Locking Multi-Laser Frequencies to a Precision Wavelength Meter: Application to Cold Atoms

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We herein report a simultaneous frequency stabilization of two 780-nm external cavity diode lasers using a precision wavelength meter (WLM). The laser lock performance is characterized by the Allan deviation measurement in which we find \( \sigma_y = 10^{-12} \) at an averaging time of 1000 s. We also obtain spectral profiles through a heterodyne spectroscopy, identifying the contribution of white and flicker noises to the laser linewidth. The frequency drift of the WLM is measured to be about 2.0(4) MHz over 36 h. Utilizing the two lasers as a cooling and repumping field, we demonstrate a magneto-optical trap of \(^{87}\text{Rb}\) atoms near a high-finesse optical cavity. Our laser stabilization technique operates at broad wavelength range without a radio frequency element.

I. INTRODUCTION

Laser frequency stabilization is of fundamental importance in various areas of optical and physical sciences [1, 2]. In quantum metrology, it is necessary to minimize the frequency instability for developing a precise and accurate atomic clock [3]. In many instances of quantum optics and quantum information, it is indispensable to stabilize the laser frequency within a range narrower than a target atomic or cavity linewidth, in order to trap and cool atoms [4–6] and ions [7], or to probe cavity modes of a high-\(Q\) resonator [8, 9]. To this end, a standard approach is to employ the well-known Pound–Drever–Hall (PDH) method [10]. Via modulating the phase or frequency of a laser field, the error signal is generated so as to apply a feedback signal to the frequency control of the laser.

In the PDH scheme, typical frequency references are atomic vapor cells or optical cavities, where we drive a transition or mode with the modulated laser field [11]. One of the key technical challenges is to construct a related radio frequency (rf) system in an optimized configuration, including a local oscillator, electro-optical modulator, phase shifter, mixer, low-pass filter, and rf amplifier [12]. It is also important to minimize the residual amplitude modulation [13] that causes an offset noise or drift of the error signal, giving rise to the frequency excursion of the locked laser. For applications that require a laser linewidth of about 1 MHz, however, the recent technique using a precision wavelength meter (WLM) might bypass the technical complexities of the PDH method [14–21]. The WLM is used to generate an error signal for the frequency stabilization. A major benefit of the scheme is that no rf elements are needed; it is possible to stabilize the laser frequency at an arbitrary value such that additional frequency shift would not be needed. Moreover, the frequency stabilization can be done from near ultraviolet (UV) to telecom band, along with the operation regime of the WLM. Furthermore, the stabilization is achieved with a relatively low laser power, below a milliwatt level.

Here, we simultaneously stabilize the frequencies of two 780-nm external cavity diode lasers (ECDLs) to a WLM. We point out two differences of our work from previous WLM-based stabilizations. First, we perform a quantitative characterization of the frequency measurement/feedback rate. Second, while the stabilized lasers were used to drive the cooling transition of Sr atoms with a natural linewidth of 32 MHz [16] and that of \(^{41}\text{Ca}^+\) and \(^{171}\text{Yb}^+\) ions with about 20 MHz [18, 19], we apply the laser field to neutral atomic rubidium that has a linewidth of 6 MHz. Previous stabilizations with the WLM are employed for a control of a dye laser [14], automatic laser control [15], incorporation with a self-made switch [16], and transportable ion clock [18]. Note that such stabilization technique was also used to control cold molecules [20, 21].

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II. MATERIALS AND METHODS

A. Experimental setup

Our frequency reference is a WLM (HighFinesse GmbH, WSL-10 PCS8) that provides a frequency resolution of 400 kHz and absolute accuracy of 10 MHz. This device is comprised of two main optical components, a mechanical switch with 8 inputs and 1 output channel, and solid Fizeau-type interferometer (Figure 1) [22–24]. In the switch system, incident optical fields are distributed to one output channel sequentially; the output field is connected to the interferometer through a photonic crystal fiber that transmits light fields from near-UV to telecom band. The frequency of the fiber output field is measured by the interferometer in which the interference pattern is detected at a charge-coupled device (CCD). The working wavelengths of this WLM range from 330 to 1180 nm. The lower limit is determined by the transmission of an intra-WLM filter to protect the CCD, and the upper limit is governed by the reduced detection efficiency of the CCD.

Our experimental setting is displayed in Figure 1. We stabilize the frequencies of two 780-nm ECDLs (New Focus, Vortex™) to the WLM. The laser output is distributed to three branches. The first one is used for locking the laser frequency, heterodyne spectroscopy, and generation of magneto-optical trap (MOT). Peripheral component interconnect (PCI); External cavity diode laser (ECDL); Photodiode (PD); Single mode fiber (SMF). Blue and red solid lines refer laser fields and black dashed lines indicate electronic signal.

B. Feedback bandwidth

The bandwidth of our laser lock is governed by the total time delay occurred in the feedback system. Major contributions to the delay include the photodetection time in the interferometer (τdet), information processing time in the computer (τpro), communication time between the computer and WLM (τcom), and switching time in the mechanical switch (τswi). When a single channel is used for the wavelength measurement, we obtain a digitized wavelength every 3.2 ms in an optimized configuration. This time delay consists of τdet = 1 ms (fixed for all measurements in this paper), τpro < 1 ms, and τcom that constitutes the rest of the time duration.

In the “switch mode” with multi optical channels, we find that wavelength values are recorded every \( n \cdot (\tau_{\text{det}} + \tau_{\text{swi}}) \), where \( n \) is the number of used channels, and \( \tau_{\text{swi}} \) is unchanged at 12 ms. Since the numerical processing and communication are performed in parallel with the detection and switching, \( \tau_{\text{pro}} \) and \( \tau_{\text{com}} \) do not contribute the measurement time interval of the switch mode. From the characterization above, we anticipate that our frequency stabilization could not give an impact on the short-term laser linewidth. However, the bandwidth would be suffi-
cient to fix the laser’s center frequency at a target value.

III. RESULTS

A. Allan deviation measurement

We characterize the laser frequency by obtaining the Allan deviation $\sigma_y$, given by

$$\sigma_y(\tau) = \sqrt{\frac{1}{2(N-1)} \sum_{i=1}^{N-1} (\bar{y}_{i+1}(\tau) - \bar{y}_i(\tau))^2}$$

where $i$ indicates the data index, $y_i$ is the recorded frequency in the WLM, and $N$ is the total number of data points. Given a total measurement time $T$, the average of $y_i$ over a duration $\tau$, i.e., from the $i$th to $(i+N/T\cdot\tau)$th data point is referred to as $\bar{y}_i(\tau)$ [26].

In Figure 2, we present the Allan deviation of the measured frequencies at the WLM, for the unlocked and locked ECDL 1 for $T = 10$ h. The frequency noise is clearly suppressed by our feedback servo: $\sigma_y$ is reduced from an unlocked value of $10^{-8}$ to $2 \times 10^{-11}$ at $\tau = 10$ s, and from $5 \times 10^{-9}$ to $10^{-12}$ for $\tau = 10^3$ s. It is also clear that the locked frequency does not undergo any pronounced time oscillations [27]. Comparing the locking performance of the single channel to that of the switch mode, we find that the behavior is degraded in the switch mode due to the reduced bandwidth. Similar feature is observed for ECDL 2 (Figure 2b). Note that our laser lock is not broken in an ordinary laboratory environment.

B. Heterodyne measurement

Another characterization is done via a heterodyne spectroscopy. We measure the beat note of two simultaneously locked lasers, using a photodiode (bandwidth 350 MHz) and spectrum analyzer. With the frequency of ECDL 1 fixed, that of ECDL 2 is varied so that the beat frequencies are 20, 60, and 100 MHz. The frequency change is done by, without any rf element, numerically setting the target laser frequency in the computer. All the spectra presented in Figure 3 are measured for 1 s, and fitted to Voigt functions, i.e., the convolution of the Gaussian function $\exp(-(\nu - \nu_0)^2/(2\sigma^2))/(\sigma\sqrt{2\pi})$ and the Lorentzian function $(\gamma/\pi)/((\nu - \nu_0)^2 + \gamma^2)$, where $\nu_0$ is the center frequency, $\sigma$ is the standard deviation, and $\gamma$ is the half width at half maximum. In semiconductor lasers [28], it is known that the white noise originating from spontaneous emission causes the Lorentzian profile, while the Gaussian profile is governed by the flicker ($1/f$) noise in the intensity and frequency fluctuations [29, 30]. The obtained $\gamma$ and $\sigma$ are 730, 830 kHz for a beat frequency of 20 MHz, 730, 880 kHz for 60 MHz, and 750, 870 kHz for 100 MHz, respectively. The fitting error is about 20 kHz for all cases. Considering that the two lasers share a same design, specification, and feedback system, we expect that the contribution of each ECDL to the measured linewidths should be almost identical.

C. WLM drift measurement

While the lasers’ frequency precision is determined by our feedback scheme and bandwidth, the accuracy is dominated by thermal expansion/shrink of the interferometer system [31, 33]. The temperature inside the WLM is not actively stabilized: The absolute wavelength is determined by taking the temperature as a correction factor (factory setting), where imperfect correction would cause an erroneous result. We proceed to characterize such effect of the WLM by measuring the frequency of another laser stabilized to an atomic transition. An ECDL operating at 795 nm is stabilized to the crossover res-
FIG. 4. Measurement result of wavelength meter’s frequency drift. Laser frequency, stabilized to a transition of atomic rubidium, is shown in red. Laboratory temperature is shown in blue. Uncertainties of temperature measurement are systematic errors.

D. Application to cold atom experiment

Harnessing the two locked lasers, we generate a magneto-optical trap (MOT) of $^{87}$Rb atoms, in order to demonstrate the applicability of our frequency stabilization to cold atom experiments. The cooling laser (ECDL 1) frequency is locked at 780.246031(2) nm (384.228100(1) THz), detuned from $F = 2$ to $F' = 3$ transition of the D$_2$ line by the atom-laser detuning $\Delta = -2.5\Gamma$. The atomic decay rate is $\Gamma = 2\pi \times 6$ MHz. The frequency of the repumping laser (ECDL 2) is fixed on resonance to the $F = 1$ to $F' = 2$ transition, 780.232684(2) nm (384.234683(1) THz). Given a magnetic field gradient of 7.9 G/cm, the atoms are successfully trapped about 6 mm above a high-finesse optical cavity [35,37]. Figure 5, shows a MOT fluorescence taken with an electron multiplying (EM) CCD, through a lens system with a numerical aperture of 0.23. In Figure 5, we vary the cooling laser frequency by setting a different target frequency in the computer, and measure the total atomic fluorescence counts obtained in the EM-CCD [38]. The atomic response to the frequency change is clear, and the maximum fluorescence counts are obtained at $\Delta = -1.5\Gamma$, where our calibration estimates $1.4(1) \times 10^5$ atoms are trapped [39]. After generating the MOT, we perform sub-Doppler cooling, release the trap, and estimate the atomic temperature from the cavity-arrival time distribution [40]. The obtained temperatures are about 25 $\mu$K that is well-below the Doppler temperature. Our experiments confirm that our laser lock technique could be utilized for trapping cold atoms.

We remark that the center of our MOT can be positioned 4 mm above the cavity through a careful alignment of the laser beams. Since this atom-cavity distance is shorter than those of other similar experiments [41–43], the influence of the gravitational acceleration is reduced when the atoms fall through the cavity. We could achieve a cavity-transit time of about 175 $\mu$s, which would assist us to investigate the atomic motion interacted with the cavity photons [44,45], quantum chaos [46], and generation of tens of consecutive single photons [42].

IV. DISCUSSION

Our technique would also be useful for experiments with trapped ions, as well as neutral atoms. Several tran-
sitions used in the Doppler cooling of ions and state detection are in the blue or UV domain, for instance, that of Ca$^+$ ion is at 397 nm, Yb$^+$ at 370 nm, and Be$^+$ at 313 nm. When a blue laser is stabilized to a cavity with the PDH method, the mirror coating would become degraded gradually owing to the oxygen depletion in the mirror coating \cite{17}. Such effect would be absent in the locking scheme using the WLM. It is also notable that, since the linewidths of such ion transitions are about 20 MHz, the influence of the laser linewidth and frequency drift would be less significant than in the present experiments with Rb atoms.

The locking performance could be improved by implementing the following approaches. First, the stabilization could be done with a WLM of a finer resolution of 200 kHz. \cite{25}. Second, it would be possible to employ a high-speed microelectromechanical system (MEMS) optical switch \cite{48,19} or micromirrors \cite{50} for reducing the time delay occurred in the multi-channel lock. Recent works reported a switching speed < 10 $\mu$s in several configurations \cite{51,52}. Moreover, a large-area, scalable, integrated photonic switch \cite{53} would assist an increase in the number of optical channels. Lastly, we expect that active temperature stabilization of the WLM, combined with a machine-learning-based temperature prediction and control of the device/environment \cite{54,55,56}, could improve the accuracy.

While we demonstrated a simultaneous frequency locking of two lasers, it would be straightforward to stabilize the frequencies of more lasers using the identical scheme. Each laser field would be coupled to separate single mode fibers to the mechanical switch, and the computer-based feedback scheme would operate for individual channels. Such laser lock would be possible up to seven lasers at the same time, among eight input channels of the switch; one last channel is used for the intermittent frequency calibration of the WLM (Section \ref{sec:3c}). As the number of used channel increases, the lock bandwidth decreases as we studied in Section \ref{sec:1b} We expect that it would be

a useful future study in which the performance of stabilization is investigated as a function of used channels.

V. CONCLUSIONS

In conclusion, we have demonstrated a simultaneous frequency stabilization of two 780-nm ECDLs to a precision WLM. The Allan deviation measurement showed that the frequency instability is reduced to $\sigma_y = 10^{-10}$ at an averaging time of 1 s, and $10^{-12}$ at 10$^3$ s. We also distinguished the contribution of white and flicker noises to the laser linewidth through a heterodyne spectroscopy. The frequency drift of the WLM is measured to be 2.0(4) MHz over one and a half days. Utilizing the two lasers as a cooling and repumping field, we generated a MOT of $^{87}$Rb atoms near a high-finesse optical cavity. Our stabilization method could be utilized for most of the single-mode lasers operating from near-UV to telecom band.

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