A simple cost-effective digital system for tuning and long-term frequency stabilisation of a CW Ti:Sapphire laser

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Abstract. We have implemented a simple and cost-effective digital system for long-term frequency stabilisation and locking to an arbitrary wavelength of the single-frequency ring CW Ti:Sapphire laser. This system is built around two confocal Fabry-Pérot cavities, one of which is used to narrow short-term line width of the laser and the other to improve long-term stability of the laser frequency. The second interferometer is also in the path of the radiation from an external-cavity diode laser stabilized to an atomic transition. Our system is an extension of a commercial Tekhnoscan laser lock. This system has been successfully used in experiments on high-resolution laser spectroscopy of ultracold Rydberg atoms.

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1. Introduction

Single-frequency CW Ti:Sapphire lasers with ring cavities are advantageous for laser spectroscopy due to their high power in single frequency and tuneability over a broad spectral range. A variety of techniques have been developed for laser frequency stabilisation needed in many applications in optics and spectroscopy. Typically, the laser output is locked to a highly stable reference cavity or to an atomic transition by means of fringe-side locking [1] or most widely used Pound-Drever-Hall (PDH) technique [2, 3]. Highly-stable Fabry-Pérot cavities commonly use ULE glass spacers, which are temperature-stabilised and kept in vacuum in order to avoid drifts of the resonant frequency induced by temperature and air pressure variations [4]. In such systems, scanning of the laser frequency is only possible through the use of external acousto-optic or electro-optic modulators, because in highly-stable cavities, the mirrors cannot be placed on piezo-ceramic transducers (PZT), which feature large frequency drifts of tens of MHz per hour [5]. Locking the laser to an atomic transition via saturation spectroscopy is commonly used in experiments on atomic spectroscopy and laser cooling. However, this technique is difficult to apply in the case when the desirable laser wavelength does not match the wavelength of available atomic transitions. Another recently developed method is based on the use of a high-precision wavelength meter, which also requires additional reference laser to achieve high accuracy [6].

We have developed a relatively simple and inexpensive alternative relying on digital measurement of the frequency difference between the output of a Ti:Sapphire laser and that of a highly stable diode laser using an auxiliary Fabry-Pérot interferometer. Essentially, the time delay is measured between emergence of transmission peaks coming from the radiation of the Ti:Sapphire laser and from that of the highly stable diode laser as the Fabry-Pérot cavity is scanned.

This method has been successfully implemented in several previous works [7, 8, 9, 10]. A rather complicated analogue electronic detection of transmission peaks in the scanning cavity was first implemented in Ref. [7]. A digital integrator was used to provide the feedback signal to the laser. Frequency drift of the laser did not exceed 1 MHz compared to the reference frequency-stabilised He-Ne laser. In later works, the electronics for laser stabilisation was substantially simplified by introduction of ADC/DAC modules with a computer control [8, 9, 10]. In Ref. [8], interference filters were used to individually measure transmission of multiple laser beams through the cavity, so that several lasers could be locked simultaneously. In Ref. [9] the scanning rate was increased to 1 kHz compared to 200 Hz in Ref. [8] and the transmission signal was sampled at 4 MHz. Increased scanning rate permits frequency locking in a wider bandwidth, but requires faster ADC conversion and data analysis. In Ref. [10] the scanning frequency was further raised to 3 kHz and the feedback signal was generated using an analogue peak detector and a fast programmable microcontroller.

Our approach relies on two confocal cavities for line narrowing and long-term frequency stabilisation of the laser. The stability of a confocal reference cavity with
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Figure 1. (Color online). Scheme of the experimental setup. The Ti:Sapphire laser is locked to cavity 2 using side-fringe locking technique. Cavity 1 is scanned at 200 Hz. The transmission peaks from two lasers are detected on PD1, and recorded using ADC, and analysed on a computer. The feedback signal from DAC is sent to the PZT of cavity 2.

the mirrors separated by a 10-cm invar spacer is much better than that of a long (approximately 70 cm) laser resonator. We use fast analogue locking electronics manufactured by Tekhnoscan Company (Novosibirsk, Russia) to lock the laser on the reference cavity, and then we only compensate for the long-term drift of the optical length of the reference cavity. This technique allows us to avoid the necessity to use high-speed electronics for peak detection and data analysis.

2. Experiment

The scheme of our experimental setup is shown in Fig. 1. The radiation of the Ti:Sapphire laser is split by semi-transparent mirror M1 and directed to confocal cavities 1 and 2. Intensity of the light transmitted through the cavities is measured with photodiodes PD1 and PD2. Semi-transparent mirror M2 is used to create a reference laser beam for side-fringe locking of the Ti:Sapphire laser to a mode of cavity 2 by measuring the difference between the intensities on photodiodes PD2 and PD3 and sending the feedback signal to the laser. Cavity 2 is a confocal Fabry-Pérot resonator with a 10-cm invar spacer and one of the mirrors mounted on a PZT. The commercially available locking electronics by Technoscan reduces the short-term line width of laser radiation to less than 10 kHz. By applying an offset voltage to the PZT of cavity 2, it is possible to tune the laser frequency within the free spectral range of the cavity, which is 750 MHz. The laser frequency drift caused by temperature and air pressure variations, as well as the drift of the PZT, is more than 30 MHz per hour even for the cavity with temperature stabilisation. This does not meet our requirements for laser spectroscopy.
of cold Rydberg atoms where resonance widths at laser excitation are less than 5 MHz.

In order to compensate for this drift, we combine on semi-transparent mirror M4 the radiation of the Ti:Sapphire laser, which is already locked to cavity 2, with the radiation of the reference external-cavity diode laser with wavelength 780 nm, locked to an atomic transition in a rubidium vapour cell via Pound-Drever-Hall technique \cite{2, 3}. The line width of the laser is less than 1 MHz. The radiation of both lasers is sent to cavity 1 which is scanned by a triangular signal at 200 Hz from a GW Instek DDS function generator SFG-2004\textsuperscript{TM}. Low-voltage output of the function generator is amplified with a home-built high-voltage amplifier, which drives the PZT. This amplifier also provides additional offset DC voltage to the PZT.

Scanning cavity 1 is a confocal Fabry-Pérot resonator with a 12.5-cm invar spacer corresponding to a free spectral range of $c/4L = 600$ MHz. The cavity can be temperature stabilised, however this does not significantly change the performance of the system. The signal from photodiode PD1, which has a bandwidth of 10 MHz, is measured using a commercial ZetLab ZET 210\textsuperscript{TM} ADC/DAC module with maximum sampling frequency of 400 kHz.

As the signal from photodiode PD1 can only be measured continuously during the period defined by the ADC buffer size of 4096 bytes, we have to use the signal from the function generator, which is measured by a second ADC channel, for synchronization of the data acquisition process. We read the data from the ADC buffer, which contains at least two periods of the synchronisation signal. Then we find the time of the first minimum of the synchronization signal $t_{\text{min}}$ and extract data from a time bin defined by the specified width and offset $T_{\text{off}}$ as shown in Fig. \ref{fig:2}(a). Adjustment of the DC offset voltage at the PZT of cavity 1 can be used to tune the positions of the peaks within the window without interrupting the frequency locking process. This is necessary to
move the transmission peaks away from the turning points of the ramp signal and to compensate for temperature drift of the cavity in order to keep all the peaks within the measurement window.

The measured time-dependent photoelectric signal on PD1, which is proportional to the transmission of cavity 1, is plotted in Fig. 2(b). We measure the time intervals $T_1$ and $T_2$ between two peaks from the reference laser and the peak from the Ti:Sapphire laser using the Peak Detect virtual instrument implemented in National Instruments Labview\textsuperscript{TM}. Then we calculate the ratio:

$$R = \frac{T_1}{T_1 + T_2}$$  \hspace{1cm} (1)

This ratio depends linearly on the frequency of the Ti:Sapphire laser and ranges between 0 and 1 depending on the relation between the frequencies of the reference laser and Ti:Sapphire laser.

Initially, the Ti:Sapphire laser is locked to cavity 2. By changing the offset voltage on the PZT of this cavity we can tune the laser to any desired wavelength which will define the initial ratio $R_0$ of time intervals between the transmission peaks of cavity 1. For long-term stability, we need to minimize the variation $\Delta R = R - R_0$. This is achieved by applying an additional voltage to the PZT of cavity 2. The feedback signal is calculated using National Instruments Labview\textsuperscript{TM} PID toolkit and then converted to voltage via the DAC of the Zetlab ZET 210\textsuperscript{TM} module.

To tune the laser locked to cavity 1, we can manually change the initially set value $R_0$ in the control program during the experiment. The locking system will then drive the laser to a newly defined locking point.

3. System performance

The results of measurement of the ratio of the time intervals $R$ during approximately 20 minutes are presented in Fig. 3(a). The standard deviation of $R$ was 0.00115 which corresponds to the error of 0.7 MHz in the determination of the laser frequency. This result is consistent with the previous measurements \cite{7, 8, 9, 10}. The output voltage of DAC, shown in Fig. 3(b), was automatically increased by the locking system from zero to around 0.7 V during the measurement due to the temperature and air pressure variations which affect the optical length of cavity 2, and due to the drift of the PZT of cavity 2.

We have also measured the wavelength of Ti:Sapphire laser output using High Finesse\textsuperscript{TM} WS6 wavemeter. Although this model has limited accuracy (200 MHz error in absolute value), we have used it to study the fluctuations and drifts of the laser frequency. In the mode when the laser was locked to cavity 2 only without temperature stabilisation of the cavity the drift was around 3 MHz per minute [see Fig. 3(c)]. When the laser was also locked to cavity 1 the measured drifts were reduced to 200 kHz per minute [see Fig. 3(d)] which can be attributed to the temperature drift of the wavemeter.
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The limiting factors for the system performance are rather low scanning rate (200 Hz), finesse of the cavity 2 \((F \sim 50)\), and stability of the reference laser. Higher scanning rate requires faster sampling, which was not possible with the ADC we used. The peak positions fluctuate from scan to scan even for a stabilised laser due to the nonlinearities and hysteresis of the PZT \([8]\). The system performance was good enough to compensate for the long-term drift of cavity 2. We have used this system to lock the Ti:Sapphire laser at 743 nm for three-step laser excitation of cold rubidium atoms into the Rydberg states \([11, 12]\).

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