Eur. Phys. J. Special Topics **163**, 89–94 (2008)

DOI: 10.1140/epjst/e2008-00811-y

THE EUROPEAN
PHYSICAL JOURNAL
SPECIAL TOPICS

Stable diode lasers for hydrogen precision spectroscopy

J. Alnis[1,a], A. Matveev[1,2], N. Kolachevsky[1,2], T. Wilken[1], R. Holzwarth[1], and T.W. Hänsch[1]

[1] MPI für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany
[2] P.N. Lebedev Physics Institute, Leninsky Prosp. 53, 119991 Moscow, Russia

Abstract. We report on an external cavity diode laser at 972 nm stabilized to a mid-plane mounted Fabry-Perot (FP) resonator with a finesse of 400000. The 0.5 Hz optical beat note line width between two similar lasers (Allan deviation 2×10^{-15}) is limited by thermal noise properties of two independent FP resonators. The long term drift of the FP resonator and mirror substrates made from Ultra-Low-Expansion glass (ULE) is small and can be well predicted on time intervals up to many hours if the resonator is stabilized at the zero thermal expansion temperature T_c. Using a Peltier element in a vacuum chamber for temperature stabilization allows stabilization of the FP cavity to T_c which is usually below the room temperature. Beat note measurements with a femtosecond optical frequency comb referenced to a H-maser during 15 hours have shown a well defined linear drift of the FP resonance frequency of about 60 mHz/s with residual frequency excursions of less than ±20 Hz.

1 Introduction

In this paper we report on an external cavity diode laser (ECDL) system at 972 nm having a sub-Hz optical line width. Previously we have shown that the light from this laser can be efficiently frequency quadrupled to 243 nm [1] which is necessary for high-resolution spectroscopy of the $1S - 2S$ transition in atomic hydrogen [2].

The narrow line width and the long term frequency stability of this ECDL is achieved by active stabilization to a Fabry-Perot (FP) resonator with a finesse of 400000 at 972 nm. The 77.5 mm long Ultra Low Expansion (ULE) glass spacer and mirrors on ULE substrates were produced by Advanced Thin Films, Colorado, USA. The FP resonator is mounted at the horizontal mid-plane with its optical axis directed vertically. Such configuration significantly reduces the sensitivity to vertical vibrations [3,4].

2 ULE FP resonator assembly

The zero thermal-expansion point of the ULE is often below room temperature. Though heating of the vacuum vessel containing the FP cavity above the room temperature poses no problems, cooling below +15 °C is very difficult due to the water condensation. Using a Peltier element installed directly inside the vacuum chamber we can easily cool or heat FP resonator in the necessary temperature range.

Our FP resonator is surrounded by two nested heat shields as shown in Fig. 1. The cylindrical shields with end caps are made from Duralumin and have a 7 mm wall thickness. The Al surface

[a] e-mail: Janis.Alnis@mpq.mpg.de

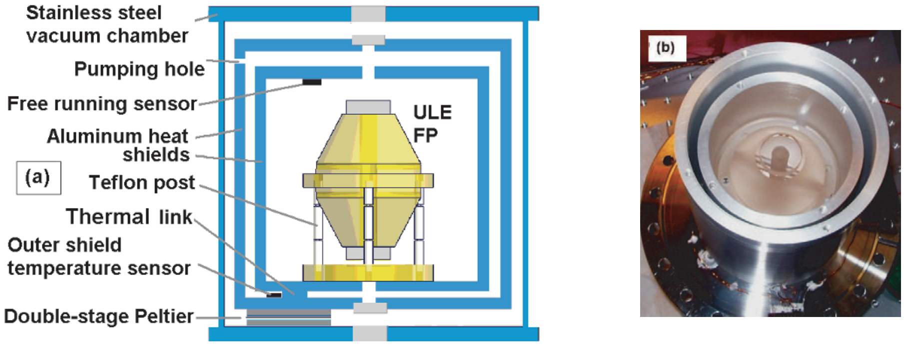

Fig. 1. (a) ULE FP cavity mounted vertically at the horizontal midplane and surrounded by two nested heat shields placed on the bottom plate of the vacuum chamber. The shields are temperature stabilized by a double-stage Peltier element placed between the outer shield and the bottom plate of the vacuum chamber. (b) A photo of the FP cavity placed inside the heat shields with the top covers removed.

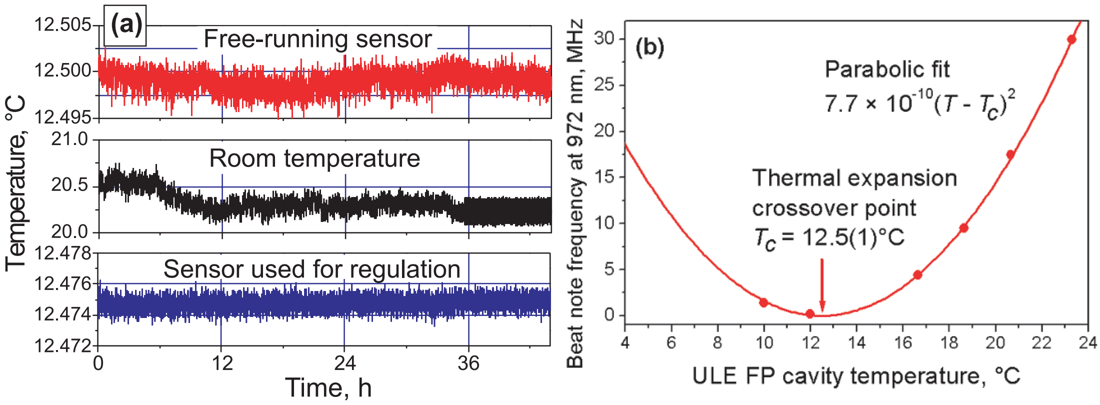

Fig. 2. (a) Temperature stability of the inner shield measured in two places and room temperature. (b) Measurement of the zero-expansion temperature T_c of the ULE FP (dots) and a parabolic fit to the data. Thermal sensitivity estimation within $T_c \pm 0.1\,°\mathrm{C}$ is less than 20 Hz/mK and it is about the same as a calculated contribution from two 5 micrometer thick FP mirror coatings assuming a linear expansion coefficient of the coatings of $0.5 \times 10^{-6}/°\mathrm{C}$.

is treated for UHV compatibility with NaOH and HNO_3 [5]. A 20 l/s ion pump achieves vacuum of 8×10^{-8} mbar.

Previously we had reported on a similar construction with two Peltier elements [6]. Now we have simplified the assembly using only one Peltier element without compromising the long term stability. The outer shield is stabilized to the zero expansion temperature of the ULE FP resonator using a $3 \times 3\,\mathrm{cm}^2$ double-stage Peltier element (type 2 SC 040 050-127-63 from *Melcor*). This Peltier element allows to cool down the shield to $+2\,°\mathrm{C}$ with a 1 A of current while the vacuum chamber serves as a heat sink. A second shield named the inner shield is thermally coupled to the outer one through a $2\,\mathrm{cm}^2$ area directly nearby the sensor used for temperature regulation of the outer shield. We use a proportional-integrating (PI) temperature controller which maintains the temperature stability of the sensor better then 1 mK in one day interval. The temperature on a very distant point of the inner shield is stable within a few mK per day, as shown on Fig. 2(a).

We determined the zero-expansion temperature T_c of this ULE FP resonator from optical beat note measurements at several different temperatures using the other stable FP cavity as a frequency reference, see Fig. 2(b).

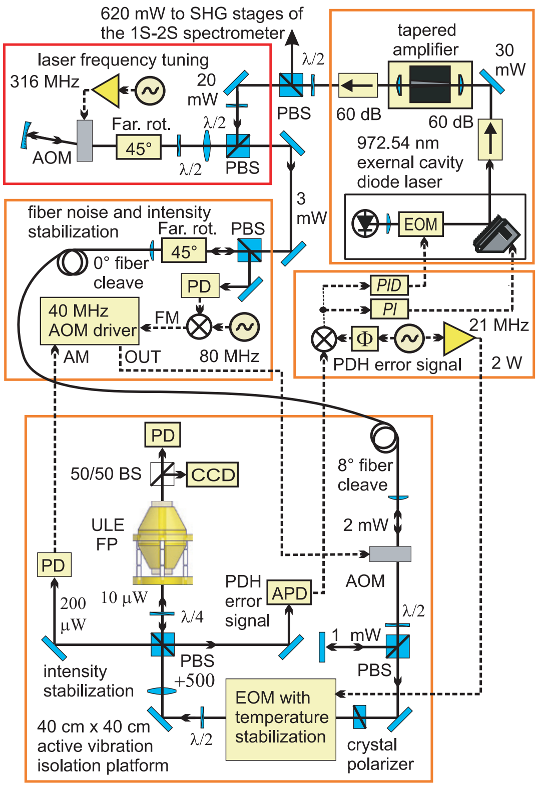

Fig. 3. Diode laser stabilization scheme to the vertical FP resonator. The diode laser has a 24 cm long Littrow external cavity with an intra-cavity electro-optic modulator (EOM) used for fast frequency regulation. The long cavity of the diode laser reduces the high-frequency noise of the laser diode so that the spectral line width of the free running laser is 20 kHz. Laser frequency can be scanned with respect to a FP cavity resonance using a double-pass acousto-optic modulator (AOM). Another AOM is used for the fiber noise cancellation. PD is a photodiode with a preamplifier, APD is an avalanche photodiode.

A parabolic fit of the data points has a minimum at $T_c = 12.5(1)\,°\mathrm{C}$. The temperature sensitivity within 0.1 °C of the T_c is around 20 Hz/mK. It is interesting to note, that the mirror coatings (CTE approximately 0.5×10^{-6}) with the total thickness of only $5\,\mu$m significantly contribute to this value on the level of 10 Hz/mK.

The FP resonator vacuum assembly and optics are placed on an active vibration isolation platform surrounded by a sound-proof box. The light is transmitted to the platform through a 10 m long optical fiber employing a fiber-noise cancellation [8].

The laser is locked to the FP resonator using the Pound-Drever-Hall (PDH) locking scheme [9]. A resonant EOM (LM 0202 PHAS) creates the modulation sidebands necessary for the PDH lock.

3 External cavity diode laser

Fig. 3 shows the optical setup used for the diode laser stabilization. The diode laser has a 24 cm long resonator in Littrow configuration with an intra-cavity electro-optic modulator used for fast control of the laser frequency [7]. The long ECDL resonator acts like a flywheel suppressing phase noise of the laser diode chip. The low phase noise property is a critical parameter for the hydrogen spectroscopy due to the noise multiplication in each two-photon process because the hydrogen resonance is at the eighth harmonic of the infrared laser frequency. The ECDL with a 24 cm long external resonator is assembled on a temperature controlled 3 cm thick

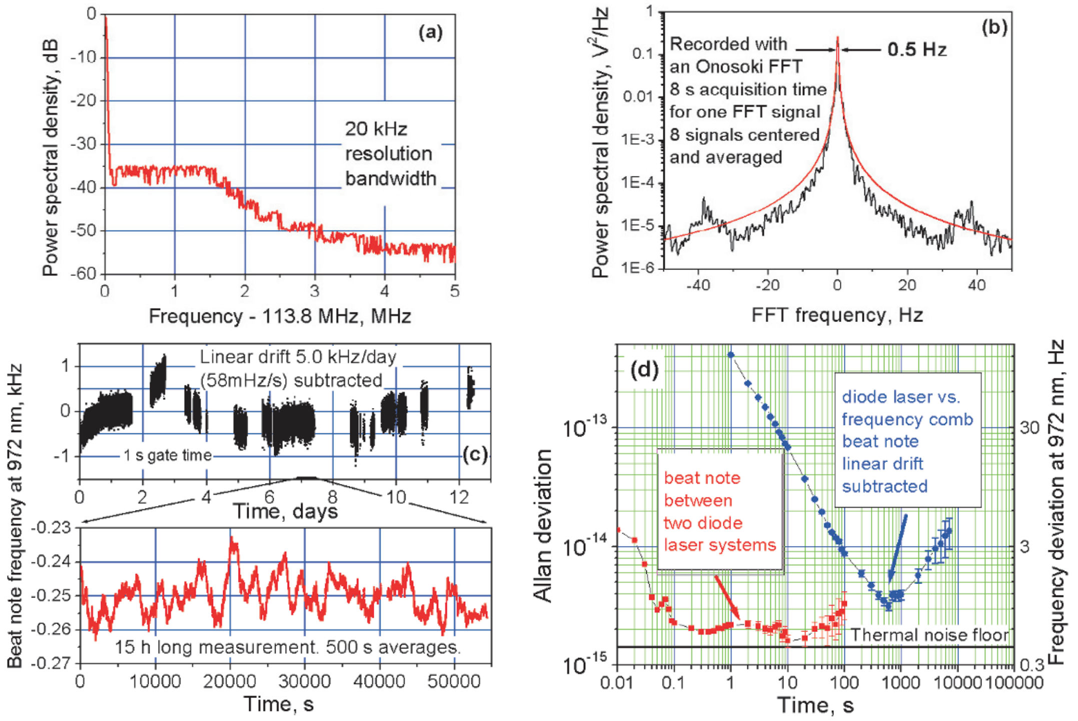

Fig. 4. (a) One-sided power spectral density of the beat note between two diode lasers stabilized to independent vertically mounted FP resonators. (b) Fast Fourier transform spectrum of the beat note between two diode lasers. (c) Long term recording of the beat note frequency between the diode laser stabilized to the FP cavity at T_c and a frequency comb referenced to an active H-maser. (d) Allan deviation of the beat note.

Al breadboard placed inside an air-tight box. We used a 150 mW laser diode (Toptica LD-0975-0150-1) that was not AR coated. We also tried a 50 mW AR coated laser diode (Toptica LD-0935-0050-AR-2), but the power was not enough to saturate the tapered amplifier (TA). A more critical part of the laser is the diffraction grating. First we tried a 1200 lines/mm grating that allowed us to get much output power, but since it diffracted back into the laser diode only 3% of power, the laser was very sensitive to a back reflection from the TA and it was necessary to use two 60 dB optical isolators in series. Afterwards we replaced the grating with one that diffracts 25% of light back into the laser diode and a single 60 dB optical isolator was enough for stable operation. The long cavity diode laser can't be tuned as usual by the injection current because now the laser diode crystal has a relatively weak influence on the light stored in the long resonator and also the small free spectral range causes more frequent mode jumps. The mode-hop free tuning range using a diffraction grating controlling piezo is 0.7 GHz. For fast frequency tuning we use an intra-cavity electro-optical modulator (EOM) (Linos PM25) with Brewster-angle crystals [7]. The EOM requires a fine – alignment possibility around the optical axis to minimize the amplitude modulation or else the electronic feedback of the lock to the FP resonator self-oscillates. The electronic feed-back loop has 1 MHz regulation bandwidth. We did not experience any trouble with the relaxation oscillations of the laser diode at 1–3 GHz frequency.

4 Optical beat note measurements

For the optical beat note measurements we have set up a second stable ECDL. It had a commonly used 2 cm long external cavity in Littrow configuration. For its frequency stabilization to an external high-finesse FP cavity the injection current was controlled via an injection current using a fast proportional-integrating-differentiating (PID) regulator. The noise pedestal shown in Fig. 4(a) originates mostly from this short-cavity ECDL. The second FP had the same optical characteristics and suspension, except its temperature could only be stabilized by heating. The stabilization point was about 20 °C above the zero expansion temperature resulting in a 10 kHz/mK frequency sensitivity to temperature variations which is three orders of magnitude larger than for the first cavity. The beat note line width between the two independent lasers recorded with a FFT analyzer was typically 0.5 Hz FWHM, see Fig. 4(b). This value is very close to the calculated thermal noise limit of our FP reference resonator [10]. The Allan deviation Fig. 4(d) shows a thermal noise limited laser performance of 2×10^{-15} between 0.1 s and 30 s. For longer times the thermal drift of the heated FP dominates. The beat note was recorded with a delay-free counter (model K+K FX-80) allowing to juxtapose the data used for Allan deviation [11].

For absolute frequency drift measurements of the stabilized diode laser we recorded an optical beat note with a femtosecond frequency comb which was referenced to an active hydrogen maser. Long term measurements during 2 weeks revealed a nearly linear drift of the FP that was stabilized at the zero expansion temperature, see Fig. 4(c). The linear slope was 5.0(5) kHz/day. The figure also shows an interval of 15 hours where after removing a linear slope of 60 mHz/s the residual frequency excursions stayed within ±20 Hz. The FP Allan deviation of this beat note reached a minimum of 3×10^{-15} at 500 s. We ascribe the linear drift mostly to the ageing process of the ULE glass. The drift rate was not exactly the same for different days and changed slightly each time the diode laser was relocked. We ascribe this effect to a change of laser locking and alignment parameters.

5 Conclusions

We have stabilized a 972 nm diode laser to a mid-plane mounted FP resonator with a finesse of 4×10^5 and have reached excellent spectral properties of the system. The achieved 0.5 Hz spectral line width of the carrier is mostly limited by the thermal noise of the FP. The long term drift of the FP resonator can be well predicted as the resonator is stabilized at the zero thermal expansion temperature where it is least sensitive to temperature fluctuations. After the removal of a linear drift of 60 mHz/s the residual frequency excursions were within ±20 Hz during 15 hours of measurement. The important advantage of the ULE FP resonator stabilized by a Peltier element in vacuum is very broad range of achievable temperatures ($+2 \cdots +35\,°$C) which lifts up the necessity of careful pre-selection the ULE glass with desired zero expansion point.

We are very grateful to Hall/Ye group at JILA for frequent help. This work is partly supported by the DFG cluster of excellence Munich Center for Advanced Photonics (MAP). N.K. acknowledges support by Alexander von Humboldt Foundation, Russian Science Support Foundation and RFBR grants 08-02-00443, 08-07-00127. J.A. acknowledges support by EU FP7 Marie Curie Actions.

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