Low phase noise diode laser oscillator for 1S – 2S spectroscopy in atomic hydrogen

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We report on a low-noise diode laser oscillator at 972 nm actively stabilized to an ultra-stable vibrationally- and thermally compensated reference cavity. To increase the fraction of laser power in the carrier we designed a 20 cm long external cavity diode laser with an intra-cavity electro-optical modulator. The fractional power in the carrier reaches 99.9 % which corresponds to a rms phase noise of $\varphi^2_{\mathrm{rms}} = 1\,\mathrm{mrad}^2$ in 10 MHz bandwidth. Using this oscillator we recorded 1S – 2S spectra in atomic hydrogen and have not observed any significant loss of the excitation efficiency due to phase noise multiplication in the three consecutive 2-photon processes.

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Frequency stabilized diode lasers have become a powerful tool for high-resolution spectroscopy and precise optical frequency measurements [1,2]. The combination of wide tuning range, compact size, low power consumption and reasonable price make them excellent light sources for e.g. transportable frequency standards [3]. Significant progress in stability and size reduction is reached by implementation of mid-plane suspended reference cavities [4]. On the other hand, semiconductor power amplifiers allow efficient generation of higher harmonics which can be used for excitation of narrow atomic transitions in the UV region [5]. In this case, requirements to the frequency stability of an oscillator become much more stringent. First, each two-photon process quadruples the spectral line width of an oscillator emitting a phase-diffusion field [6]. Secondly, the multiplication of phase noises in a multi-photon process results in a reduction of the power accumulated in the carrier and losses in the excitation efficiency of narrow atomic resonances [7]. The latter is a serious problem for diode lasers because of their excessive noise level [8]. The spectral line width of a solitary laser diode may reach hundreds of megahertz while optical and/or electronic feedback can suppress phase fluctuations only to a certain extent.

Previously [5, 9] we reported on a frequency-quadrupled master-oscillator power-amplifier (MOPA) diode laser system for high-resolution two-photon 1S – 2S spectroscopy in atomic hydrogen at 243 nm. The presence of short-correlated phase noise of the oscillator reduced the excitation efficiency to about 40% compared to the case if the whole power was concentrated in the carrier. This paper describes design and characterization of a low phase noise diode oscillator at 972 nm which has already been used in a number of precision measurements providing the significant increase of their accuracy [10,11]. Besides applications in high-resolution spectroscopy of hydrogen and, probably, of anti-hydrogen [12–14], this laser system may be used for creating an intense cold beam of metastable hydrogen atoms. The latter may improve the accuracy of spectroscopy of highly excited states in H [15] and facilitate resolving the proton charge radius puzzle [16].

The key improvement was the design of the external cavity diode laser (ECDL) in a Littrow configuration at 972 nm with a cavity length of $L = 20$ cm long (see Fig. 1). According to [17], reduction of the phase noise and narrowing of the (unlocked) ECDL spectral line width is achieved by increasing the length of the external cavity according to $\Delta\nu = \Delta\nu_{\mathrm{LD}}/(1+L/(nL_{\mathrm{LD}}))^2$, where $\Delta\nu_{\mathrm{LD}}$ is the spectral line width of the solitary diode, n and L_{LD} are its refractive index and the length. Other approaches [18] may be used as well.

Our long ECDL consists of a 100 mW laser diode (without anti-reflection coating), an electro-optical modulator (EOM, model PM25 from Linos) and a

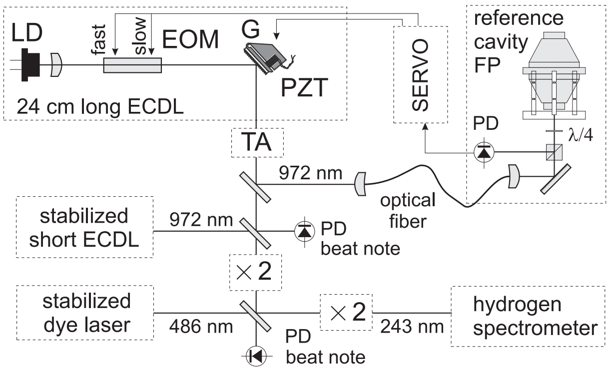

Fig. 1. Schematic of the setup. EOM – electro-optical modulator; G – diffraction grating; PZT – piezo actuator; TA – tapered amplifier; PD – photodiode. The long ECDL is actively stabilized to the vibrationally and thermally compensated ULE cavity FP [9].

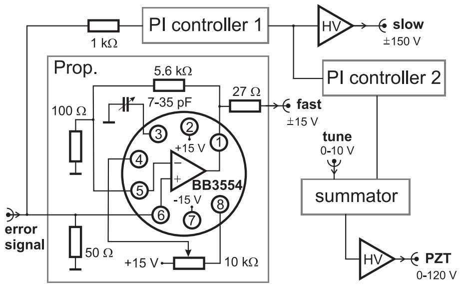

Fig. 2. Schematics of the servo loop used to control the frequency of the long cavity ECDL. Notations of output signals correspond to Fig. 1. The error signal is taken directly from the output of the phase detector RPD-1 (Mini-Circuits) heterodyning the PDH photodiode output. PI denote conventional proportional-integrating controllers, HV — high voltage amplifiers.

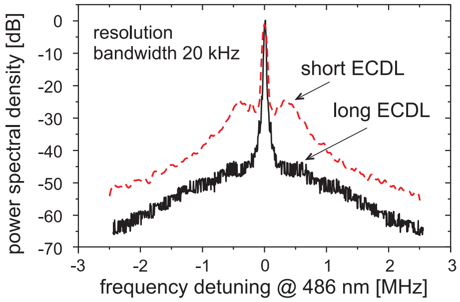

Fig. 3. (Color online) Power spectrum density of the beat notes between the stabilized dye laser and the second harmonic of the long ECDL (solid line) or the short ECDL (dashed line). Carrier amplitudes are normalized to 0 dB.

1200 lines/mm holographic diffraction grating with a diffraction efficiency of 30%. The single mode operation was readily achieved by adjustment of the injection current while the typical mode hop-free tuning range is of 500 MHz. The ECDL is mounted on a temperature-controlled breadboard placed in a sealed metal box additionally protected from outside by a heavy plywood box. This setup allows to find the desired wavelength in a few minutes and provides robust operation in an air-conditioned laboratory over the whole day.

Similar to [19, 20] we used a Brewster angle intracavity EOM to control the ECDL frequency. An attempt to use the injection current modulation resulted in increased phase noise and caused mode hops. To suppress noise coming from injection current we filter it by a chain of capacitors and inductances directly at the laser diode. Fine rotation and tilt adjustments of the EOM are necessary to minimize the amplitude modulation which strongly influences the lock quality.

The laser is phase-stabilized with the help of the Pound-Drever-Hall (PDH) method [21] to the vibrationally and thermally compensated Ultra Low Expansion (ULE) glass Fabry-Pérot cavity described in details in [9]. Electronics used for locking the laser is sketched in Fig. 2. For compensation of fast fluctuations a fast proportional BB3554-based amplifier with 3 MHz bandwidth is connected to one of the EOM's electrodes. Robust long-term locking is achieved using a proportional-integrating controller (PI 1) and the high-voltage amplifier connected to the second electrode of the EOM. Even better long-term lock stability is reached by the second controller (PI 2) working as pure integrator with a time constant of 1 s used to stabilize the average output of PI 1 via controlling the voltage on the piezo-element attached to the grating. Such combination provides stable and robust lock over more than 5 hours.

The ULE cavity has a symmetrical configuration which significantly suppresses the influence of vertical accelerations [4] while low sensitivity to thermal fluctuations is provided by cooling the cavity to the ULE zero expansion point of +12.5 °C using Peltier elements [9]. This design provides sub-hertz spectral line width of the laser at a drift rate of about 50 mHz/s.

To characterize the phase noise of the ECDL we recorded the beat note of its second harmonic with a stabilized 486 nm dye laser [22]. Although the carrier of the dye laser is much broader than that of the diode laser (60 Hz compared to 1 Hz at 486 nm), it is a useful tool to study short-correlated phase fluctuations of the diode laser. The dominating phase perturbations in the dye laser come from acoustic fluctuations in the dye jet and have much lower frequencies compared to ones in the diode lasers.

The beat note spectrum is shown in Fig. 3. We ascribe the noise pedestal around the carrier to the ECDL since it shows some sensitivity to the parameters of ECDL's electronic feedback and is independent of the dye laser electronics. When we switch off the feedback of the long ECDL, the spectrum shape remains almost the same which indicates that the free running ECDL has a line width of less than 20 kHz. Calculating the power fraction in the noise pedestal, we evaluate the rms phase noise of the long ECDL of $\varphi^2_{\text{rms}} = 1\,\text{mrad}^2$ at 972 nm in 10 MHz bandwidth.

Using the same method we investigated the phase noise of a short 972 nm ECDL with a cavity length of 2 cm [5, 9]. The laser is locked to the second vibrationally and thermally compensated ULE cavity with the same characteristics as the first one. For this laser we could achieve the lowest rms phase noise of only $\phi^2_{\text{rms}} = 13\,\text{mrad}^2$ (10 MHz bandwidth) by a fine adjustment of the electronic feedback. It was a compromise between the light power coupled to the cavity, bandwidth and gain of the servo loop.

When amplifying and frequency quadrupling the long ECDL, up to 15 mW of spectrally pure light at 243 nm become available for hydrogen spectroscopy. The direct comparison between 1S – 2S excitation rates for the long ECDL oscillator based system and the frequency doubled dye laser is shown in Fig. 4. Atoms excited from the ground state in the cold beam at 13 K are detected

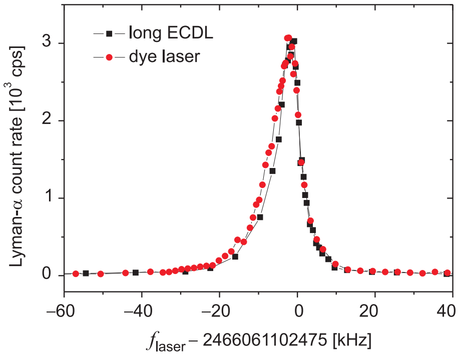

Fig. 4. (Color online) 1S − 2S spectrum of atomic hydrogen recorded with the 20 cm long ECDL (squares) and dye laser (circles). The power levels of light at 243 nm exciting the two-photon transition were equal for both cases. The broader spectrum recorded using the dye laser is the result of its broader line width.

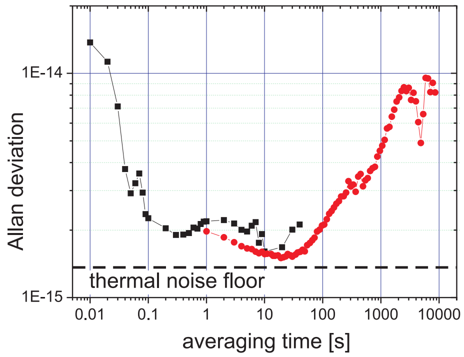

Fig. 5. (Color online) The Allan deviation of the beat note frequency between the long and the short ECDL's stabilized to two equivalent independent ULE cavities. Drift is not subtracted. Data are recorded by FX80 Klische+Kramer counter with the gate times of 10 ms (squares) and 1 s (circles).

by counting Lyman-α photons which are emitted when the 2S state decays in an electric field (for details see e.g. [11]). Recording the spectra in a few minutes interval we have not observed any significant difference in the excitation efficiencies.

Since 8 photons at 972 nm contribute to an excitation of the 2S state, for the long ECDL we expect the change of an excitation efficiency by a factor of only $\eta = \exp[-(8\varphi_{\mathrm{rms}})^2] = 0.94$ [7] which turned out to be rather insensitive on adjustments of the electronic feedback. For comparison using the short ECDL one could reach an excitation efficiency of only $\eta = 0.44$, which, together with a high sensitivity to feedback parameters, did not make it suitable for high-precision experiments.

Along with excellent short-correlated phase noise characteristics, long ECDL possesses high long-term stability of the temperature and vibrationally compensated ULE cavity. Fig. 5 shows an Allan deviation plot recorded for the beat note between the long and the short ECDLs stabilized to two independent but similar ULE cavities. The Allan deviation nearly reaches the thermal noise floor evaluated as 1.4×10^{-15} for the cavities [23].

In conclusion, we have developed a diode laser system at 972 nm with a low phase noise level of $\varphi^2_{\mathrm{rms}} = 1\,\mathrm{mrad}^2$ in 10 MHz bandwidth and 0.5 Hz spectrally narrow carrier containing 99.9% of the laser power. This compact system allows efficient excitation of the $1S - 2S$ transition in H and D, which is useful for high precision experiments and production of metastable H beams.

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