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.

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Some of the more common methods to arbitrarily shift the laser frequency from a stabilized reference point include using an acousto-optical modulator (AOM) or an electro-optical modulator (EOM). Laser stabilization using a 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 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 $5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 3, 4)$ 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.

Figure 1. (a) Simplified energy level diagram for \(^{87}\text{Rb}\) 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. \(\delta\) 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 \(^{87}\text{Rb}\)-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. The different colored arrows indicate different wavelengths of light, red for 780 nm and blue for 482 nm.

Figure 2. (a) Saturated absorption spectrum for \(^{87}\text{Rb}\) obtained from a commercial frequency locking interface (Digilock, Toptica). The frequency separation between the \(^{87}\text{Rb}\) \(5S_{1/2}(F = 3)\) \(\rightarrow\) \(5P_{3/2}(F') = 3\), \(4\)\(\text{co}\) transition and the \(5S_{1/2}(F = 2)\) \(\rightarrow\) \(5P_{3/2}(F' = 3)\) 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 \(^{87}\text{Rb}\) \(5P_{3/2} \rightarrow 29D_{5/2}\) transition.

III. PERFORMANCE AND DISCUSSION

The RF signal applied to the EOM was varied to ensure that the sidebands were detuned from the \(^{87}\text{Rb}\) cooling transition, \(5S_{1/2}(F = 2)\) \(\rightarrow\) \(5P_{3/2}(F' = 3)\), by \(\delta\). 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. The lock 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 \(^{87}\text{Rb}\) cooling transition manifold. Beyond the Doppler broadened absorption, it becomes harder to obtain a 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.
laser beams which are hundreds of nm apart. In contrast, our technique provides significantly more complicated and limited to reference and [27]. However, the implementation of this technique would be more or less arbitrarily without changing the light intensity of time when frequency locking is on.

Figure 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 $\delta = 0$.

[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. This method of achieving a subnatural linewidth stable target laser with a long range frequency scan (1.6 GHz) could be used for atomic physics experiments involving Rydberg levels [23]. Other than for Rydberg experiments, this frequency locking and shifting method could provide a simple alternative when lasers with a large detuning 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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