Laser Frequency Offset Locking with Dual-modulation

Wang Bisong, Peter Yun*, Hao Qiang
Key Laboratory of Time Reference and Applications, National Time Service Center, Chinese Academy of Sciences, Xi'an, 710600, Shaanxi, China
University of Chinese Academy of Sciences, Beijing 100049, China
*yunenxue@ntsc.ac.cn

***Abstract*—We report a laser frequency offset locking scheme for coherent population trapping (CPT) atomic clock. Based on a usual half-wave modulation in CPT atomic clocks, we add a radio frequency signal to the laser driving current to form dual-modulation to compensate the frequency shift of optical transition due to buffer gas in the clock cell. The Doppler-free absorption enhanced spectrum produced by dual-modulation is observed and successfully applied to the laser frequency offset locking. In our scheme, a frequency shift device is no longer necessary, thus the clock's size, weight, power, complexity, environmental sensitivity, and cost are reduced, this is suitable for implementing compact and high-performance CPT and POP atomic clocks.**

Keywords*—Laser frequency offset locking, Doppler-free, Miniaturization atomic clock

I. Introduction

In a coherent population trapping (CPT) atomic clock, buffer gas is usually filled into its clock cell besides the alkali metal to obtain a narrow clock transition line thanks to the Dicke effect[1]. However, it will result in the frequency shift and broadening of the electric dipole optical transition, and the Doppler-free spectrum cannot be obtained, which causes difficulties for laser frequency locking. Usually, a separated alkali metal vapor cell without buffer gas, noted as the reference cell, is employed to obtain the Doppler-free spectrum by saturation absorption spectrum, polarization spectrum, modulation transfer spectrum, etc. What's more, a frequency shift device, such as an acousto-optic modulator (AOM), is needed to compensate for this optical frequency shift. However, this increases the size, weight, power, complexity, and cost of the clock system.

Here, we report a compact laser frequency offset locking scheme that adds an extra modulation to the laser diode besides a transitional half-wave modulation (HWM), noted as dual-modulation. Laser frequency offset locking can be realized with the Doppler-free enhanced absorption, which is obtained after the interaction between the dual-modulated multichromatic laser and ^{87}Rb atomic ensemble in the reference cell.

II. Experimental setups & results

Our experimental setup for dual-modulation is shown in Fig. 1(a), in which a distributed Bragg reflector (DBR) laser emits 795 nm light with a linewidth of about 1 MHz. As HWM in traditional CPT atomic clocks, a 3.417 GHz microwave signal is coupled to the laser diode current through a bias-tee to generate a multichromatic light, in which the ±1 sidebands from a coherent bichromatic light for successive CPT resonance. What's more, thanks to an electronic power combiner, a radio frequency signal is also added to the bias-tee then the laser driving current to form dual-modulation. The dual-modulated light is split into two arms, one is sent to a clock cell for CPT experiments, where the ^{87}Rb isotope-enriched vapor and buffer gas are filled. A uniform magnetic field is applied along the cell axis employing a solenoid to remove the Zeeman degeneracy. The vapor cell is surrounded by two layers of magnetic shields to reject stray magnetic fields. The other is used as a pump light and sent to a reference cell (ref cell) for laser frequency locking, where only pure ^{87}Rb is present. Thanks to a mirror, the pump transmission is reflected as a probe light, which is overlapped with the pump light and incident on the cell again. A polarization beam splitter (PBS) is used to separate the probe transmission from counter-propagated pump light and sent to a PD. For the ref cell, no static magnetic field is applied, only one layer of mu-metal magnetic shield is added.

For comparison, a high-performance CPT atomic clock's main optical setup with a traditional frequency shift device (AOM) is also plotted in Fig. 1(b).

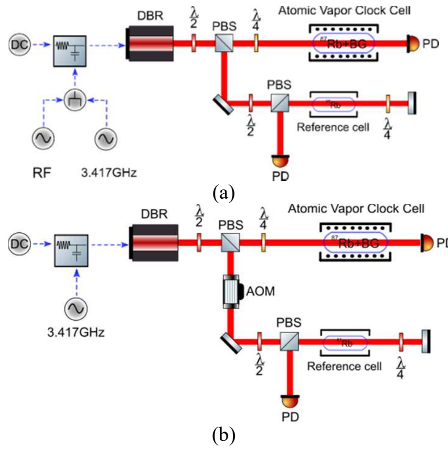

Fig. 1. The experimental setup. (a) the dual-modulation laser frequency locking scheme. (b) the traditional laser frequency locking scheme with AOM.

Typical spectra of D1 line in the ^{87}Rb obtained with multichromatic light with HWM laser incident on the reference cell (black) and clock cell (red) are shown in Fig.2. The laser detuning is defined as the frequency difference between the laser carrier frequency and the central frequency of the two optical transition, i.e. $|5^2S_{1/2}, F = 1\rangle \rightarrow |5^2P_{1/2}, F' = 1\rangle$ and $|5^2S_{1/2}, F = 2\rangle \rightarrow |5^2P_{1/2}, F' = 1\rangle$, where F is the hyperfine quantum number. The ~200 MHz frequency shift and the broadened optical transitions are observed from the clock cell due to buffer gas induced collision effect. Usually, the frequency shift can be compensated by an AOM in traditional laser frequency locking, as shown in Fig.1(b).

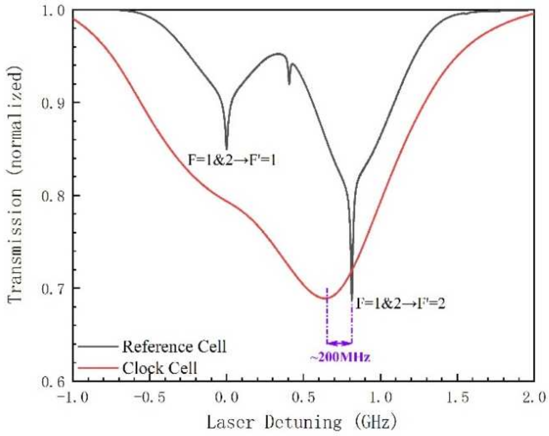

Fig. 2. Spectra of the ^{87}Rb D_1 line with HWM laser observed in the ref cell (black) and clock cell (red).

In the dual-modulation scheme, the laser diode is also modulated by a $f_b = 200$ MHz radio frequency (RF) besides the half-wave modulation. Fig. 3(a) shows the D1 line of the ^{87}Rb spectra with the dual-modulated laser in the clock and ref cell. We can see that the resonance peak (indicated by an arrow in the figure.) appears with the forms of Doppler-free absorption enhanced spectroscopy and with the frequency coinciding with the CPT involved $|5^2S_{1/2}, F = 1\&2\rangle \rightarrow |5^2P_{1/2}, F' = 2\rangle$ optical transitions from the clock cell, which is generated by the interaction between the 1st sideband of RF modulation add to the HWM laser and ^{87}Rb atomic ensemble in the ref cell. With the help of synchronous modulation-demodulation methods, error signals of CPT involved optical transitions are obtained from the ref cell as shown in Fig. 3 (b), which can be used to lock the laser frequency by feedback to the laser driving current.

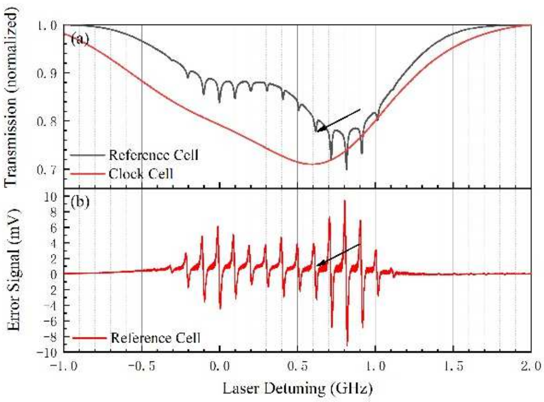

Fig. 3. (a) Spectra of the ^{87}Rb D_1 line with dual-modulated laser observed in the ref cell (black) and clock cell (red). (b) Error signals correspond to spectra from the ref cell.

III. Conclusions

We report a new laser frequency offset locking scheme. The collision frequency shift of CPT involved optical transition due to the introduction of buffer gas is compensated by an electronics method. Without the need of a bulky, costly, and power-hungry AOM anymore, our method can be used to implement compact and high-performance CPT and POP atomic clocks. It is also compatible with other laser locking methods, such as polarization spectroscopy, modulation transfer spectroscopy, etc.

References

[1] O Firstenberg, M Shuker, A Ben-Kish, et al, "Theory of Dicke narrowing in coherent population trapping," Physical Review A 76.1(2007).

[2] P Yun, Q Li, Q Hao, et al. "High-performance coherent population trapping atomic clock with direct-modulation distributed Bragg reflector laser." Metrologia, 58(4) (2021).

[3] S Micalizio, A Godone, F Levi, et al. "Pulsed optically pumped ^{87}Rb vapor cell frequency standard: A multilevel approach." Physical Review A 79.1(2009).

[4] J Vanier. "Atomic clocks based on coherent population trapping: A review." Applied Physics B 81.4(2005).

[5] S Ignatovich, I Mesenzova, M Skvortsov, et al. "Light shifts in the rubidium CPT atomic clock with laser current modulation at 3.4 and 6.8 GHz." Journal of Physics: Conference Series 2067(2021).

[6] D W Preston. "Doppler-free saturated absorption: Laser spectroscopy." American Journal of Physics 64.11(1996).

[7] M A Hafiz, G Coget, E De Clercq, et al. "Doppler-free spectroscopy on the Cs D1 line with a dual-frequency laser." Optics Letters 41.13(2016).

[8] H Kettering, J Camparo. "Energy dependence of the Rb $5^2S^{1/2}$-$5^2P^{1/2}$ noble-gas collision shift." Phys, B: At. Mol. Opt. Phys. 56 085201.

[9] Y Kang, Y Niu, D Chen, et al. "Laser frequency offset locking via tripod-type electromagnetically induced transparency." Applied Optics 53.12(2014).