Phase Stabilized Diode Laser Frequencies for Raman Beam Generation

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Abstract

The advancement of cold atom gravimeters (CAG) is based on the precise control and stabilization of lasers used for the atom interferometry. The 5S → 5P transition in rubidium (Rb) at 780.241 nm is crucial for such quantum technology applications. In this study, the hyperfine structure of $5^2S_{1/2} \rightarrow 5^2P_{3/2}$, D_2 transition line of ^{87}Rb atoms obtained through saturation absorption spectroscopy, are used as a reference for the frequency stabilization of an external cavity diode laser (ECDL) operating at 780 nm. The ECDL is locked to the hyperfine saturated absorption peak of ^{87}Rb (F = 2 → 3'). This laser beam is combined with another 780 nm ECDL laser to obtain the beat frequency spectrum, generating a beat note signal of ~ 6.8 GHz, which is needed for phase stabilization between lasers. These are critical for the Raman beam generation in the CAG, as the ^{87}Rb atoms ground hyperfine states (F = 1 and F = 2) have separation of ~ 6.834 GHz, and two Raman beams with an 6.8 GHz offset can drive transitions between these hyperfine states of ^{87}Rb to realize the CAG interferometry scheme.

1. Introduction

Cold atom gravimeters (CAG) are used for the measurement of gravitational acceleration with high precision and utmost accuracy. The principal of operation is based on the atom interferometry, where atoms are cooled to near absolute zero temperatures through the laser cooling techniques. After cooling, critical component in the functioning of CAG is the generation of Raman beams, which are used for the manipulation of atomic states and create the necessary interference pattern [1, 2, 3]. The generation of Raman beams involves the use of phase stabilized diode lasers, which is crucial for accurate measurements of gravity and in this context beat frequency generation between diode lasers is essential, which is obtained by mixing the unstabilized diode laser beam with the frequency stabilized diode laser.

In this study, ^{87}Rb atoms hyperfine saturated absorption peaks are used as a reference for the locking of diode laser [4]. Precise hyperfine transitions of Rb atoms are obtained using saturation absorption spectroscopy (SAS). The SAS is a Doppler free spectroscopy technique that allows atomic transitions to be resolved to their natural line width, which is typically much narrower than the Doppler width. Natural broadening occurs due to the finite lifetime of the atomic state, causing spectral lines to broaden even when atoms do not interact with the environment. In contrast, Doppler broadening results from the thermal motion of atoms [5]. We focused on the Doppler free spectroscopy of Rb atoms. The Rb SAS is used for frequency stabilization of diode lasers by leveraging the precise atomic transitions of Rb atoms. This process is fundamental for ensuring the stability and accuracy of laser systems employed in a wide range of scientific and technological applications, such as atomic clocks, quantum gravimeters, and high resolution spectroscopy. The principal behind this technique involves the interaction between a 780 nm laser and Rb atoms in a vapor cell, which exhibits well defined spectral lines due to their hyperfine structure. By utilizing SAS, these spectral lines can be resolved with high precision, eliminating Doppler broadening effects and identifying narrow Doppler free absorption peaks. The laser frequency is locked to a specific Rb hyperfine transition using an electronic feedback loop. This feedback loop continuously monitors the absorption signal and adjusts the laser frequency to maintain resonance with the atomic transition and helps in achieving a stable and precise frequency output. This frequency stabilized laser is mixed with another 780 nm ECDL for the beat frequency generation, which is essential for the phase stabilization of lasers.

2. Experimental Setup

The schematic of the setup is displayed in the figure 1. Two external cavity diode lasers operating at 780 nm serve as the laser light source. The laser beam passes through a combination of half wave plate (HW_1) and a polarizing beam splitter (PBS) to control its intensity. The laser beam is then divided into two parts by the PBS. One part is used for the beat frequency generation, while the other part is used for the SAS of the laser. In the beat frequency setup, this laser beam is mixed with another diode laser beam through non polarizing beam splitter (NPBS) and then focused on the photodiode for beat frequency detection. The beat frequency signal is observed on the spectrum analyzer. While in the SAS setup, the laser beam further passes through a quarter wave plate (QW), another PBS and through the Rb vapor cell. This beam known as the pump beam which is accompanied by another counter propagating beam with reduced intensity, achieved using a neutral density filter (NE), referred to as the probe beam. The probe beam then passes through a photodetector (PD) to observe the saturation absorption spectrum. The transmitted beam from the PBS is coupled to the wavelength meter for the simultaneous measurement of the laser wavelength.

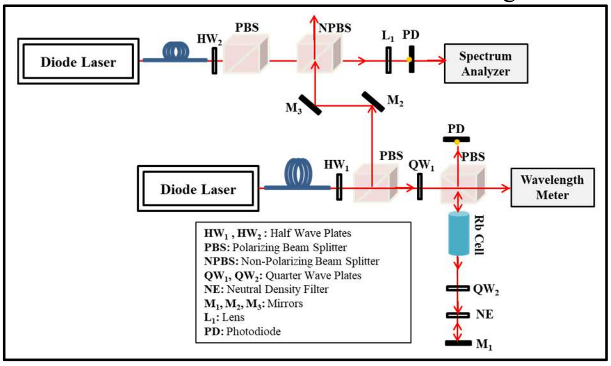

Figure 1. Schematic for saturation absorption spectroscopy of Rb atoms and beat frequency generation

3. Results and Discussion

Figure 2 displays the saturation absorption spectra obtained for the ^{87}Rb atoms, respectively, corresponding to the $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ transitions. The transition has a resonant frequency of 384.2304844685 THz, corresponding to a vacuum wavelength of 780.241209686 nm [6]. The spectra exhibit six peaks; three normal hyperfine transition peaks and three crossover transition peaks. For ^{87}Rb, F = 2 → 1', F = 2 → 2', and F = 2 → 3' are normal hyperfine transition peaks, while the crossover hyperfine transition peaks are F = 2 → 1' 2', F = 2 → 1' 3', and F = 2 → 2' 3'.

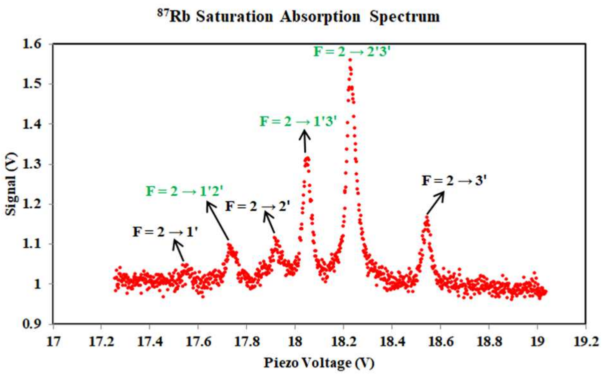

Figure 2. Saturation absorption spectrum for the ^{87}Rb, D_2 transition line

The spectra along with their corresponding error signals are shown in figure 3. After obtaining the spectra, ECDL laser was locked to the F= 2 → 3' crossover transitions of ^{87}Rb. Figure 4 illustrates the reduction in the line width of the locked laser compared to the unlocked laser. The laser locked to the rubidium transition exhibits a drift of ~ 2 fm over a short term period, whereas the unlocked laser shows a drift of around 45 fm. This laser beam is combined with another diode laser beam to generate the beat frequency signal of ~ 6.8 GHz, as shown in the figure 5.The inset shows beat signal at reduced span. The 6.8 GHz offset is needed to coherently transfer population using Raman beams between the hyperfine states of ^{87}Rb, whose ground hyperfine states have an energy difference corresponding to a frequency difference of ~ 6.834 GHz.

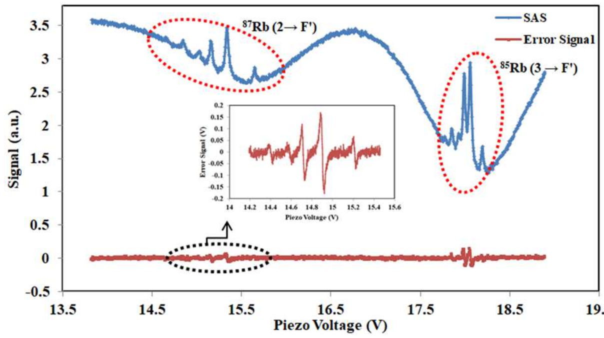

Figure 3. Saturation absorption spectrum for the ^{87}Rb and ^{85}Rb with error signals

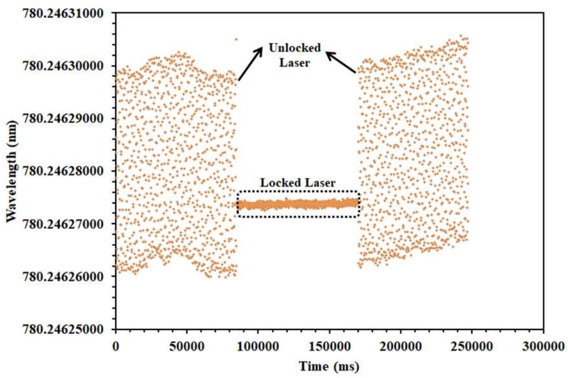

Figure 4. Laser locking at F = 2 → 3' transition of ^{87}Rb

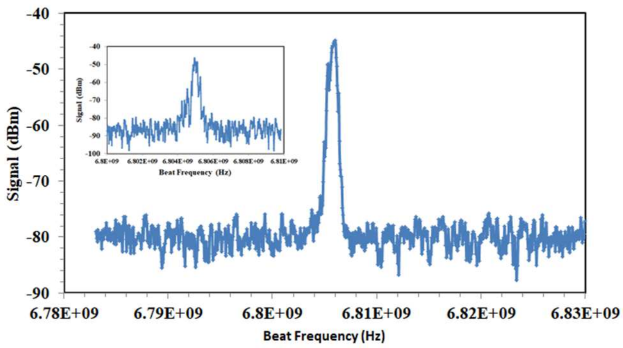

Figure 5. Beat-note signal between two 780 nm ECDLs.

5. Conclusion

This study presents the process for beat frequency generation of diode lasers to achieve phase stabilization. The results of saturation absorption spectroscopic studies on Rubidium atoms, laser frequency stabilization, and beat note signal for Raman beam generation have been discussed. The recorded SAS spectrum shows six saturated absorption peaks: three normal peaks and three crossover absorption peaks. These peaks serve as a reference for laser locking. By locking an external cavity diode laser operating at 780 nm to the F = 2 → 3' crossover transition of ^{87}Rb, the laser frequency drift was reduced to ~ 2 fm, compared to the ~ 45 fm drift observed in the unlocked laser. Additionally, the beat frequency signal generated between the two ECDLs is at 6.8 GHz frequency to realize the CAG atomic interferometry scheme through the sequence of Raman pulses.

6. Acknowledgements

The authors would like to thank Director, TCG CREST, India, for providing the facilities to carry out this work. One of the authors, Anju, would like to thank CQuERE, TCG CREST, India, for the funding.

7. References

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