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 ultrastable 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 intracavity electro-optical modulator. The fractional power in the carrier reaches 99.9%, which corresponds to an rms phase noise of $\varphi^2_{\rm rms} = 1\,{\rm mrad}^2$ 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 two-photon processes. © 2011 Optical Society of America

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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, e.g., for transportable frequency standards [3]. Significant progress in stability and size reduction is reached by implementation of midplane 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 of the frequency stability of an oscillator become much more stringent. First, each two-photon process quadruples the spectral linewidth of an oscillator emitting a phase-diffusion field [6]. Second, the multiplication of phase noises in a multiphoton 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 linewidth 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 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 Letter describes design and characterization of a low phase noise diode oscillator at 972 nm. It 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 antihydrogen [12], 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 [13] and facilitate resolving the proton charge radius puzzle [14].

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 $L = 20\,{\rm cm}$ (see Fig. 1). According to [15], reduction of the phase noise and narrowing of the (unlocked) ECDL spectral linewidth is achieved by increasing the length of the external cavity according to $\Delta\nu = \Delta\nu_{\rm LD}/(1 + L/(nL_{\rm LD}))^2$, where $\Delta\nu_{\rm LD}$ is the spectral linewidth of the solitary diode, n and $L_{\rm LD}$ are its refractive index and the length. Other approaches [16] may be used as well.

Our long ECDL consists of a 100 mW laser diode, an electro-optical modulator (EOM, model PM25 from Linos), and a 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 500 MHz, which is approximately 10 times less compared to a short ECDL with a cavity of only 2 cm length [9]. The long ECDL is mounted on a temperature-controlled breadboard placed in a sealed metal box

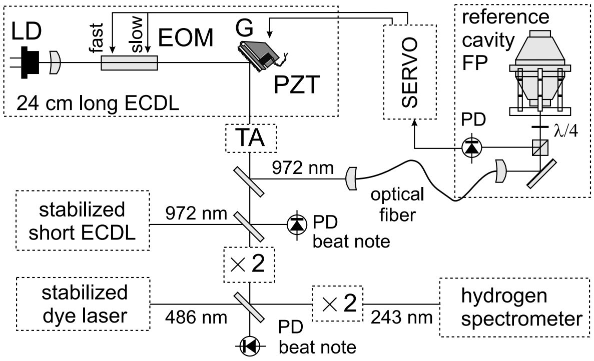

Fig. 1. Schematic of the setup. EOM, electro-optical modulator; G, diffraction grating; PZT, piezo actuator; TA, tapered amplifier; PD, photodiode. The long ECDL is actively stabilized to the vibrationally and thermally compensated ULE cavity FP [9].

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additionally protected from laboratory ambient 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 [17,18], 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 the 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 [19] to the vibrationally and thermally compensated ultralow expansion (ULE) glass Fabry–Perot cavity described in detail in [9]. The cavity is placed on a separate vibrationally isolated platform connected with the main table by an optical fiber with an active noise cancellation. Similar to [9], phase modulation at 20 MHz for PDH locking scheme was set by an EOM placed on the cavity's platform.

Electronics used for locking the laser are 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). It works as a pure integrator with a time constant of 1 s and is 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 h.

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].

To characterize the phase noise of the ECDL we recorded the beat note of its second harmonic with a stabilized 486 nm dye laser [20]. 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 the ones in the diode lasers.

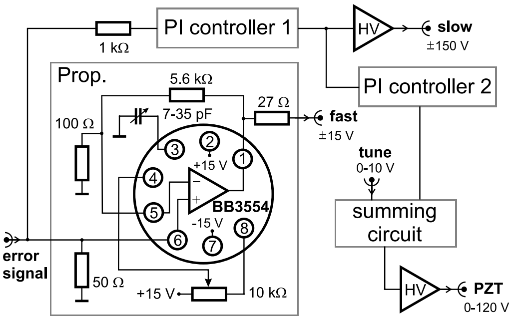

Fig. 2. Schematics of the servo loop used to control the frequency of the long cavity ECDL. Notations of output signals correspond to Fig. 1. The error signal is taken directly from the output of the phase detector RPD-1 (Mini-Circuits) heterodyning the PDH photodiode output. PI denotes conventional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

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 the ECDL's electronic feedback and is independent of the dye laser electronics. Beating the light emitted by the ECDL with the amplified light shows that the tapered amplifier does not contribute additional noise at a detectable level [9]. When we switch off the feedback of the long ECDL, the spectrum shape remains almost the same. The free-running ECDL has a linewidth of less than 20 kHz, which is given mainly by vibrations and injection current noise. It is a reduction of more than an order of magnitude compared to a free-running short 2 cm ECDL described in [9]. Calculating the power fraction in the noise pedestal, we evaluate the rms phase noise of the long ECDL of $\varphi_{\mathrm{rms}}^2 = 1\,\mathrm{mrad}^2$ 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 $\phi_{\mathrm{rms}}^2 = 13\,\mathrm{mrad}^2$ (10 MHz bandwidth) by a fine adjustment of 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 became 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 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 eight 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

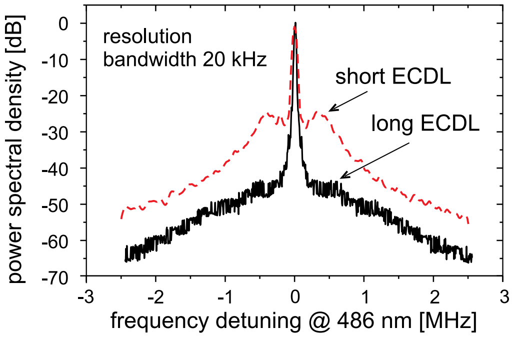

Fig. 3. (Color online) Power spectrum density of the beat notes between the stabilized dye laser and the second harmonic of the long ECDL (solid line) or the short ECDL (dashed line). Carrier amplitudes are normalized to 0 dB.

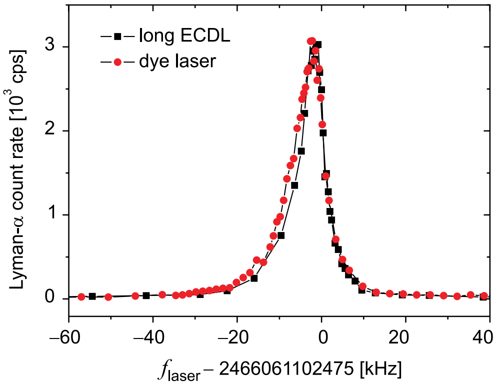

Fig. 4. (Color online) 1S–2S spectrum of atomic hydrogen recorded with the 20 cm long ECDL (squares) and dye laser (circles). The power levels of light at 243 nm exciting the two-photon transition were equal for both cases. The broader spectrum recorded using the dye laser is the result of its broader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

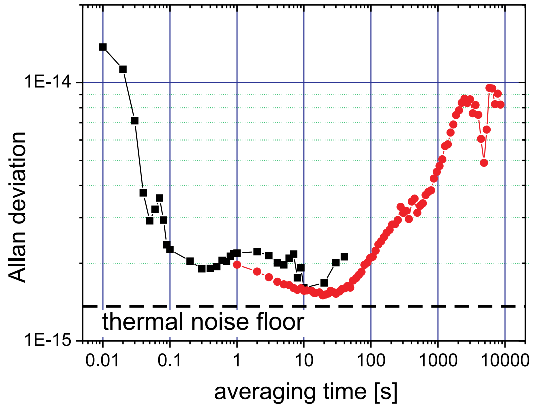

Fig. 5. (Color online) The Allan deviation of the beat note frequency between the long and the short ECDLs stabilized to two equivalent independent ULE cavities. Drift is not subtracted. Data are recorded by FX80 Klische+Kramer counter with a gate time of 10 ms (squares) and 1 s (circles).

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, the long ECDL possesses high long-term stability of the temperature and vibrationally compensated ULE cavity. Figure 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 [21]. The long ECDL's carrier has a spectral linewidth of 0.5 Hz (10 s averaging time) at a drift rate of about 50 mHz/s.

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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