, while maintaining a very compact device (volume $\leqslant 1.5$ l, mass $\leqslant 1.5$ kg, and power consumption < 15 W). Compared to the conventional lamp-pumped atomic clocks, implementation of narrow-band pump light from a laser offers the advantage of more selective optical pumping, resulting in narrower linewidths and increased contrast of the microwave transition, and thus in improved short-term stability. Furthermore, use of semiconductor laser diodes allows for a significantly lower power consumption in comparison to the conventional discharge lamps that are operated at high temperatures.

Fig. 5 shows a picture of our laser-pumped clock, consisting of the stabilised laser head described in Section 2.1 (left) and a modified commercial Rb clock module,

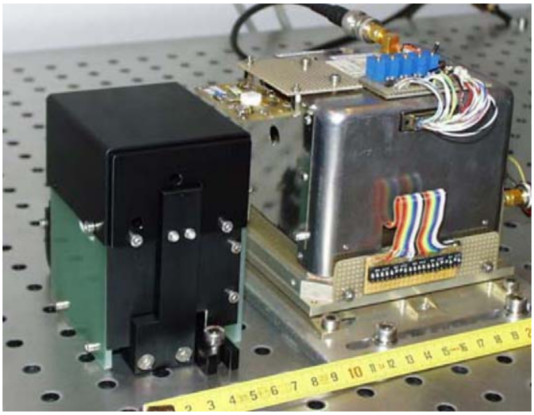

Fig. 5. The laser-pumped atomic clock. Left: laser head, right: the clock module.

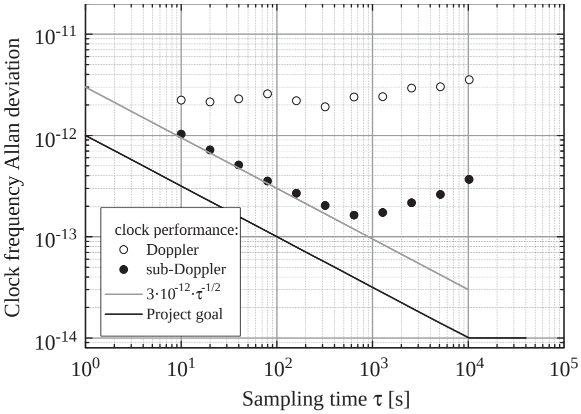

Fig. 6. Clock stabilities measured with the demonstrator setup of Fig. 4 for the Doppler (○) and sub-Doppler (●) stabilisation schemes.

from which the lamp was removed (right). A preliminary frequency stability measurement of the clock is shown in Fig. 6. The results using sub-Doppler laser stabilisation reproduce the $3 \times 10^{-12}\ \tau^{-1/2}$ characteristics of the lamp-pumped device up to 10^3 s, in spite of the improved contrast of the microwave signal. We thus attribute the short-term stability to be limited by the not yet fully optimised clock electronics and light shift effects arising from the FM modulation used for laser stabilisation. On longer time-scales the clock performance is limited by effects due to the light shift induced by the narrow-band laser pump light. Reduction of the light shift effect in other types of gas-cell atomic clocks has already been an active field of research in the past [18–20] and we have developed a method for its suppression in laser-pumped clocks using a FM modulation method [14]. Further improvement of the clock performance in the medium-term time scales is expected from the implementation of such techniques for the suppression of light shift as well as careful matching of the laser head and clock module operation parameters. Improvement of the short-term stability can be reached by optimisation of the detection and rf electronics.

3.3. High spectral resolution LIDARs

Atmospheric measurements by advanced LIDAR techniques can profit from stabilised laser sources used to seed their high-power transmitter lasers. For example, narrow-band Faraday Anomalous Dispersion Optical Filters (FADOF) [21] based on alkali atomic vapours offer improved background light reduction in the LIDAR receiver units compared to simple interference filters and thus allow daylight-operation even of compact PRN-cw (pseudo-random noise) instruments [22,23], but they also require the transmitter laser to operate within the narrow transmission windows of the filters (cf. Fig. 7). Thus the transmitter lasers have to be stabilised to the alkali resonance exploited in the FADOF filter, where stabilisation based on Doppler-broadened absorption can be sufficient.

As a second example, the Differential Absorption Lidar (DIAL) technique [24] for selective measurement of specific atmospheric constituents also requires stabilised seeding lasers. This technique relies on measurements performed with the transmitter laser tuned to the centre or out of the absorption lines of the molecules considered, and thus requires well-stabilised seeding signals. We are currently developing a seeding laser system for the ESA Water Vapour Absorption Lidar in Space (WALES), a satellite-borne DIAL instrument for measurement of atmospheric water vapour [25,26]. In order to increase the dynamic range of the instrument, measurements will be made simultaneously on four wavelengths corresponding to

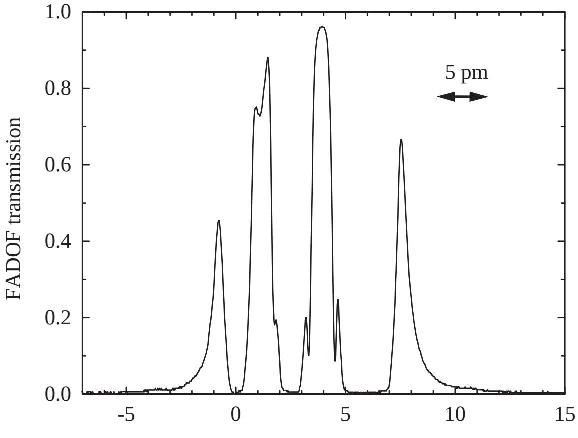

Fig. 7. Transmission curve of a Rb FADOF filter for daylight PRN LIDAR measurements [23].

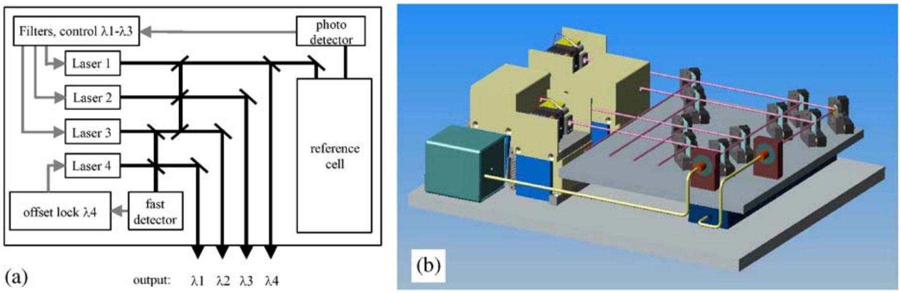

Fig. 8. Wavelength stabilisation scheme for injection seeding the transmitter laser of a water vapour LIDAR at 4 different wavelengths. (a) System schematics, (b) CAD design view: Three independent ECDLs (upper left) are stabilised to the signals from a reference cell (right lower part). In the lower left corner the detector for offset-locking of the fourth laser.

water vapour resonances of different absorption strength, as well as one off-line wavelength which requires the fourth laser to be offset-locked with a detuning of several GHz relative to one of the three first lasers [26]. Here exploitation of compact laser modules will allow to realise a system of four narrow-band lasers stabilised to a reference water vapour cell, with a volume well below 27 l (see Fig. 8).

4. Conclusion

We have realised a compact laser module based on an extended-cavity diode laser, which includes frequency stabilisation to a sub-Doppler Rubidium atomic resonance. With properly chosen parameters, this stabilisation scheme offers Allan standard deviations of the laser frequency on the level of $\leqslant 2 \times 10^{-11}$ (i.e. below 1 kHz) for integration times from 1 to 10^4 s. For less demanding applications, the significantly simpler Doppler absorption still offers Allan deviations around 10^{-11} on these timescales, representing thus an alternative method when simplicity of the stabilisation scheme is critical.

The realised sub-Doppler frequency stabilised laser head was successfully used for optical pumping of a compact Rb gas-cell atomic clock for space applications. While the medium-term stability of the clock is limited by pump light intensity fluctuations, the short-term stability already reaches $3 \times 10^{-12}\ \tau^{-1/2}$ and further improvement is expected with an optimised rf electronics.

The current design of the laser head already constitutes a compact, secondary wavelength reference and an extension towards a 2-photon stabilisation at 778 nm can be envisaged, as well as the realisation of wavelength references close to 1560 nm for telecommunications via frequency doubling. Similar compact laser modules stabilised to other atomic or molecular resonances will also be realised for applications in LIDARs with high spectral resolution, both for ground-based, airborne and space instruments.

Acknowledgements

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