Frequency Stabilization of the Extended Cavity Diode Laser to the ^{87}Rb-D$_2$ transition by using Zeeman Modulation Method

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***Abstract*— The extended cavity diode lasers' frequencies were stabilized by the usage of the 1st and 3rd derivatives signals obtained from hyperfine resonances of the ^{87}Rb D$_2$ line with the Zeeman modulation technique. By using the 1st derivatives, obtained from F=1→F′=2 and a crossover resonance of F=1→F′=0,1 the stability was measured $2.2\times10^{-12}\tau^{-1/2}$ @1s, decreased to $4.9\times10^{-13}\tau^{-1/2}$ @150 s, and $2.5\times10^{-12}\tau^{-1/2}$ @10^4 s integration times. The frequency stability $4.2\times10^{-12}\tau^{-1/2}$, $3.5\times10^{-13}\tau^{-1/2}$, $1.2\times10^{-12}\tau^{-1/2}$ values were obtained at 1, 400, and 10^4 s integration times respectively by using the 3rd derivatives of the resonances**

Keywords—atomic clock; laser frequency stabilization; Zeeman modulation method

I. INTRODUCTION

The frequency stabilized diode lasers, frequency stabilizes with the usage of energy transitions of atoms are of great importance for atomic clocks, laser cooling of atoms, and atomic magnetometers [1,2,3,4]. In order to stabilize the laser frequency, the laser interacts with atoms, and the resonances resulting from the interaction are detected by Doppler-free saturated absorption spectroscopy [5,6]. The derivative of the detected resonance signal is obtained and applied to either the laser current or the piezoelectric transducer as a feedback signal [7]. This generates frequency noise (FM noise) at the frequency while at the same time causing optical power fluctuations, as known as Relative Intensity Noise (RIN), of the laser. The short-term frequency stability of atomic clocks depends on RIN (AM-AM) and laser frequency noise (PM-AM). The derivative of the resonance can be obtained in many methods such as frequency modulation (FM) spectroscopy [8], polarization spectroscopy [9,10], dichroic atomic laser lock (DAVLL) [11], and velocity–selective saturated–absorption spectroscopy [12,13]. If any of these techniques are used to stabilize the laser frequency, except for the FM technique, there is no modulation frequency in the laser frequency. This is the desired situation for atomic clocks, and laser cooling of atoms [1,2,3,14,15] whereas the short and long-term frequency stability values cannot meet the necessities of the clock applications [13,16,17,18,19,20]. The laser frequency stability values obtained by using the FM technique meet the requirements of atomic clocks whereas the noise added to the frequency of the laser due to the frequency modulation converts into the amplitude noise (PM-AM) and this degrades the frequency stability of the atomic clocks [2,21,22,23].

In this study, the frequencies of the extended cavity diode lasers (ECDL) were stabilized by the usage of the feedback signals obtained from 1st and 3rd derivatives of the hyperfine resonances of the ^{87}Rb D$_2$ line by Zeeman modulation technique [25,26,27]. To provide the unmodulated laser frequency, circularly polarized counterpropagating pump and probe laser beams interacted with the Rb atoms that were placed in a longitudinal oscillating magnetic field. The effects of ^{87}Rb atomic gas temperature on the linewidth and amplitude of the $5S_{1/2}$F=1→$5P_{3/2}$F′=0,1,2 were investigated and discriminator slope was defined for F=1→F′=2 and a crossover resonance of F=1→F′=0,1(CO_{10-11}). The frequencies of ECDLs were stabilized by applying the 1st and 3rd derivatives of resonances as a feedback signal to both the current and PZTs of the ECDLs.

II. LINEWIDTH AND AMPLITUDE MEASUREMENTS OF ^{87}RB D$_2$ LINE RESONANCES

It is well known that the frequency stability of laser when using atomic resonances as a reference, depends on resonance linewidth and amplitude [28]. The effect of Rb atomic gas temperature on the linewidth and amplitude measurements of the hyperfine resonances ^{87}Rb were performed for the F=1→F′=2, and CO_{10-11}. For the measurements, the experimental setup in figure 1 was installed. Two ECDLs with a linewidth of ≤ 150 kHz were used in the measurements. One of the lasers (reference laser, L_{ref}) frequency was stabilized with different resonances (such as to the F=1→F′=2 or CO_{10-11}) according to the resonance to be measured. The other laser (recording laser, L_{rec}) was stabilized to the transmission resonances of temperature-controlled Fabry-Perot interferometer (TFPI) for recording the resonances. A frequency scale of measurement was created by establishing a heterodyne beat measurement set up between the lasers. As seen in figure 1, two optical paths were obtained by splitting the laser beam of the L_{rec} using a beam splitter (BS_1). An optical isolator (OI) was placed in front of the laser to get rid of the

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back reflection. The laser beam of the first optical path was divided by beam splitter (BS_3) and some part of it was used for the beat frequency measurement with a reference laser while the other part was sent to TFPI with the usage of a mirror (M_4) for creating a transmission resonance of the interferometer. The laser beam in the second optical path was passed through the beam expander (BE) for enlarging the beam and using a diaphragm (D) a beam diameter of 3 mm was obtained. To constitute the pumping and probe beam, the beam was reflected (transmitted) from the polarizing beam splitter (PBS_1). A reference laser beam, reflecting from the beam splitter (BS_2), was attained. The probe and reference beam powers were set to 10 μW (0.14 mW/cm^2) with the neutral density filter (ND_1) and changed linearly to circular polarization by using a quarter-wave plate (λ/4). These laser beams passed through the magnetically screened temperature-controlled enriched ^{87}Rb cell, a length 5 and diameter of 3 cm, and the resonances were detected by a differential photodetector (DFD). The probe laser beam was used to detect the resonances while the reference laser beam was made use of removing background signal originating from the probe laser beam on the DFD. The Rb cell was magnetically shielded in two layers and a magnetic field inside the shielding was measured ≤ 1 μ T. The temperature stabilizing of the Rb cell was provided with the use of a polyimide heater and negative temperature control (NTC) sensors wrapped on magnetic shielding. The temperature stabilization of the Rb cell was stabilized peak to peak ≤ 5 mK. The pumping beam reflected from PBS_1, by using M_1, ND_2, M_2, PBS_2, and a half-wave plate (λ/2) was sent to the Rb cell in the counter propagate direction. The half-wave plate was used to

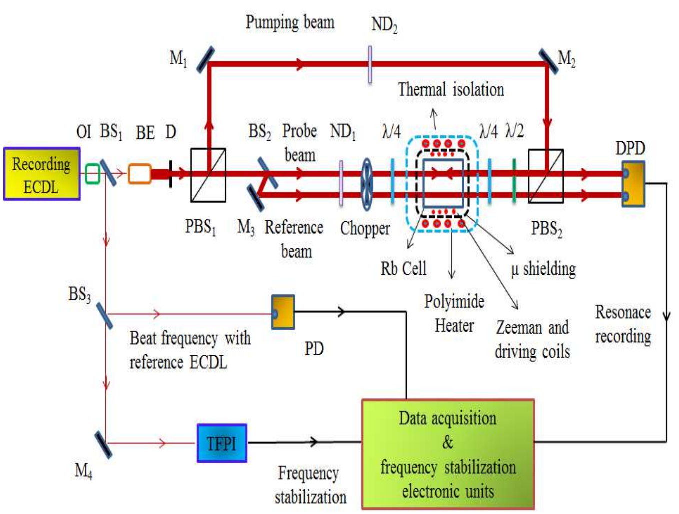

Fig 1. Experimental setup for resonance linewidth and amplitude measurements.

adjust the angle of the pumping beam polarization, which was 90^o different linear polarization according to the probe, and to generate probe and pumping laser beams with parallel linear polarizations. The quarter-wave plate (λ/4), placed after the half-wave plate, was used to convert the polarization of the pumping beam from linear to circular polarization, and by using ND_2 the power of the pumping beam was adjusted to 250 μW (3.54 mW/cm^2). During the frequency stabilization of L_{rec} laser, no modulation signal applied neither current nor PZT of the laser to the do the measurements accurately and precisely. The modulation signal was applied to the PZT of TFPI, and the 1st derivative of transmission resonance was used for frequency stabilization by giving feedback to the current of L_{rec}. The stabilized L_{rec} laser frequency was scanned with the signal by applied to the PZT of TFPI from the signal generator. The resonances were registered by using a chopper, computer-controlled lock-in amplifier, digital voltmeter, and frequency counter. The frequency scale was constituted by detecting beat frequency between the L_{rec} and L_{ref} on the photodetector (PD) and simultaneously recording the ramp signal applied to the TFPI from the signal generator.

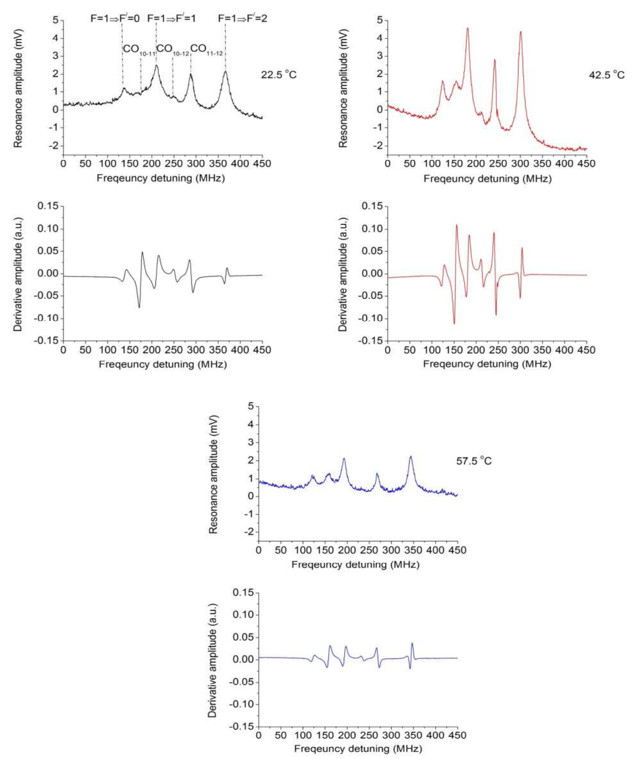

Fig 2. The effect of the ^{87}Rb atomic gas temperature on $5S_{1/2}F=1 \rightarrow 5P_{3/2}F'=0,1,2$ saturation absorption resonances and 3rd derivatives.

The effect of the ^{87}Rb atomic gas temperature on $F=1 \rightarrow F'=0,1,2$ saturation absorption resonances and the 3rd derivatives of are seen Fig 2. To determine at which temperature value has a high discriminator value the change of linewidth, amplitude, and discriminator slope of $F=1 \rightarrow F'=2$, and CO_{10-11} resonances with Rb atomic gas temperature were measured. Since the measurable linewidth and amplitude value of the CO_{10-11} crossover resonance starts at 42.5 ºC, it was calculated for this value and beyond. Each point value and uncertainty of measurements were calculated by taking the average of five consecutive measurements and as indicated graphics that are seen in Fig 3.

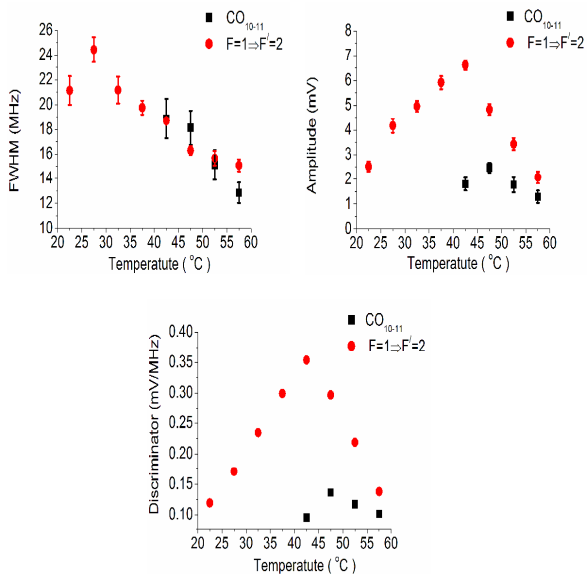

Fig 3. The effect of the [87]Rb atomic gas temperature on the linewidth, amplitude and discriminator slope F=1→F/=2, and $CO_{10\text{-}11}$ resonances.

III. FREQUENCY STABILITY MEASUREMENTS

It is well known that the laser frequency stability described by Allan deviation statics [28,29] and the short term frequency of the lasers can be estimated with

$$\sigma_f(\tau) = \frac{N_{PSD}}{\sqrt{2}\,D\,f_L}\tau^{-1/2}$$

and in the equation N_{PSD} is a detection noise power density of resonances, f_L is a laser frequency, D is a discriminator slope of the feedback signal that the ratio of resonance signal amplitude to the line width of resonance, and τ is the integration time of the measurement [30]. Reaching the high-frequency stability values is only possible when the feedback signal with a large discriminator slope value is used. As seen in Fig 3. the highest discriminator slope value was measured at 42.5 °C for F=1→F/=2, and $CO_{10\text{-}11}$ resonances for this reason the Rb cell temperatures of the lasers were kept at this temperature. During stability measurements, the pumping laser intensity values for each laser were 150 µW (2.12 mW/cm^2), and the probes were 10 µW (0.14 mW/cm^2). The frequencies of ECDLs (L_{rec} and L_{ref}) were stabilized by applying the 1st and 3rd derivatives of resonances as a feedback signal to both the current and PZTs of the ECDLs.

For constituting the derivatives of the resonances Zeeman modulation method was used, and neither the current nor the PZT of the laser was modulated instead of these Rb atoms were modulated with the longitudinal oscillating magnetic field that obtained from driving and Zeeman solenoid coils wrapped around the Rb cell under the magnetic shielding. The purpose of using two different coils instead of one was to ensure the magnetic field with low voltages. The amplitude of the magnetic field is proportional to the number of turns and represented by

$$B = \mu_0.n.i$$

in the equation μ_0 is permeability constant, n the number of turns per unit length, and i the current. On the other hand, the inductance of the coil is related to the square of n

$$L = \mu_0.n^2.A.l$$

where A is the cross-section area of the coil, and l is coil length. The back electromotive force induced in a coil is expressed by

$$\varepsilon = -L\frac{d}{dt}i$$

and the maximum value of voltage required to drive the coil is written by

$$\varepsilon_{max} = L.i_0.\omega$$

if it is driven by a current with sinusoidal radial frequency ω and amplitude of i_0. For realizing a magnetic field with low currents, it needs to get n high which causes an increase in inductance, in other words, an increase in the voltage value of the driver that will drive the coil because of the depth of the magnetic field proportional with n whereas the inductance with the square of n. For obtaining the derivative of resonances with a modulation width of several MHz, a magnetic field of 1 mT is required [27]. In our case the Rb cell lengths are 5 and their diameters 3 cm when 0.5 mm wire of diameter are used to make a coil with 100 turns, in this case, n=2000 m^{-1}, i =0.4 A and L=177.5 µH for 1 mT magnetic field generation. If the coils are driven with an oscillating at 30 kHz the amount of voltage required is approximately 17 V which requires an additional voltage source. With low voltages, it is possible to create an oscillating magnetic field at the desired magnitude without the need for the use of an additional device, for instance by using a lock-in amplifier. Thereby both the derivative signals of the resonances and the error signals used to stabilize the frequency of the lasers can be attained. The way to achieve this is by using a second solenoid (driving) with fewer turns, wrapped on a multi-winding one (Zeeman solenoid), instead of a single one. The driving coil is excited inductively by using a lock-in amplifier, and the oscillating magnetic field can be generated by the Zeeman coil that capacitive impedance matched to the driving coil. The driving can have 5 to 10 turns, while Zeeman solenoid coil 100 to 200 turns that indicated in figure 4 [31]. For instance, if the driver solenoid with 10 turns and the Zeeman solenoid with 100 turns are used to generate oscillating magnetic of 1 mT, this time a 1.3 V voltage requires.

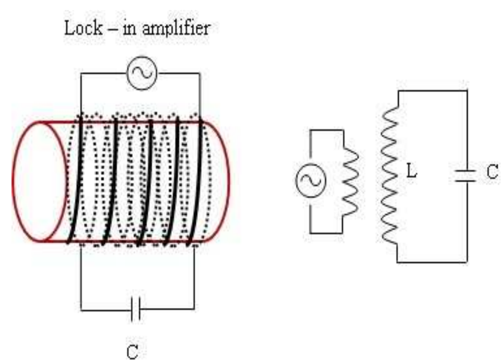

Fig 4. Zeeman and driving coil diagrams.

If the inductive impedance $X_L = \omega . L$ equals the capacitive impedance $X_C = \frac{1}{\omega . C}$, a value of the capacitor should be chosen

$$C = \frac{1}{\omega^2 . L}$$

according to the equation and this is in a range of several nF. In our case, the inductances and capacitance values of Rb cells used to reference and recording lasers were measured by impedance analyzer and the values are $L_{(ref)}$=756 μH, $L_{(rec)}$=915 μH, $C_{(ref)}$=32.5 nF, and $C_{(rec)}$=31 nF when driven the solenoids with an oscillating frequency of 29.98 kHz for reference and 31.78 kHz for recording lasers.

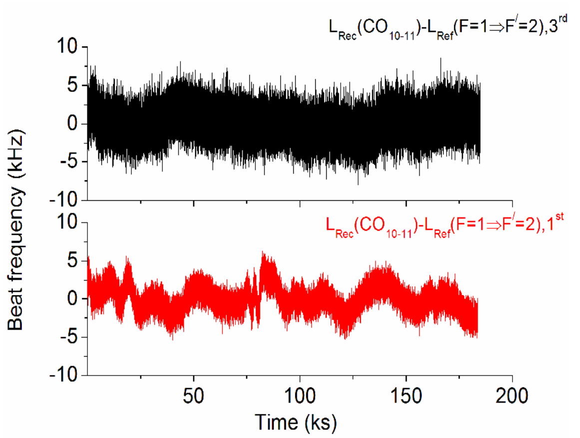

Fig 5. Beat frequency between the stabilized lasers.

The beat frequency of the stabilized lasers, by using the 1st and 3rd derivatives of the resonances, is shown in Fig 5 whereas the frequency stability of the lasers obtained by the Allan deviation statics is given in Fig 6. The frequency stability values were analyzed with the Stable 32 software program [32]. When the L_{rec} and L_{ref} lasers were stabilized by using the 1st derivatives, obtained from F=1→F'=2 and CO_{10-11} resonances, the stability was measured $2.2\text{x}10^{-12}\ \tau^{-1/2}$ @1s, decreased to $4.9\text{x}10^{-13}\ \tau^{-1/2}$ @150 s, and $2.5\text{x}10^{-12}\ \tau^{-1/2}$ @10^4 s integration times.

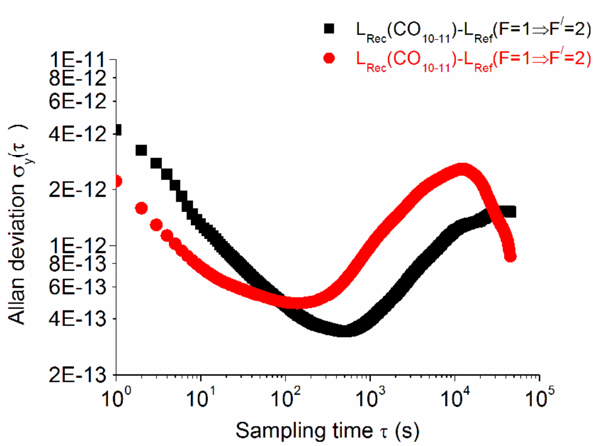

Fig 6. Frequency stability of lasers in terms of Allan deviation

The frequency stability $4.2\text{x}10^{-12}\tau^{-1/2}$, $3.5\text{x}10^{-13}\tau^{-1/2}$, $1.2\text{x}10^{-12}\tau^{-1/2}$ values were obtained at 1, 400, and 10^4 s integration times by using the 3rd derivatives of the resonances.

IV. Conclusions

The frequencies of the ECDL lasers were stabilized by the Zeeman modulation technique. The effect of ^{87}Rb atomic gas temperature on the linewidth and amplitude of the $5S_{1/2}$F=1→$5P_{3/2}$F'=0,1,2 and the discriminator slope values of F=1→F'=2, and CO_{10-11} resonances were measured. The frequency stability values obtained are considerably improved compared to the values obtained without using FM techniques [11,17,18,19,20,25,26,27], they are at the level of FM technique results [21,22]. Lasers with long-term frequency stability without modulating the frequency, which is of great importance for atomic clock applications, have been developed.

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