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# Simple digital system for tuning and long-term frequency stabilization of a CW Ti:Sapphire laser

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**Abstract.** We have implemented a simple digital system for long-term frequency stabilization and locking to an arbitrary wavelength of the single-frequency ring CW Ti:Sapphire laser. This system is built using two confocal Fabry-Pérot cavities, one of which is used to narrow the short-term linewidth of the laser and the other to improve the long-term stability of the laser frequency. The length of the second cavity is stabilized using the radiation from an external-cavity diode laser locked to an atomic transition. Our system is an improvement of a commercial Tekhnoscan laser lock. This system has been successfully used in our experiments on high-resolution laser spectroscopy of ultracold rubidium Rydberg atoms. *© 2015 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.54.3.034111]

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## 1 Introduction

Laser cooling and multiphoton spectroscopy of atoms and molecules commonly require the use of narrow-band frequency stabilized lasers working at various wavelengths. Single-frequency CW Ti:Sapphire lasers with ring cavities are advantageous for laser spectroscopy due to their high power at single frequencies and tuneability over a broad spectral range. A variety of techniques have been developed for the laser frequency stabilization 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 the most widely used Pound–Drever–Hall (PDH) technique.[2,3] Highly stable Fabry-Pérot cavities commonly use ultra-low expansion glass spacers and are temperature stabilized and kept in vacuum in order to avoid drifts of the resonant frequency induced by temperature and air pressure variations.[4–6] In such systems, the mirrors cannot be placed on piezo-ceramic transducers (PZT), which feature large frequency drifts of tens of megahertz per hour.[7] Therefore, the laser frequency can only be stabilized at a series of fixed values that are separated by the free spectral range of the cavity. To overcome this obstacle, it is possible to shift the laser frequency using an external acousto-optical modulator or sideband locking technique with an electro-optical modulator.[8] 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. The same difficulty occurs when the reference cavity is locked to a highly stable reference laser. 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.[9]

One of the common experimental demands is multistep excitation of ultracold atoms which requires locking of the laser to a transition between excited atomic states. For two-step excitation, it is possible to use the resonances of an electromagnetically induced transparency in a gas cell to lock the lasers.[10] However, generalization of this scheme for three-step laser excitation is technically challenging due to small dipole moments of transitions to Rydberg states and the necessity to combine three laser beams in a vapor cell.

We have developed a relatively simple and inexpensive method relying on the 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. The diode lasers which are locked to an atomic transition between the ground and first excited states of alkali-metal atoms are commonly used in laser cooling experiments. It is important that a single reference laser can be used to lock other lasers to the arbitrary wavelengths.

Essentially, in our locking system, 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.[11–14] A rather complicated analogue electronic detection of transmission peaks in the scanning cavity was first implemented in Ref. 11. A digital integrator was used to provide the feedback signal to the laser. The

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frequency drift of the laser did not exceed 1 MHz compared to the reference frequency-stabilized He-Ne laser. In the later works, the electronics for laser stabilization was substantially simplified by introduction of ADC/DAC modules with a computer control.[12–14] In Ref. 12, the interference filters were used to individually measure the transmission of multiple laser beams through the cavity, so that several lasers could be locked simultaneously. In Ref. 13, the scanning rate was increased to 1 kHz compared to 200 Hz in Ref. 12 and the transmission signal was sampled at 4 MHz. The increased scanning rate permits frequency locking in a wider bandwidth but requires faster and more expensive ADC conversion and data analysis. In Ref. 14, 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 stabilization of the laser. The confocal reference cavity with the mirrors separated by a 10-cm invar spacer is more stable than a long (~70 cm) laser resonator. We use fast analogue locking electronics manufactured by the 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 of using high-speed electronics for peak detection and data analysis compared to the previous works.[13,14] We use a relatively cheap ZetLab™ Zet210 ADC/DAC module (Russia) sampled at 400 kHz for data acquisition and generation of the feedback output voltage and National Instruments LabView™ for 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 semitransparent mirror M1 and directed to confocal cavities 1 and 2. The intensity of the light transmitted through the cavities is measured with photodiodes PD1 and PD2. Semitransparent mirror M2 is used to create a reference laser beam for the 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. This is a part of the commercial Tekhnoscan laser lock. 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 Tekhnoscan reduces the short-term linewidth of the 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/h even for the cavity with temperature stabilization. This does not meet our requirements for experiments with cold Rydberg atoms where resonance widths at laser excitation are <5 MHz, and we need to keep the laser on resonance with the atomic transition for tens of minutes.

In order to compensate for this drift, on semitransparent mirror M4, we combine 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 a wavelength 780 nm, locked to an atomic transition in a rubidium vapor cell via PDH technique.[2,3] The linewidth of this laser was measured by observing the beat spectrum of two identical lasers averaged during 100 ms and was found to be <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™. The 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.

The 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 stabilized, 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™ ADC/DAC module with a 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 synchronization signal. Then we find the time of the first minimum of the synchronization signal

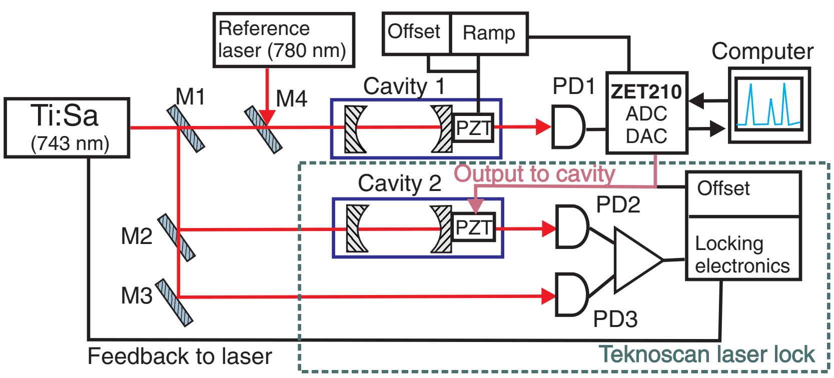


**Fig. 1** Scheme of the experimental setup. The Ti:Sapphire laser is locked to cavity 2 using a side-fringe locking technique. Cavity 1 is scanned at 200 Hz. The transmission peaks from two lasers are detected on PD1, and recorded using ADC, and analyzed on a computer. The feedback signal from DAC is sent to the PZT of cavity 2. The part of the experimental setup that represents the commercial Teknoscan laser lock is shown in the rectangular box.



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$t_{min}$ and extract data from a time bin defined by the specified width and offset $T_{off}$ as shown in 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™, which uses quadratic fit approximation for accurate determination of the peak centers. Then we calculate the ratio:

$$R = \frac{T_1}{T_1 + T_2}. \quad (1)$$

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. We apply a three-point average filter to an array of measured ratios.

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 defines 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™ PID toolkit and then converted to voltage via the DAC of the Zetlab ZET 210™ 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 then drives 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 an error of 0.7 MHz in the determination of the laser frequency. This result is consistent with the previous measurements.[11–14] 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 the Ti:Sapphire laser output using High Finesse™ WS6 wavemeter. Although this model has limited long-term accuracy (200 MHz error in absolute value), we have used it to study the short-term fluctuations and drifts of the laser frequency. In the mode when the laser was locked to cavity 2 but without temperature stabilization of the cavity, the drift was around 3 MHz/min [see Fig. 3(c)]. When the laser was also locked to cavity 1, the measured drifts were reduced to 200 kHz/min [see Fig. 3(d)] which can be attributed to the temperature drift of the wavemeter. Another possible source of error could be the drift of the reference laser, but we have not observed it in the beat spectrum of two identical reference lasers locked to 780 nm.

Our approach is close to the laser locking system described in Ref. 12 where low-frequency data acquisition at 400 kHz had been used along with fully digital data analysis. However, it has been noted in Ref. 12 that their system was unable to compensate for acoustic noises, and an additional stable cavity and analog electronics for line width narrowing has been proposed. In our work, the laser is locked to cavity 2 by analog electronics via fringe-side locking, which removes the acoustic noises and provides less than 10 kHz rms laser linewidth relative to cavity 2. Our digital locking system compensates only for slow drifts of cavity 2. These are the main differences from the previous work.[12]

The limiting factors for the system performance are a rather low scanning rate (200 Hz), finesse of cavity 2 ($F \sim 50$), and stability of the reference laser. A higher scanning rate requires faster sampling, which was not possible with the ADC we used. However, the peak positions fluctuate from scan to scan even for a stabilized laser due to the nonlinearities and hysteresis of the PZT.[12] Therefore, we believe that an increase of the scanning rate will not substantially improve the performance of our system, and we need to compensate only for slow temperature drifts of cavity 2 and air pressure variations. There is no need to further increase the bandwidth of the locking system by the use of high-speed digital electronics, in contrast to previous works.[13,14] Besides

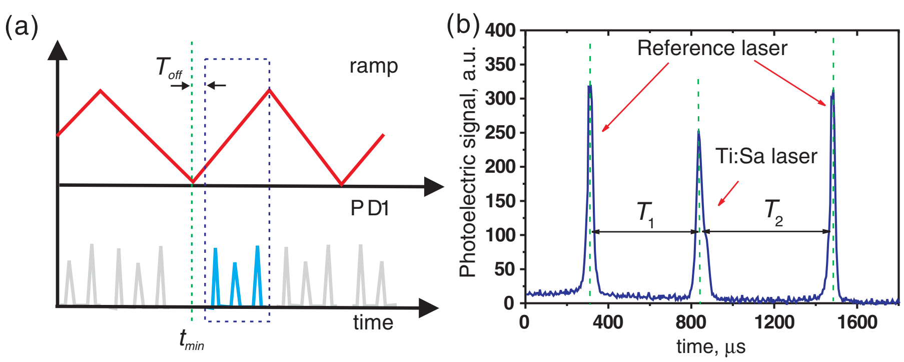


**Fig. 2** (a) Timing diagram of the measurement. The ramp signal is used for synchronization. The first minimum of the ramp signal and the measurement time bin are separated by offset time $T_{off}$; (b) time-dependent photoelectric signal on PD1.



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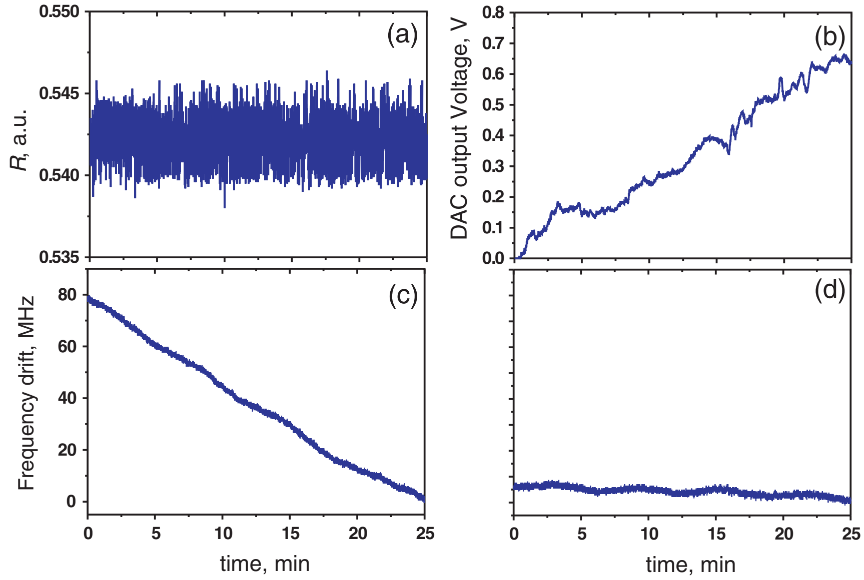


**Fig. 3** (a) Measured time trace of ratio $R$ of time intervals between the transmission peaks; (b) time trace of DAC output voltage; (c) measured laser frequency drift with the Ti:Sapphire laser locked to cavity 2 only (without temperature stablization of the cavity); (d) measured laser frequency drift with the Ti: Sapphire laser locked to both cavity 1 and cavity 2. The absolute long-term accuracy of the wavemeter is 200 MHz, but the relative accuracy is much better.

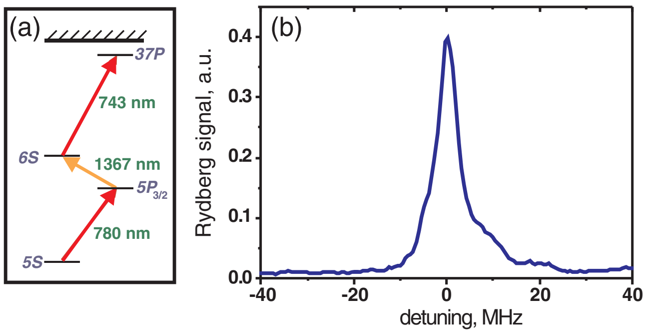


**Fig. 4** (a) Scheme of the three-photon excitation of rubidium Rydberg atoms; (b) a typical spectrum of laser excitation of cold rubidium 37$P$ Rydberg atoms obtained by scanning of the Ti:Sapphire laser working at 743 nm.

that, for a faster lock, the fluctuations of the peak positions can substantially increase the linewidth of the laser.

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, as shown in Fig. 4(a).[15,16] We used a cooling 780 nm laser diode as a reference source. The typical spectrum of laser excitation of 37$P$ Rydberg rubidium atoms obtained by scanning of the Ti:Sapphire laser by linear ramp voltage applied to cavity 2 is shown in Fig. 4(b). The width of the atomic resonance in our experiment was around 5 MHz. Therefore, the stability of our laser lock was good enough for Rydberg excitation of ultracold rubidium atoms.

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