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A compact laser head with high-frequency stability for Rb atomic clocks and optical instrumentation

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We present a compact and frequency-stabilized laser head based on an extended-cavity diode laser. The laser head occupies a volume of 200 cm^3 and includes frequency stabilization to Doppler-free saturated absorption resonances on the hyperfine components of the ^{87}Rb D_2 lines at 780 nm, obtained from a simple and compact spectroscopic setup using a 2 cm^3 vapor cell. The measured frequency stability is $\leqslant 2\times 10^{-12}$ over integration times from 1 s to 1 day and shows the potential to reach 2×10^{-13} over 10^2-10^5 s. Compact laser sources with these performances are of great interest for applications in gas-cell atomic frequency standards, atomic magnetometers, interferometers and other instruments requiring stable and narrow-band optical sources.

I. INTRODUCTION

Narrow-band, tunable diode laser sources are today indispensable in many fields of atomic and molecular physics and spectroscopy,[1] precision metrology, or interferometry. Compact diode lasers frequency-stabilized to atomic or molecular reference lines are also of high interest for the development of transportable high-performance instruments, such as atomic frequency standards,[2] atomic magnetometers,[3–5] optical wavelength references,[6] and others. Depending on the specific application, different properties of the laser source such as narrow linewidth, spectral purity, output power, intensity and frequency noise, or short- and long-term frequency stability can be of major concern and may require individual optimization.

Here we report on the realization of a compact extended cavity diode laser (ECDL) source at 780 nm, frequency-stabilized to saturated absorption resonances on the D_2 line of atomic ^{87}Rb. The laser head includes both the ECDL and the stabilization reference and was successfully used in the development of laser optically pumped Rb gas-cell atomic frequency references.[7] Such laser-pumped "Rb clocks" offer the promise for improved frequency stability performance compared to existing lamp-pumped devices, which already are highly compact (volumes around 2 l or less) and still offer excellent frequency stability better than 10^{-13} over time scales from several hours to one day.

II. DESIGN REQUIREMENTS

In order to fully exploit the advantages of laser optical pumping in Rb clocks,[8–10] stringent requirements are imposed on the pump light laser source. Reliable single-mode operation at the ^{87}Rb D_2 wavelength of 780 nm is needed, including continuous tuning over all Rb D_2 lines to facilitate the clock evaluation and high stability with respect to mode drifts. The laser should have low AM and FM noise levels around $\mathrm{RIN}\approx 3\times 10^{-13}$ Hz^{-1} and $S_f \approx 10^8$ $\mathrm{Hz}^2/\mathrm{Hz}$, respectively, at low frequencies (100–300 Hz) and exhibit excellent frequency stability better than $5\times 10^{-11}\tau^{-1/2}$ up to $\tau = 1000$ s integration time and $\leqslant 2\times 10^{-12}$ at medium-term time scales from $\tau = 1000$ s up to 1 day. To realize such stabilities narrow laser linewidths $\lesssim 6$ MHz are necessary, that allow to obtain well-resolved Doppler-free spectroscopy lines. However, for the Rb clock application itself these narrow linewidths are not mandatory, and low laser output powers around 1 mW are sufficient.

In the past years, highly compact[11–17] and first MEMS-based[18,19] extended-cavity diode lasers as well as compact setups for laser stabilization[20] have been demonstrated, and detailed studies of different types of ECDLs have been conducted.[21,22] In the work presented here, the main challenge thus lies in the realization of a combined ECDL laser and atomic spectrometer within a compact instrument (physics package volume <0.25 l) that maintains the advantageous low volume of Rb clocks, but still offers the required state-of-the art laser frequency stability, low noise levels, and high reliability.

III. INSTRUMENT REALIZATION

Figure 1 shows a design view of the laser head, consisting of a ECDL laser source (upper part in Fig. 1) and a compact reference spectroscopy setup (lower part in Fig. 1). In the ECDL source we use Hitachi HL7859MG laser diodes that provide up to 35 mW of output power at 780 nm. These diodes do not have antireflection coatings for improved ECDL tuning performances, but represent an advanced development delivered with ESD reliability data compared to the similar HL7851G type already used in space environment,[23] which makes them good candidates for use in space-borne Rb clocks. The laser diode output is collimated using a singlet biaspheric lens (Kodak A-352, AR-coated for 780 nm, focal length 4.58 mm, numerical aperture 0.47). A

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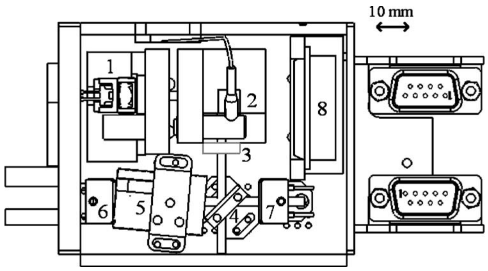

FIG. 1. Schematic drawing of the laser head. Upper left: ECDL consisting of (1) laser diode and collimator, (2) grating mount with tuning piezo, (3) miniature optical isolator. Lower part: reference spectroscopy setup with (4) beamsplitter, (5) Rb cell, (6) retroreflecting mirror, (7) photodetector. (8) preamplifier circuit.

holographic diffraction grating (Edmund Optics 43-775, 1800 lines/mm, nominal efficiency ≈40%) is mounted in Littrow configuration and provides selective optical feedback for single-mode laser operation and frequency tuning. In order to keep the design simple and compact, the laser's external cavity is built around a 1-in. precision mirror mount, similar to a previously reported design[15] but with strongly reduced volume of the whole ECDL of 54 cm^3 only. The support holding the laser diode and collimator lens is thermally isolated from the other parts of the external cavity and is thermally stabilized via a Peltier element mounted on its back side. A second circuit controls the temperature of the remaining ECDL and the whole laser head via resistive heater pads.

Optimization of the optical feedback as well as coarse frequency tuning of the laser frequency is achieved by turning the two thumb-screws of the mirror mount. A piezostack actuator (PI, type P-810.10) controls the external cavity length (and grating angle) and thus serves for fine tuning of the laser frequency via the piezovoltage. A miniature optical isolator (OFR IO-D-780, isolation ⩾40 dB) is mounted directly on the ECLD's grating support and serves to suppress unwanted optical feedback to the ECDL that originates from the reference spectroscopy setup or from outside the laser head. In spite of the small aperture (1.75 mm) and low transmission (50% within the aperture) coming along with its small dimensions, light power levels after the isolator are typically around 3 mW, sufficient for the reference spectroscopy setup and light levels required in many applications.

The frequency reference unit consists of a small and simple saturated absorption spectroscopy setup that relies on one single retroreflected beam without subtraction of the Doppler-broadened background (≈500 MHz) due to linear absorption, and that delivers narrow (FWHM≈20 MHz) Doppler-free resonances. The reference cell is a small 2 cm^3 evacuated glass cell containing Rb vapor. Since application in a Rb atomic clock requires the laser to be stabilized to the ^{87}Rb lines, the cell is filled with isotopically enriched ^{87}Rb with strongly reduced ^{85}Rb content. Thus, compared to a cell with the natural isotope mixture at the same temperature, the reference absorption signal from the ^{87}Rb is increased and detrimental absorption from the wings of the ^{85}Rb Doppler-broadened absorption is reduced. The Rb cell is surrounded by a single-layer mu-metal shield in order to reduce stray magnetic fields originating from the optical isolator or other environmental sources. In this way, changes in amplitude and position of the saturated absorption lines with the magnetic field strength or orientation are suppressed,[24,25] which otherwise would degrade the laser frequency stability. At the vapor cell, the light polarization is linear and parallel for the pump and probe beam (lin‖lin configuration). This configuration also results in a sub-Doppler line on the $F=1$ component showing increased absorption (see Fig. 3), whose existence confirms good magnetic shielding of the cell to below the microtesla level.

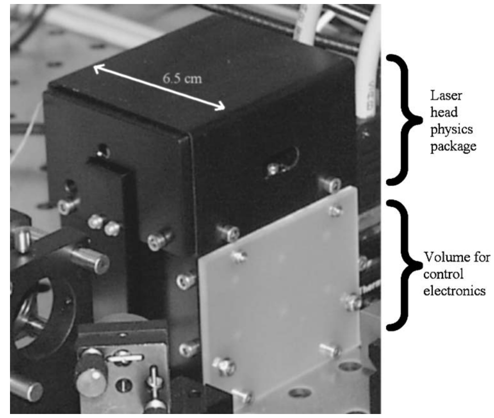

FIG. 2. Photo of the assembled laser head. The laser beam exits from the opening visible on the right-hand side of the physics package.

Figure 2 shows a photograph of the assembled laser head, which has a total mass of 500 g. The 500 cm^3 volume splits into 200 cm^3 for the physics package and 300 cm^3 for the electronics volume.

IV. EXPERIMENTAL RESULTS

Under typical operating conditions the ECDL delivers around 10 mW from the diffraction grating, and around 3 mW with the miniature isolator in place. Using the piezoactuator, continuous tuning over >10 GHz is achieved under single-mode operation. Figure 3 shows an example of a saturated absorption spectrum obtained in this way from the laser head's reference cell. We measured a tuning coefficient of 480 MHz/V for variations of laser frequency with piezovoltage and a −3 dB bandwidth of 1 kHz. When acting on the diode's injection current, a frequency tuning rate of

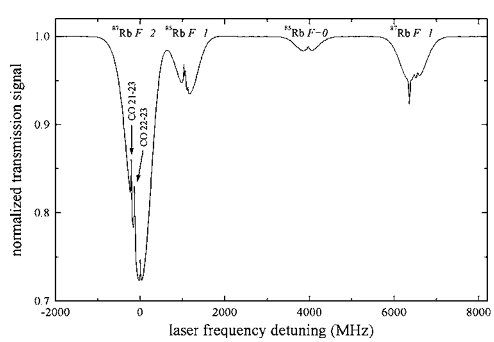

FIG. 3. Saturated absorption spectrum of the Rb D_2 line obtained from the laser head's reference setup. Continuous tuning over >10 GHz is demonstrated when acting on the grating piezo only. The crossover resonances 21-23 and 22-23 studied for laser frequency stabilization are labelled.

TABLE I. Typical intensity and frequency noise levels measured for the laser light at two key frequencies.

Fourier frequency	300 Hz	50 kHz
FM noise (kHz $\mathrm{Hz}^{-1/2}$)	3.2	0.6
AM RIN (Hz^{-1})	1×10^{-13}	3×10^{-14}
AM noise after Rb cell (Hz^{-1})	4×10^{-13}	1×10^{-13}

350 MHz/mA was observed, which is consistent with typical values for this type of laser diodes and about ten times smaller than for the solitary diode alone, due to the influence of the external cavity. With increasing frequency of the current signal, this tuning rate slightly decreases to 150 MHz/mA at 50 kHz. Corresponding changes in output power amount to 0.4 mW/mA for a total output power of 3 mW.

Table I lists the laser noise measured both before and after passage through the Rb cell at two frequencies of special interest: at the modulation frequency around 50 kHz used for laser frequency stabilization and at a lower frequency of 300 Hz, of interest for applications in atomic clocks. The frequency noise roughly reproduces the values reported by Turner *et al.*[26] Figure 4 also shows an example of an AM noise spectrum from which the values in Table I were calculated. After passage through the Rb cell, a RIN of $4\times10^{-13}\ \mathrm{Hz}^{-1}$ at 300 Hz is measured. For the applications example of a laser optically-pumped Rb gas-cell clock this value results in a laser noise limited short-term stability of the clock frequency of $2\times10^{-13}\tau^{-1/2}$,[27] that would surpass the performance of today's best lamp-pumped Rb clocks. Note, that for a typical detector current around $2-3\ \mu$A in a Rb clock, the contributions from the laser frequency noise and shot noise result in short-term stability limits $\leqslant 5\times10^{-14}\tau^{-1/2}$ and around $1\times10^{-13}\tau^{-1/2}$, respectively, significantly lower than for the intensity noise.

A. Spectral characteristics

The spectral characteristics of the laser head emission were determined using heterodyne beat measurements between two identical laser head units. An example of such measurement results is shown in Fig. 5. No side mode signals are found at frequency differences of ±4.8 GHz (corresponding to the free spectral range of the laser external cavity), which gives a side mode suppression ratio SMSR

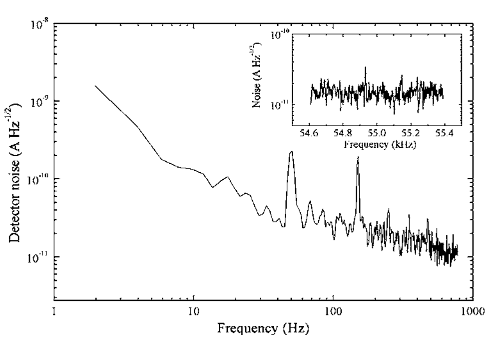

FIG. 4. Intensity noise spectrum measured on the photodetector in the laser head. dc photocurrent was $I_{dc}\approx 63\ \mu$A, corresponding to a shot noise level of 5×10^{-12}A $\mathrm{Hz}^{-1/2}$.

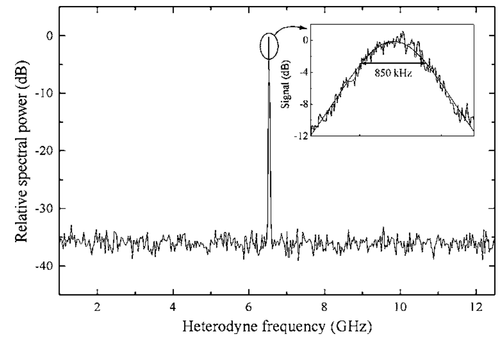

FIG. 5. Heterodyne beat spectrum between two identical laser heads. The resolution bandwidth was 300 kHz for the large span and 30 kHz for the inset.

$\geqslant$35 dB, limited by the detection noise here. The -3 dB width of the beat note signal was <900 kHz, corresponding to a linewidth for each individual laser of <450 kHz—by far sufficient to obtain well-resolved saturated absorption spectra.

B. Frequency stability

Stabilization of the laser frequency to the reference absorption lines is achieved by frequency modulation of the laser frequency at 50 kHz via the injection current and subsequent lock-in demodulation of the absorption signal. The raw and integrated error signals obtained in this way are applied to the laser diode current and piezovoltage, respectively, in order to correct for frequency deviations on both fast and slow time scales. Due to the $1f$ demodulation implemented, the broad ($\approx$500 MHz) Doppler-background superimposed on the narrow ($\approx$20 MHz) Doppler-free resonances translates into a nonzero offset in the error signal.[28] When, for example, the laser is stabilized to the crossover 21-23 line, its frequency is thus shifted by about 0.5 MHz with respect to the line's true frequency position. Such frequency shifts can be suppressed when using a $3f$ demodulation scheme[29,30] and were not studied in detail here. Similarly, the inevitable amplitude modulation (AM) of the light field arising from the current modulation can vary in time and thus might cause some drifts of the laser frequency bias from the exact resonance frequency. This AM level was not controlled nor monitored in the experiments. However, both shifts arising from sloping background and AM modulation are implicitly included in the evaluation of laser frequency drifts given below.

The laser frequency stabilization was realized using homemade dedicated analog electronics. Under standard laboratory conditions and with the setups protected from air draught by simple plastic boxes, the laser heads routinely stay locked over many weeks, as required for applications in atomic clocks. For an evaluation of the laser frequency stability, two identical units of the realized laser heads were stabilized to the CO 21-23 and CO 22-23 crossover resonances of the ^{87}Rb $F=2$ transition (see Fig. 3). The two output beams were superimposed on a fast photodetector and the laser frequency difference was measured by comparing the frequency of the resulting beat note signal to an active Hydrogen Maser (EFOS, Observatoire de Neuchâtel) using a

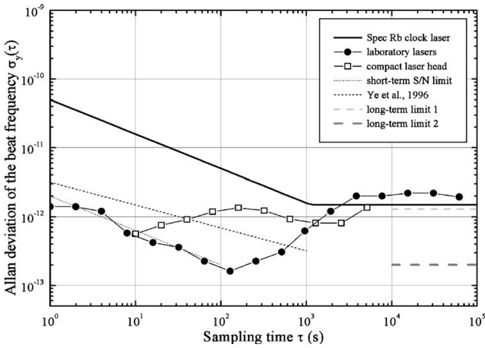

FIG. 6. Relative laser frequency stability in terms of the Allan standard deviation. □: compact stabilized laser head. ●: laboratory version of the simple saturated absorption setup (Refs. 25 and 28), reproducing the performance of the more sophisticated setup by Ye *et al.* (Ref. 30). Long-term limit 1 indicates the stability level estimated from measured parameter drifts, limit 2 the estimated performance limit for an optimized device (cf. Table II).

frequency counter. The measurement result is given in Fig. 6 in terms of the relative Allan standard deviation for the two compact laser heads (squares), as well as for a laboratory test assembly using identical techniques but somewhat larger setups (circles). For the compact laser head, a slightly degraded stability is found around 200 s, probably due to residual oscillations in the not yet fully optimized thermal control for the coupled system of ECDL and reference cell. In both cases, however, the measured stabilities fulfill the frequency stability requirements for laser-pumped Rb clocks and show short-term stabilities around $2\times 10^{-12}\tau^{-1/2}$ at $\tau \leqslant 10$ s and medium-term stabilities around 2×10^{-12} at $\tau = 10^4$ s or beyond.

We estimate the signal-to-noise limit for the short-term stability $\sigma_f(\tau)$ of the laser frequency f_L from the detection noise power spectral density N_{PSD} for the locked laser and the discriminator slope D of the error signal via[27]

$$\sigma_f(\tau) = \frac{N_{PSD}}{\sqrt{2}Df_L}\tau^{-1/2}, \tag{1}$$

and from the measured values we obtain $\sigma_f(\tau) \approx 2\times 10^{-12}\tau^{-1/2}$. This value coincides with the measured short-term stability, and is also competitive with the best results previously reported by Ye *et al.* for diode laser stabilization to Rb saturated absorption resonances, which however used a significantly larger and more sophisticated setup.[30]

In order to evaluate the sources of limitations to the frequency stability measured at medium-term integration times around $\tau \approx 10^4$ s and beyond, the influence of several experimental parameters on the frequency position of the saturated absorption reference lines was evaluated for the simple spectroscopic setup used in the laser head.[25,28] Table II lists the measured sensitivity of the Doppler-free resonance frequencies to variations of selected parameters, which are in good agreement with the values reported in previous studies[29,30] for more elaborated setups. Table II also gives the resulting frequency drifts of the stabilized laser, calculated from typical parameter variations over $\tau = 10^4$ s encountered in our experiments. Variations in the reference cell temperature show the strongest impact on the laser frequency, probably due to changes in the background Doppler profile and light absorption in the cell varying with the Rb atomic density.[32] Second important are changes in the angle between pump and probe beam, caused by the turning diffraction grating. The resulting total frequency drift over 10^4 s amounts to 1.4×10^{-12} (i.e., 0.6 kHz), consistent with the measured laser frequency stability over these time scales.

We estimate that further improvement of the medium-term stability limit by about a factor of 10 is possible by reducing the identified limitations due to experimental parameters. Such measures include improved thermal control of the reference cell by implementation of a separate temperature stabilization, that would overcome current limita-

TABLE II. Sensitivity of the stabilized laser frequency to changes in experimental parameters applying to the saturated absorption setup, and frequency drift estimates due to parameter variations typically encountered in the setup. Experimental values are given for the crossover lines showing the strongest shift rates, while values for the $F=2\rightarrow 3$ line were found to be 3–10 times smaller. [Literature values by Barwood *et al.* (Ref. 29) refer to Doppler-free saturated absorption resonances of the ^{85}Rb D_1 line, those from Ye *et al.* (Ref. 30) to the ^{87}Rb D_2 line. Both works used $3f$ lock-in detection.]

Parameter	Measured	Literature sensitivity	Parameter drift over 10^4-10^5 s	Frequency drift over 10^4 s(kHz)
Magnetic flux density	1.2 kHz/μT	2 kHz/μT[a]	0.01 μT[b]	0.012
Optical pump beam intensity	0.2 kHz cm^2/μW	7 Hz cm^2/μW[c]	0.25 μW/cm^2[d]	0.05
Cell temperature	4 kHz/K	<10 kHz/K[e]	0.1 K[d]	0.4
Pump-probe beam angle	80.2 kHz/mrad	40 kHz/mrad[f]	0.9 μrad[d]	0.07
FM modulation amplitude	5 kHz/MHz	5 kHz/MHz[f]	4 kHz[g]	0.02
Total drift				0.6 kHz
Total stability σ_f				1.4×10^{-12}
Optimized prediction σ_f				2×10^{-13}

[a]Reference 29.
[b]Field drifts estimated for typical laboratory conditions.
[c]Reference 30. Barwood *et al.* (Ref. 29) report 0.1 kHz cm^2/μW, close to our experimental result.
[d]Experimentally measured parameter drifts.
[e]Estimate for Rb from Ref. 31. Têtu *et al.* (Ref. 32) estimate the rate to be smaller than the corresponding 110 kHz/K shift rate for the linear (Doppler) absorption line.
[f]Reference 29.
[g]Amplitude drifts estimated from the electronics' temperature dependence.

tions arising from the coupled temperatures of the cell and the ECDL. Implementation of a $3f$ demodulation scheme would reduce the sensitivity to changes in the Doppler background, and frequency shifts related to laser intensity changes can be reduced by active control of the laser output power, for example, by acting on the temperature of the laser diode.[10] Providing the entire laser head with an additional layer of magnetic shielding (as would be the case in a Rb clock) and a modified ECDL design to provide a stable output beam direction[1,16,33] should further contribute to reach an improved laser frequency stability around 2×10^{-13} at 10^4 s or beyond.

V. APPLICATION EXAMPLES

The reported results make our compact laser head well suited for use in laser-pumped Rb atomic clocks, and possibly in other applications such as atomic magnetometers, optical interferometers or as compact wavelength references. In the latter case, the frequency accuracy of the laser head will have to be studied in more detail, while up to today we only roughly estimated its reproducibility to be better than about 5 MHz. However, this accuracy is already sufficient for calibration of high-resolution optical wavelength meters. We have also successfully used the laser head as reference radiation source for spectral characterization of other diode lasers with broader emission spectra.[34]

A modified version of the laser head operating at the Cs D_2 line at 852 nm was also realized, showing similar performances. Furthermore, several versions of the compact (54 cm^3) ECDL design described here but without the compact reference unit were realized, that emit at 935 nm for water vapor spectroscopy, and at the Cs D_1 and D_2 lines at 894 nm and 852 nm, respectively. We finally note that recently intrinsically single-mode diode lasers such as, for example, distributed feedback (DFB) or distributed Bragg reflector (DBR) laser diodes have started to become commercially available, that show narrow linewidths around 6 MHz without the need for external optical feedback,[34] which are sufficiently narrow to resolve Rb saturated absorption resonances. These diodes therefore offer excellent perspectives to eliminate the need for the ECDL's moving diffraction grating with its sensitivity to vibrations and for further miniaturization of the laser source and thus of the entire laser head, while maintaining an excellent frequency stability.

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