Light Shift in Modulated Coherent Population Trapping Atomic Clocks

Ke Deng, Tao Guo, Juan Su, Dengzhu Guo, Xuzong Chen, and Zhong Wang
School of Electronics Engineering & Computer Science,
Peking University, Beijing, 100871, People's Republic of China,
E-mail:arc2008@126.com

***Abstract*—We have studied the light shift in coherent population trapping (CPT) atomic clocks under full band modulation (FBM) and under half band modulation (HBM). The theoretical results show that the light shift under FBM is only 1/4 of the light shift under HBM. Our experimental results confirm the theoretical results. Therefore, we can easily improve the stability of CPT clocks by replacing HBM with FBM.**

I. INTRODUCTION

Coherent population trapping (CPT) resonance in alkali atoms has been well known in recent years. It is generally observed through the coherent excitation of the atomic ensemble by means of two laser fields coupling the two hyperfine components of the ground-state to a common excited state. When the frequency difference of the two laser fields exactly equals to the atomic ground-state splitting, the atoms are coherently trapped in the ground-state and they cannot interact with the laser field any more. Hence no atoms are excited and the atomic ensemble becomes transparent for the laser field.

Now the CPT phenomenon has been widely used, one of its applications is atomic clock [1]-[3]. When CPT technology is adapted in the atomic clock, it is possible to substantially miniaturize the physics package to realize a chip scale atomic clock (CSAC). In a typical modulated CPT atomic clock, a vertical-cavity-surface-emitting laser (VCSEL) is modulated by a local oscillator (LO) with a frequency equaling to half of the atomic ground-state splitting. This modulation makes the single mode light of the laser into a comb of optical sidebands. The two first-order sideband of the laser are used to excite the CPT resonance, which is detected by monitoring the optical power of the laser field absorbed or transmitted by the atoms as a function of the frequency difference between the two first-order sideband. We call this method as half band modulation (HBM). Compared to it, there is another method to modulate the VCSEL in the CPT clocks. The laser is modulated by LO with a frequency equaling to the atomic ground-state splitting, the carrier and one of the first-order sideband of the laser are used to excite the CPT resonance. We call this method full band modulation (FBM).

Due to the interaction between the atom and the laser field, the energy levels for the clock transition are shifted, which is called light shift. The light shift is one of the factors limiting the long term stability of the CPT clock. There are some methods proposed to reduce the light shift in the CPT clock. It was shown that the light shift can be cancelled out by an appropriate index of modulation for the laser [4]. The basic reason behind the canceling is that the carrier and first two order band cause positive light shift while the other sidebands all cause negative light shift. However, it is impossible to keep the modulation index unchanged for long time. Light shift will come out after a certain period. It was demonstrated a technique to continuously correct the light shift [5]. However, this technique makes the atomic clock system complicated and gives rise to new instable factors. Therefore this technique is not suitable for fabricating a low cost clock.

We calculate the light shift under two ways of realizing modulated CPT clock. We find that the light shift under FBM can be only 1/4 of the light shift under HBM, while the conditions for light shift canceling point are the same for the two ways. The experiment results confirm the calculation results. It means that by using FBM we can improve the long-term stability of the CPT clock.

II. THEORY

Due to interaction between the atom and the laser field, energy levels for the clock transition are shifted (light shift). The light shift is one of the factors limiting long term stability of the CPT clock. Based on the three-level system theory [6], the light shift of a ground-state hyperfine level i (i=1, 2) is given by

$$\Delta\omega_i = (1/4)\,|\,\omega_{iR}\,|^2\,\frac{\Delta}{\Delta^2+\Gamma^{*2}/4}. \qquad (1)$$

Here Γ^* is the decay rate of the excited state; ω_{iR} is the Rabi frequency of ω_i as shown in figure 1. It is assumed that the decay from excited state to each ground-state is $\Gamma^*/2$. Δ is the detuning of the laser field frequency relative to central frequency of the optical transition resonance. The observed shift of the hyperfine splitting frequency is

$$\Delta\omega_{LS} = \Delta\omega_1 - \Delta\omega_2 \,. \tag{2}$$

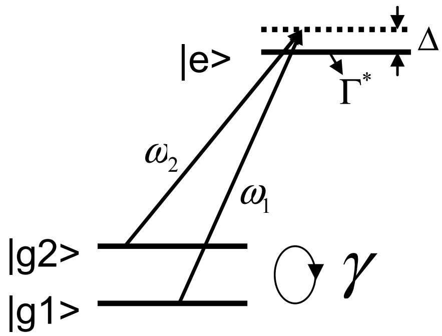

Figure 1. Three-level system considered. State |e> corresponds to the first excited state of the alkali atom.

In the CPT clocks, since there is a comb of optical sidebands in the laser spectrum, the total light shift should include interaction of all the optical frequency components with the two transitions. For simplicity, we assume that the J_n's give the amplitude of the sidebands. When the HBM is applied, the resultant clock frequency shift is [4]

$$\frac{\Delta\omega_{LS}}{\omega_0} = (\frac{\omega_R}{\omega_0})^2 * \Theta \,, \tag{3}$$

where

$$\Theta = J_0^2(m) + \frac{1}{2}J_1^2(m) - \sum_{n=2} J_n^2(m)(\frac{2}{n^2-1}) \,. \tag{4}$$

In this calculation, it is assumed that Δ is much smaller than the ground state hyperfine splitting frequency, ω_0 (3.0GHz for ^{85}Rb and 6.8 GHz for ^{87}Rb). There is another approximation that the sidebands separation $\omega_0/2$ is very large compared to the line width of the optical resonance Γ^*. Using the same method with FBM, the result becomes

$$\frac{\Delta\omega_{LS}}{\omega_0} = (\frac{\omega_R}{\omega_0})^2 * \frac{\Theta}{4} \,. \tag{5}$$

Comparing this to Eq. (3), we see that the light shift under FBM is only 1/4 of that under HBM. This result can be easily explained, as the off-resonance light is far from resonance in the FBM. From this point of view, light shift under FBM in ^{85}Rb is almost the same as light shift under HBM in ^{87}Rb. If FBM is applied to ^{87}Rb, light shift will only be 1/4 of that under HBM.

The theoretical calculations show that when the modulation index is 2.4, the light shift given by Eq. (3) and Eq. (5) can be cancelled [4, 7]. However, the long term stability of modulation index should be considered. The RF power directly decides the sideband power distribution. Besides that, there are also other factors, which can change due to laser aging, external environmental fluctuations, laser current and so on. The modulation index will change after a certain period. This is because the laser impedance, external temperature, and laser current cannot be kept constant. Therefore, we cannot keep the light shift at zero. From Eq. (3) and Eq. (5) it can be seen that the HBM scheme is more sensitive to small variation of modulation parameters. Furthermore, a modulation index of 2.4 is not a good operating condition. For some VCSELs, the clock does not operate under this modulation index. Therefore it is necessary to use the FBM to obtain good long term stability.

We also find that under the HBM, the two sidebands used to excite CPT are always very disequilibrium [8], which will decrease the contrast of CPT signal since CPT is an interfere effect. When the FBM is applied, the two sidebands used to excite CPT can be adjusted to improve the signal quality of the CPT resonance. Therefore when the FBM, rather than the HBM, is used, we can also obtain better short term stability.

III. Experiment

We did experiment to prove the above analyses. Figure 2 shows the experimental setup to measure the light shift. The setup is the same as described in Ref. 9. The VCSEL drive current is 1.2mA, with which the laser frequency is on the absorption spectrum of ^{85}Rb D1 line. A bias-tee is used to couple the VCSEL injection current and RF, which comes from an analog signal generator. The signal generator is lock on a cesium atomic clock. When the RF is on, a substantial fraction of the laser power will be transferred to the sidebands from the carrier band.

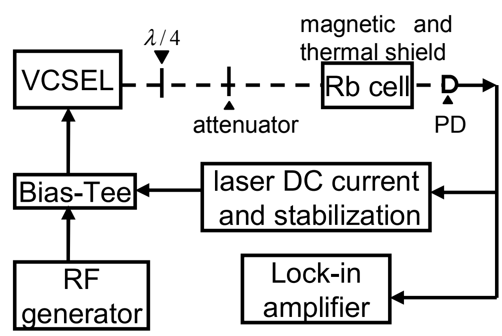

Figure 2. Sketch of the experimental setup for measuring frequency of CPT resonance.

The laser beam is circularly polarized and attenuated; the beam diameter was 3mm at the entrance to the vapor cell which is 4cm long and 2.5 cm in diameter containing a natural mixture of Rb with 19 mBar of Ne and 16 mBar of Ar. The cell is temperature controlled at 25˚C and magnetically shield. The RF generator is frequency modulated and the error signal (generated by a lock-in amplifier) is monitored. The frequency of the RF generator is adjusted, and when the error signal is zero, the frequency of the RF generator is the CPT resonance frequency.

We modulated the VCSEL under 1.5GHz and 3.0GHz in the experiment, and measured the light shift at a modulation index of approximately 1.7. This modulation index is the case for a real clock. For this modulation index, the carrier is equal to the larger one of the first-order sideband. Under this modulation index the first-order band is at its maximum. The overall intensity of the laser was adjusted by changing the neutral-density filter attenuator in front of the cell. The light shift under the two cases as a function of total light intensity entering the cell is plotted in Fig. 3.

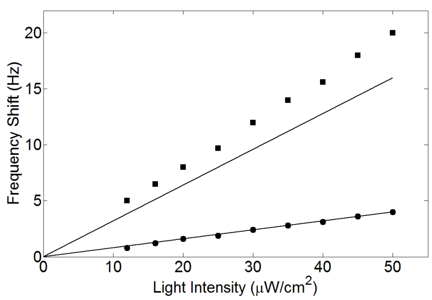

Figure 3. Frequency shift of CPT resonance as a function of the light intensity under FBM (circles) and under HBM (squares). The solid curves are fits to Eq. (3) and Eq. (5).

It can be seen that the light shift is nearly linear with the light intensity and light shift under FBM is about 1/5 of the light shift under HBM. This is slightly different from the theoretical result due to the disequilibrium of the two laser fields under HBM. When the RF is 1.5GHz and the modulation index is 1.7, the intensity ratio of the two sidebands is about 3:1. For a light intensity of $50\mu W/cm^2$, a change of 2% in light intensity will cause an instability of $2.6*10^{-11}$ under FBM (compare with $1.3*10^{-10}$ under HBM). For the FBM case the slope is approximately $0.06Hz/\mu W/cm^2$, compared to a slope of $0.3Hz/\mu W/cm^2$ in Ref. 10 where the intensity ratio of the two laser fields is adjusted to be 0.3.

IV. Conclusion

In conclusion, the performed theoretical and experimental comparison of FBM and HBM for CPT excitation has shown that using FBM significantly reduces the light shift. The results will be useful for the implementation of CPT atomic clocks - for improving their frequency stability and for their simplification and miniaturization.

Acknowledgment

The authors acknowledge helpful discussions with Qi Xianghui, Miao Zhu, and Xin Wang.

References

[1] S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, and J. Kitching, “A microfabricated atomic clock,” Appl. Phys. Lett., vol. 85, p. 1460, 2004.

[2] R. Lutwak, D. Emmons, W. Riley, and R.M. Garvey, “The Chip-Scale Atomic Clock – Coherent Population Trapping vs. Conventional Interrogation,” in: Proceedings of the 34th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, Reston, Virginia, 2002, p. 539.

[3] J. Vanier, “Atomic clocks based on coherent population trapping: a review,” Appl. Phys. B., vol. 81, p. 421, 2005.

[4] J. Vanier, A. Godone, and F. Levi, in proceedings of the IEEE International Frequency control Symposium, 1999, pp. 96-99.

[5] V. Shah, V. Gerginov, P. D. D. Schwindt, S. Knappe, L. Hollberg, and J. Kitching, Appl. Phys. Lett., vol. 89, p. 151124, 2006.

[6] J. Vanier and C. Audoin, The Quantum Physics of Atomic Frequency Standards, Adam Hilter, Bristol, UK, 1989.

[7] M. Zhu, L. S. Cutler, “Theoretical and experimental study of light shift in a CPT-based Rb vapor cell frequency standard,” in: 32nd Annual Precise Time and Time Interval (PTTI) Meeting, Reston, VA, 2000, p. 311.

[8] Ke.Deng, Tao Guo, Juan Su, Dengzhu Guo, Xinyuan Liu, Lu Liu, Xuzo ng Chen and Zhong Wang, “Full hyperfine frequency modulation in the implementation of coheren t population trapping atomic clocks” , *Phys. Lett*. A, vol. 373, p. 1130, 2009.

[9] K. Deng, T. Guo, D. W. He, X. Y. Liu, D. Z. Guo, X. Z. Chen, Z. Wang, “Effect of Buffer gas ratios on the Relationship between cell temperature and frequency shifts of the coherent population trapping resonance,” *Appl. Phys. Lett*., vol. 92, p. 211104, 2008.

[10] M. Merimaa, T. Lindvall, I. Tittonen, and E. Ikonen, “All-optical atomic clock based on coherent population trapping in ^{85}Rb,” J. opt. Soc. Am. B., vol. 20, p. 273, 2003.