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Long-term stabilization of the length of an optical reference cavity

Gaëtan Hagel, Marie Houssin, Martina Knoop,[a] Caroline Champenois, Michel Vedel, and Fernande Vedel
Physique des Interactions Ioniques et Moléculaires, Université de Provence-CNRS (UMR6633), Centre de Saint Jérôme, Case C21, 13397 Marseille Cedex 20, France[b]

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To obtain a high degree of long-term length stabilization of an optical reference cavity, its free-spectral range is locked by means of an accurate and stable frequency synthesizer. The locking scheme is twofold: a laser is locked on the *N*th mode of a reference Fabry-Perot cavity and part of the laser light is shifted in frequency to be in resonance with the (N+1)th mode of the cavity. This shift is generated by an acousto-optical modulator (AOM) mounted in a double-pass scheme, matching half of the free-spectral range of the reference cavity. The resulting absolute stabilization of the length of the cavity reaches the 10^{-11} level per second, limited by the lock transfer properties and the frequency stability of the AOM control synthesizer. © *2005 American Institute of Physics.*
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I. INTRODUCTION

In recent years, optical frequency metrology has made spectacular progress with the implementation of femtosecond frequency combs.[1] Today, the precision and stability of laser frequencies reach beyond the 10^{-14} level, removing the last obstacles for an ultimate investigation of optical frequency standards outpassing the performances of the actual cesium atomic clock by orders of magnitude.[2] Nevertheless, many experimental applications require lasers with less stringent performances, such as a sub-MHz linewidth and an absolute frequency stability, better than the spectral width for time scales of a minute. In our experiment,[3] probing of an atomic transition requires a narrow interrogation laser linewidth, which can be obtained in a straightforward way by stabilizing a laser on a Fabry-Perot cavity of high finesse. The use of the Pound-Drever-Hall (PDH) locking technique[4] permits one to counteract rapid frequency fluctuations and to obtain laser linewidths largely inferior to 100 kHz.

To reach integration times of a couple of minutes, frequency drifts have to be suppressed, which requires stabilization of the length of the reference cavity of the interrogation laser. This can be realized by a maximum isolation from mechanical, acoustic, and thermal perturbations, or by an absolute stabilization on an atomic transition, generally by making use of an additional (diode) laser setup. Stabilization on an atomic transition is often made by the saturated absorption technique to avoid Doppler broadening effects in gas at room temperature. The employed crossover transitions have spectral widths of about 10 MHz (for example, Rb: 5.9 MHz and Cs: 14 MHz), limiting the attainable frequency stabilities to almost three orders of magnitude below these values.

Very few different techniques have been used to ensure an absolute-length stabilization of a reference cavity. They all compare the frequency difference between two eigenmodes of a reference cavity with an external rf frequency applied to a phase or frequency modulation device. The dual-frequency-modulation (DFM) technique with two-phase electro-optic modulators (EOM) in a row has been used in Ref. 5. It has been applied in a slightly modified setup to measure the frequency of molecular transitions with an uncertainty of 2×10^{-8}, where the change in the free-spectral range (FSR) of an optical cavity is tracked by a servo on an EOM.[6] Another implementation is reduced to the use of a single EOM.[7] Long-baseline interferometry uses double-modulation techniques to ensure length determination of the interferometer arms[8] which can reach a relative uncertainty of 10^{-11}.

In this manuscript we describe an alternative scheme for the use of a DFM method for the absolute-length stabilization of an optical cavity for measurements on time scales reaching from several seconds up to hours. In order to avoid a long-term drift of the laser frequency we have chosen to stabilize the length of the reference cavity by locking the frequency difference between its *N*th and (N+1)th longitudinal mode. The frequency difference is generated by an acousto-optical modulator at a fixed value matching half of the FSR of the reference cavity. The high accuracy and stability of a frequency synthesizer are thus transferred to the FSR. The use of acousto-optical modulators at frequencies largely beyond 100 MHz allows the stabilization of short optical cavities. Furthermore, the described method is independent of the existence of nearby atomic transitions. We have demonstrated excellent frequency stability for periods up to an hour.

II. EXPERIMENTAL REALIZATION

The complete experimental setup is shown in Fig. 1. The 729 nm laser is a broad-area diode laser (BAL) mounted in an external cavity to ensure single-mode lasing and to reduce its linewidth.[9] The diode is then stabilized onto a reference

[a]Electronic mail: Martina.Knoop@up.univ-mrs.fr
[b]URL: http://www.up.univ-mrs.fr/ciml/

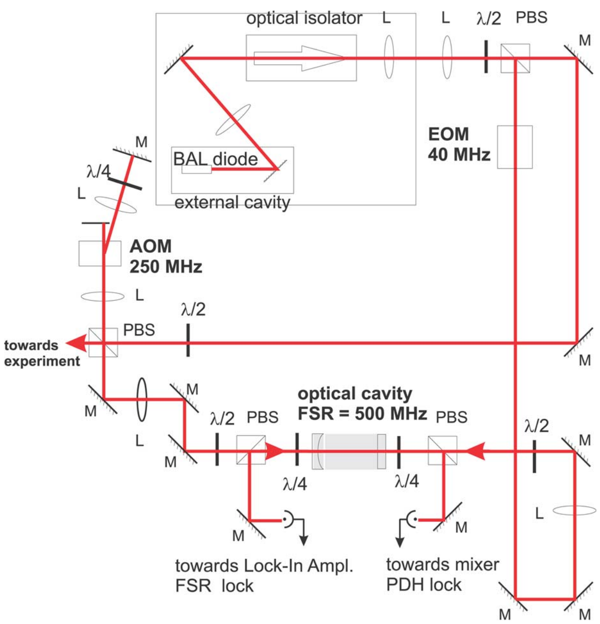

FIG. 1. Experimental setup of the described locking scheme. The signal for the PDH lock of the diode laser enters the cavity from the right, while the signal for the length stabilization of the cavity is injected into the reference cavity from the left side, after a double pass through the 250 MHz AOM. L designs the lenses used for efficient mode matching, while mirrors are noted M, and polarization beam splitters PBS. See text for a detailed description.

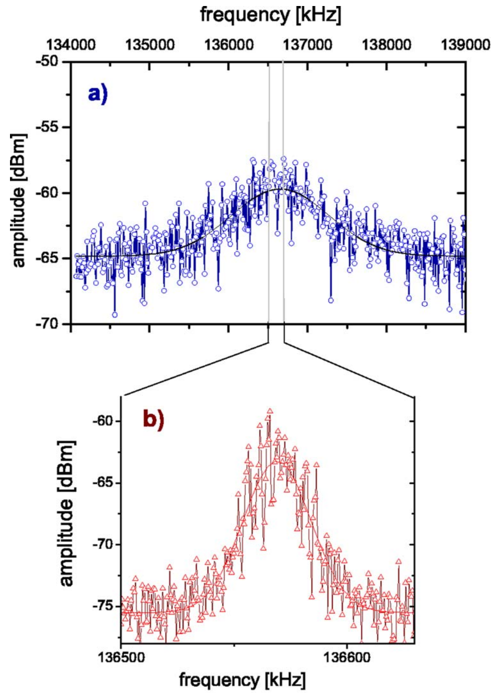

FIG. 2. Beat signal of one part of the 729 nm diode laser with another part of the same laser having passed through a 10 km optical fiber. Part (a) shows a recording for the free-running diode resulting in a spectral linewidth of several hundred kHz; (b) has been recorded with the diode laser being locked to the reference cavity, and results in a spectral linewidth lower than 25 kHz.

cavity by using the Pound-Drever-Hall lock.[4] The laser light is phase modulated at 40 MHz by an EOM. The signal reflected by the cavity is composed of two totally reflected sidebands and a central carrier whose phase depends on the frequency difference with a cavity resonance. Detected by a rapid photodiode, the beat signals between the carrier and the sidebands allow the generation of an error signal that permits frequency corrections up to the cutoff frequency of the cavity and phase corrections beyond.

Our present goal is to enhance the long-term stability of the optical reference cavity. The cavity has a finesse of about 1000, and the spacer between the two mirrors is made out of Invar. This homemade cavity spacer has an outer diameter of 50 mm, an inner diameter of 10 mm, and a length of about 300 mm. The cavity is formed by commercial broadband mirrors (700–900 nm), a plane and a curved one (radius of curvature of 2 m). The plane mirror is mounted on a piezoelectric transducer (PZT) allowing the adjustment of the length of the cavity by application of a dc voltage from 0 up to 150 V, corresponding to a maximum length variation of about 2 μm. In the course of a day, the reference cavity undergoes a slow frequency drift mainly due to temperature variations, in a laboratory where the ambient temperature is stabilized to approximately 1°.

The instantaneous linewidth of the diode laser locked onto the reference cavity has been measured by an autocorrelation technique.[10] The beat signal of a part of the laser beam with a second part of the same beam which has passed through 10 km of an optical fiber is shown in Fig. 2. This beat signal has been acquired with an HP ESA 1500A spectrum analyzer at a 3 kHz bandwidth. While the free-running laser [Fig. 2(a)] has a linewidth of the order of several hundred kHz, which is a typical result for a broad-area diode laser in an external cavity, the linewidth of the locked laser is lower than 25 kHz [Fig. 2(b)]. This is achieved by feeding the frequency corrections of the PDH signal to different elements in the diode-laser cavity setup. Slow fluctuations (up to 200 Hz) are corrected by the piezoelectric element supporting the cavity grating with a resistor-bias stabilization integrator (pseudointegrator).[11] Intermediate corrections (up to 20 kHz) are applied via the diode-laser current source, and rapid frequency corrections are made directly on the anode of the diode laser, making use of a field-effect transistor (FET) mounted as a passive voltage-current convertor.[12] The difference in gain between slow and rapid corrections is approximately 20 dB. The total bandwidth of the servo loop is about 1 MHz.

To increase the stability of the reference cavity in order to avoid a long-term drift of the laser we have chosen to stabilize the length of the cavity by locking the frequency difference between its Nth and $(N+1)$th longitudinal mode. The frequency difference is fixed by a highly stable frequency synthesizer driving the acousto-optical modulator at a frequency corresponding to half of the cavity's FSR. We use an Aeroflex 2030-series frequency synthesizer[13] with an internal frequency standard at 10 MHz [oven-controlled crystal oscillator (OCXO)] having a 0.1 Hz accuracy and a fractional frequency stability at 1 min. of about 5×10^{-10}.

In the described locking scheme, the frequency of the diode laser corresponds to the Nth multiple of the cavity's free-spectral range[14]

$$\nu_{\mathrm{DL}} = (N + \varphi + \Phi)\nu_{\mathrm{FSR}}, \tag{1}$$

where N is the mode number, φ the Fresnel phase shift due to the curvature of the cavity mirrors, and Φ the phase shift which occurs upon reflection due to the finite conductivity of the mirrors. In the following, we are only interested in the frequency difference of two neighboring modes; we may thus assume that these phase shifts are almost identical and that their differences can therefore be neglected.

In addition to the PDH lock of the diode onto the reference cavity, one part of the laser output which has double passed an acousto-optical modulator is injected into the cavity. Note that in our setup this second beam enters the cavity from the opposite side of the PDH lock.

This beam has been offset in frequency by two times $\nu_{\mathrm{AOM}}=249.82$ MHz, fixing the FSR of the reference cavity

$$\nu_{\mathrm{DL}} + 2\nu_{\mathrm{AOM}} = (N+1)\nu_{\mathrm{FSR}}. \tag{2}$$

For the lock loop the driving frequency of the AOM is modulated at $f_m=22$ kHz, with a 100 kHz amplitude corresponding to 6% of the width of the Airy peak of the cavity. The light reflected by the cavity is then collected by a photodiode and demodulated at 22 kHz by a lock-in amplifier. The output of this lock-in is integrated before being sent to the piezoelectric transducer controlling the length of the reference cavity. For long-term corrections a time constant of 1 s has been chosen.

In the present optical setup the two photodiodes generating the error signals are sensitive to both parts of the beam. To avoid crosstalk of the photodiodes in response to both beams, we have separated the counter-reaction by choosing different bandwidths for the two lock loops. In practice, our locking electronics has been realized with a pure integrator in the length stabilization of the reference cavity and a pseudointegrator in the PDH lock limiting the gain at zero frequency. As a consequence, at frequencies below 1 hertz, the corrections applied to the diode laser are negligible compared with those sent to the FSR lock.

The separation of the locks by their bandwidths is the most simple solution, as both loops work on different time scales. In a more general scheme, the lock loops could be separated by making use of orthogonal polarizations. However, the optical separation should be made with Glan-Laser prisms as the polarization beam-splitter cubes used in our setup present an extinction ratio of only 0.01.

A second essential point for a stable configuration of the locking scheme is to choose a frequency modulation f_m of the FSR lock larger than the cutoff of the current corrections in the diode lock ($\approx$2 kHz). At small frequency modulation values (e.g., 1 kHz) the gain of the PDH servo is high (55 dB for the electronic part), producing a strong reaction by correcting the modulation as noise. As a consequence, the lock of the laser on the reference cavity becomes unstable. For best results, we have chosen to modulate the driving frequency of the AOM at 22 kHz, with an amplitude of 100 kHz. At this frequency the electronic PDH gain is about 35 dB, and the modulation does not perturb the PDH lock.

The overall response of the lock is given by the resolution of the employed frequency synthesizer. In fact,

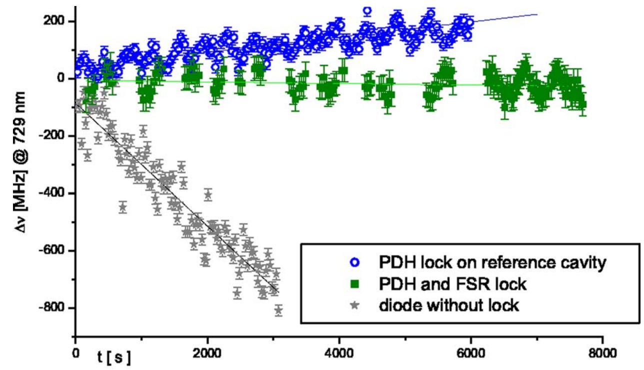

FIG. 3. Temporal evolution of the laser frequency for a free-running laser (★), the laser locked by the PDH method on the optical cavity (○), and the FSR of the cavity locked on the frequency synthesizer (■).

$$\frac{\Delta\nu_{\mathrm{DL}}}{\nu_{\mathrm{DL}}} = \frac{\Delta\nu_{\mathrm{FSR}}}{\nu_{\mathrm{FSR}}} = \frac{\Delta\nu_{\mathrm{synth}}}{\nu_{\mathrm{synth}}}, \tag{3}$$

and the ratio of the FSR to the diode frequency is, in our case,

$$\nu_{\mathrm{DL}} \approx 0.8 \times 10^6 \nu_{\mathrm{FSR}} = 1.6 \times 10^6 \nu_{\mathrm{synth}}. \tag{4}$$

The time constant of the locking electronics is about 1 s to ensure a high long-term stability of the system; the time scale of interest for our experiment is of the order of a couple of minutes. To test the achieved stability, we have therefore measured the evolution of the diode-laser frequency every 30 s making use of a wavemeter, where the employed reference wavelength is a temperature-stabilized HeNe transition at 632.8 nm. The absolute precision of the wavemeter is better than 40 MHz, which has been verified by the frequency resolution obtained on the atomic transition of a single calcium ion during periods of a couple of hours.[15] The temporal evolution of the diode-laser frequency is reported in Fig. 3; the straight lines in this graph are linear fits to the acquired data, reflecting the long-term frequency drifts. On the considered time scales (1 min–3 h) the observed frequency variations have all presented a linear evolution.

The lower curve in Fig. 3 reflects the frequency of the diode laser in an external cavity without any additional stabilization. The frequency drift is almost 800 MHz/h, mainly due to thermal drifts of the high-power diode-laser component, which is a very typical value for a nonstabilized laser. The upper curve shows the fluctuations of the diode frequency as it is stabilized onto the described Invar cavity. A reduction of the frequency drift to values below 100 MHz/h can be observed. The center graph monitors the frequency of the diode locked to the reference cavity, with the cavity's FSR stabilized by the synthesizer frequency. The apparent drift of the frequency has been reduced to less than 3 kHz/s, corresponding to a frequency variation per hour of less than 9 MHz, limited by the frequency stability of the employed frequency synthesizer.

III. DISCUSSION

We have presented a method to stabilize the length of an optical reference cavity on a long time scale implementing the lock of its FSR by an AOM. The cornerstone of this method is a thorough frequency separation of the two lock loops; the result is dependent on the quality of the locking schemes adopted. The stability reached by this method is only limited by the technical performance of the employed frequency synthesizer. The implemented technique is a pure frequency lock; no phase condition has to be fulfilled. Compared with existing DFM methods which have been designed using phase modulators, the use of an acousto-optical modulator in our scheme allows application of the technique to cavities which are shorter than some tens of centimeters. Furthermore, the presented method can be used in a wavelength regime where no atomic transitions are accessible. The stability performances described could be easily improved by using an external frequency standard with higher precision and stability for the frequency synthesizer fixing the length of the optical cavity.

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