1.6 GHz Frequency Scanning of a 482 nm Laser Stabilized Using Electromagnetically Induced Transparency

Krishnapriya Subramonian Rajasree, Kristoffer Karlsson, Tridib Ray, and Síle Nic Chormaic

***Abstract*— We propose a method to continuously frequency shift a target laser that is frequency stabilized by a reference laser, which is several hundreds of nanometers detuned. We demonstrate the technique using the $5S_{1/2} \rightarrow 5P_{3/2} \rightarrow 29D_{5/2}$ Rydberg transition in ^{87}Rb vapor and lock the 482 nm target laser to the 780 nm reference laser using the cascaded electromagnetically induced transparency signal. The stabilized frequency of the target laser can be shifted by about 1.6 GHz by phase modulating the reference laser using a waveguide-type electro-optical modulator. This simple method for stable frequency shifting can be used in atomic or molecular physics experiments that require a laser frequency scanning range on the order of several GHz.**

***Index Terms*— Laser frequency stabilization, Rydberg atom, electromagnetically induced transparency, laser scanning.**

I. Introduction

MANY modern atomic and molecular physics experiments require a laser with a stabilized frequency, which can be shifted or scanned over a desired amount, typically up to a few GHz, in order to address a specific transition between energy levels of interest. Usually, resonant absorption on optical transitions, frequency combs, or optical cavity resonances are used as a reference to stabilize lasers to a particular frequency. Some techniques in common use for direct frequency referencing include saturated absorption spectroscopy [1], Sagnac interferometry [2], Pound-Drever-Hall locking [3], [4], and dichroic atomic vapor laser locking [5]. In addition, techniques such as electromagnetically induced transparency (EIT) or beat note locking can be used to lock the relative frequency of two lasers [6]–[10]. The first method is widely employed in situations where it is difficult to obtain a direct absorption signal, such as the excitation of a neutral atom to a Rydberg level using a cascaded process [11]–[13]. The disadvantage of this technique is that it tends to provide discrete frequency reference shifts. Beat note locking can be used for a continuously varying frequency shift, but the target laser can only be separated from the reference laser by up to a few GHz.

Some of the more common methods to arbitrarily shift a laser frequency from a stabilized reference point include using an acousto-optical modulator (AOM) or an electro-optical modulator (EOM). Laser stabilization using an AOM by modulating the carrier frequency has been demonstrated [14] and this method is suitable for probing very narrow absorption features. To reach GHz shifts using an AOM, a single pass is typically not sufficient. Therefore, configurations including 2-, 3-, 4-, 6-, and even 12-passes [15]–[19] have been implemented. When using an AOM, the frequency-shifted light is separated from the carrier (that is the zeroth order beam) via diffraction. However, the entire frequency range under consideration cannot be covered by a single modulator. Moreover, the change in frequency can cause a change in intensity of the frequency-shifted light if the diffraction efficiency of the modulator is not uniform over the full frequency range.

In contrast, when using an EOM, the attainable frequency shift can be much larger (for the non-resonant or broadband case); up to 40 GHz offset using a 10 GHz modulator has been demonstrated [20] by using the 4th-order sidebands and, more recently, up to 46 GHz was obtained using the 10th-order sidebands [21]. However, EOMs require a high driving voltage over the desired range and the shifted sidebands co-propagate with the carrier, meaning they cannot be spatially separated unless a narrow-band cavity is used [22].

In this letter, we demonstrate laser locking and subsequent frequency shifting up to ±800 MHz of a 482 nm target laser using EIT with a waveguide-type EOM employed for shifting the frequency of a 780 nm reference laser. The quality of the frequency stabilization achieved is demonstrated in terms of both stability and scanning range. The work was motivated by our need for a tunable, frequency-stabilized laser for cascaded Rydberg atom excitation in ^{87}Rb [23].

II. Experimental Details

We focused on frequency shifting a frequency stabilized laser so as to excite ^{87}Rb atoms from the $5S_{1/2}$ ground level to the $29D_{5/2}$ Rydberg level via the $5P_{3/2}$ intermediate level

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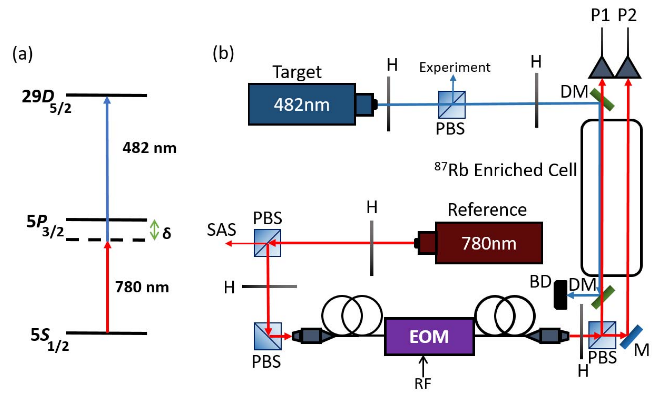

Fig. 1. (a) Simplified energy level diagram for ^{87}Rb showing the relevant transitions. The ground level $5S_{1/2}$, the intermediate level $5P_{3/2}$ and the Rydberg level $29D_{5/2}$ constitute the cascaded three-level system. δ is the frequency shift on the 780 nm reference laser from the resonance condition. (b) Schematic of the experimental setup. The 482 nm target laser and the 780 nm reference laser pass through the ^{87}Rb-enriched vapor cell in a counter-propagating configuration. Absorption of the 780 nm light in the absence and presence of the 482 nm light is detected on P1 and P2, respectively. The difference between the two signals yields the Doppler-free EIT signal, which is used to frequency stabilize the 482 nm laser. EOM: electro-optic modulator; H: half-wave plate; PBS: polarizing beam splitter; M: mirror; DM: dichroic mirror; BD: Beam dump; P1, P2: balanced photodiodes. The different colored arrows indicate different wavelengths of light, red for 780 nm and blue for 482 nm.

using a cascaded excitation process, as shown in Fig. 1(a). The experimental setup is shown in Fig. 1(b). We used a natural abundance rubidium vapor cell to frequency lock a 780 nm laser (DL pro, Toptica) on the ^{85}Rb $5S_{1/2}$(F = 3) $\rightarrow$ $5P_{3/2}(\mathrm{F}' = 3, 4)_{co}$ transition using saturated absorption spectroscopy (SAS). The locked 780 nm laser acted as the reference while the target laser at 482 nm was derived from a frequency-doubled high power laser (TA SHG pro, Toptica). The aim was to scan the target laser across the Rydberg transition (see Fig. 1(a)), for which the direct absorption strength is very weak, hence a signal is difficult to detect.

For stabilizing the target laser frequency we relied on Rydberg EIT [24]; the 780 nm reference laser at a low power (50 μW) was used as the probe and the 482 nm target laser (90 mW) acted as the pump to produce the EIT signal. The Rydberg EIT experiments were done in a ^{87}Rb-enriched vapor cell (TT-RB87-75-V-P, TRIAD Technology Inc.) of dimensions 25 mm $\times$ 75 mm, at room temperature. Since the reference laser addressed the ^{85}Rb $5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 3, 4)_{co}$ transition and the vapor cell was enriched with the ^{87}Rb isotope, the conditions necessary to observe EIT were not met. To overcome this, we sent the reference laser through an EOM (NIR-NPX800 LN-10, Photline Technologies) to produce sidebands at the desired frequency. The EOM used is a Mach-Zehnder waveguide-type intensity modulator with a high bandwidth, low drive voltage, and low insertion loss, driven by a radio frequency (RF) synthesizer. Almost any wideband EOM and modulation method that can create frequency tunable narrow sidebands could be used. The frequency separation between the ^{85}Rb $5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 3, 4)_{co}$ and the ^{87}Rb $5S_{1/2}(F = 2) \rightarrow 5P_{3/2}(F' = 3)$ transition, used to drive the Rydberg excitation, is 1.0662 GHz and δ represents a shift from this frequency (see Figs. 1(a) and 2(a)).

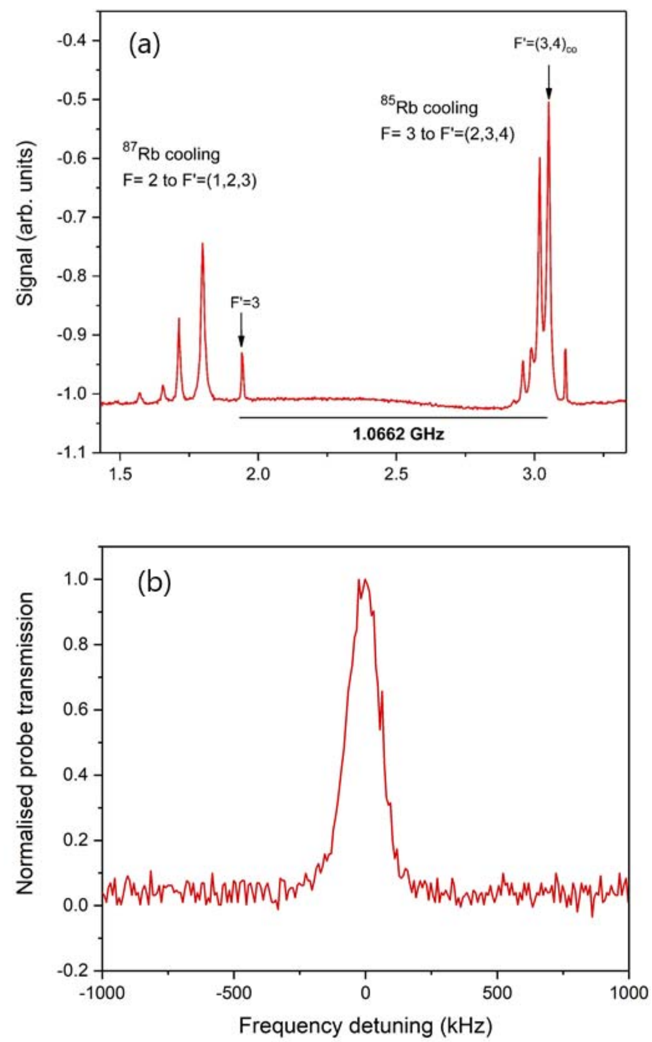

Fig. 2. (a) Saturated absorption spectrum for Rb obtained from a commercial frequency locking interface (Digilock, Toptica). The frequency separation between the ^{85}Rb $5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 3, 4)_{co}$ and the ^{87}Rb $5S_{1/2}(F = 2) \rightarrow 5P_{3/2}(F' = 3)$ transition is 1.0662 GHz as shown. (b) A typical 780 nm probe EIT signal used for locking the 482 nm target laser to the ^{87}Rb $5P_{3/2} \rightarrow 29D_{5/2}$ transition.

The radio frequency (RF) signal to the EOM was chosen so as to adjust the sideband frequency by (1.0662$\pm\delta$) GHz, thereby ensuring that the EOM output satisfied the EIT condition in ^{87}Rb. This then guaranteed that the frequency of the 482 nm laser was also correct. The transmission of the 780 nm probe laser through the atomic vapor in the presence or absence of the 482 nm pump was detected using photodiodes, P1 and P2, respectively, see Fig.1(b). When the 482 nm laser was resonant with the Rydberg transition, we observed a peak in the 780 nm transmission and this was the desired EIT signal, see Fig. 2(b). Here, in this EIT-based locking technique, the EIT signal was generated from a two-photon resonance and, as such, the target laser was locked relative to the reference laser. Only one of the EOM sidebands participated in the EIT process and both the carrier and the other sideband

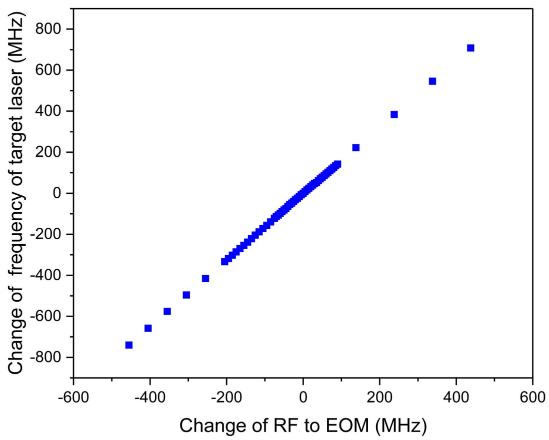

Fig. 3. Shift in the frequency of the 482 nm target laser as a function of the applied radio frequency to the EOM. The total shift achievable is on the order of 1600 MHz. The zero frequency corresponds to $\delta = 0$.

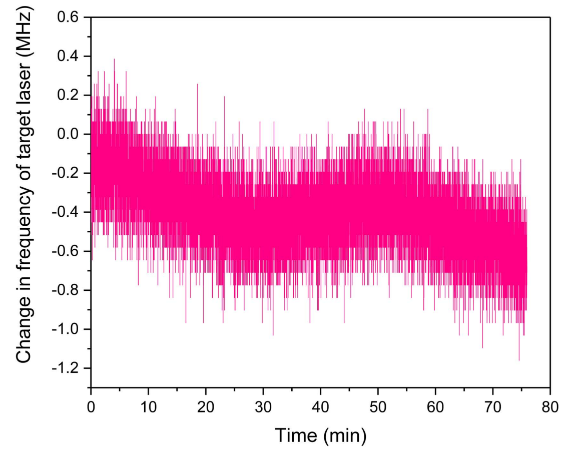

Fig. 4. Fluctuations (rapid changes) and drift (slow variation) in the frequency of the 482 nm target laser as a function of time when frequency locking is on.

passed through the vapor cell without any interaction. The EIT signal was modulated so as to yield an error signal, which was then used to lock the target laser.

III. Performance and Discussion

The RF signal applied to the EOM was varied to ensure that the sidebands were detuned from the ^{87}Rb cooling transition, $5S_{1/2}(F = 2) \rightarrow 5P_{3/2}(F' = 3)$, by δ. To satisfy the resonance condition, the frequency of the target laser shifts by an equivalent amount $-\delta$. In fact, the RF signal to the EOM could either be kept fixed so as to lock the target laser to a specific frequency or it could be varied continuously in order to shift the frequency of the target laser. Importantly, this technique does not change the intensity of the target laser output. Figure 3 is a plot of the 482 nm target laser frequency shift as a function of the applied RF signal to the EOM. We see that the target laser shifted over about 1600 MHz ($\pm$800 MHz) as the RF signal was changed by 892 MHz ($\pm$446 MHz). Note that the power of the 482 nm laser was constant over the frequency scan and no compensation techniques, such as those usually required when an AOM is used to shift the frequency, were needed.

Figure 4 presents the frequency stability of the 482 nm target laser over a reasonably long time of 75 minutes when locked using the presented technique. We can see rapid frequency fluctuations of $\pm$0.4 MHz and an overall frequency drift of $\sim$0.5 MHz. These values are within the range of the wavemeter used for the measurements (HighFinesse Ångstrom WS-6/600 with a stability of $\pm$2 MHz). The lock stability using the first order output from the EOM was comparable and equivalently as good as the zeroth order lock previously demonstrated for a Rydberg level [25] and the frequency stability demonstrated was sufficient for a typical atomic physics experiment [23].

The limitation on the frequency scanning range was $\pm$800 MHz. This arises from the Doppler width of the ^{87}Rb cooling transition manifold. Beyond the Doppler broadened absorption, it becomes harder to obtain an EIT peak. An alternative approach would be to lock the frequency of the 482 nm laser to a reference laser using an optical phase-locked loop [26]. The beat note generated could be referenced to an RF signal and the frequency of the target laser could then be varied more or less arbitrarily without changing the light intensity [27]. However, the implementation of this technique would be significantly more complicated and limited to reference and target lasers with adjacent frequencies, typically not separated by more than a few GHz. In contrast, our technique provides a simple, stable method to produce a phase-coherent pair of laser beams which are hundreds of nm apart.

IV. Conclusion

In summary, we have shown a novel method to shift a stabilized laser by a desired frequency. A reference laser at 780 nm, which was hundreds of nanometres away from the target laser at 482 nm, was used for the frequency stabilization. Though the methods of using amplitude or phase modulation by an EOM or using EIT in a hot alkali vapor cell to stabilize a laser are well-established in their own rights, combining the phase-modulated light with an isotope-enriched ^{87}Rb cell to generate the EIT signal is novel. This technique involves only one sideband (which can be scanned in frequency) to take part in the EIT process while the carrier and the second sideband pass through the cell without participating in the process. This simple trick is exploited to scan or shift the frequency of the target laser deterministically, while it remains locked in frequency with respect to the reference laser. This method of achieving a subnatural linewidth stable target laser with a long range frequency scan (1.6 GHz) can be used for atomic physics experiments involving Rydberg levels [23]. The frequency shift is limited by the Doppler width of ^{87}Rb, which is used for obtaining the EIT signal. The range could be extended by heating the vapor cell. Alternatively, a larger pump power could be used to get an EIT-signal that is beyond the Doppler width.

While we have focused on a specific ladder-type EIT configuration, the technique could also be used to lock any laser used for excitation from $5P_{3/2}$ to $nS_{1/2}$, $nD_{3/2}$ or $nD_{5/2}$. For example, a 776 nm laser could be locked to a master 780 nm laser using a similar technique. It can also be extended to lock lasers in Λ- or V-type EIT configurations. Other than for Rydberg experiments, this relatively easy frequency locking and shifting method could provide a simple alternative in a wide range of AMO experiments when lasers with a large detuning or large scan are required, for example, in long-term precision measurements, such as frequency chirping, atom clocks, atom interferometers, and laser frequency modulation.

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