光 子 学 报
ACTA PHOTONICA SINICA

doi:10.3788/gzxb20184704.0414002

应用于光抽运铯原子钟的小型稳频激光器

石浩[1,2]，马杰[1]，李孝峰[1]，刘杰[1]，张首刚[1]
（1 中国科学院国家授时中心 中国科学院时间频率基准重点实验室，西安，710600）
（2 中国科学院大学，北京，100049）

摘　要：设计了一种应用于光抽运铯原子钟的稳频激光器，用小型化的饱和吸收装置对激光进行稳频，用于产生饱和吸收谱的泵浦光的偏振方向与检测光的偏振方向相互垂直，通过调节激光的偏振方向增大铯原子的跃迁几率.相对于一般简化的饱和吸收装置，小型化的饱和吸收装置产生的用于锁频的参考信号的幅度更大.当激光频率被锁定在铯原子的 $6S_{1/2}$，$F=4\rightarrow 6P_{3/2}$，$F=5$ 能级跃迁线上时，对激光器的稳定度进行了测量，百秒稳定度为 1.88×10^{-11}.该稳频激光器的体积较小，有利于光抽运铯原子钟的小型化和工程化应用.

关键词：光学设计；激光稳频；半导体激光器；吸收光谱；频率稳定度
中图分类号：TN365　　**文献标识码**：A　　**文章编号**：1004-4213(2018)04-0414002-7

Compact Frequency Stabilized Laser for Optically Pumped Cs Beam Clocks

SHI Hao[1,2], MA Jie[1], LI Xiao-feng[1], LIU Jie[1], ZHANG Shou-gang[1]
(1 *Key Laboratory of Time and Frequency Standards, National Time Server Center, Chinese Academy of Sciences, Xi'an* 710600, *China*)
(2 *University of Chinese Academy of Sciences, Beijing* 100049, *China*)

Abstract: A frequency stabilized laser used in optically pumped cesium beam clocks is designed. The concise saturated absorption frequency stabilization system, in which the polarization direction of pumping laser is perpendicular to the polarization direction of probing laser, is utilized to lock laser frequency. The transition probability of the cesium atom is improved by the adjustment of the polarization direction of pumping laser. The amplitude of reference signal produced by the proposed system is higher than the signal produced by the simplified saturated absorption frequency stabilization system. When laser is locked at the frequency of the cycling transition $6S_{1/2}$, $F=4\rightarrow 6P_{3/2}$, $F=5$ of cesium, the frequency stability is measured as 1.88×10^{-11} at 100 s. The setup of the system is compact, which is beneficial to the miniaturization and engineering of the optically pumped cesium beam clocks.

Key words: Optical design; Laser frequency stabilization; Semiconductor lasers; Absorption spectroscopy; Frequency stability
OCIS Codes: 140.4050; 020.1335; 300.6210; 120.3930; 120.4570

0 Introduction

Steady single mode diode lasers emitting at 852nm are significant components for systems such as

---

Foundation item: National Special Research Program for Major Scientific Instruments and Equipment of China (No.2012YQ200183), and the General Armament Department's Special Research Program for Fundamental Technology (No.ZKGSZ20132JL01).

First author: SHI Hao (1990-), male, Ph.D. degree candidate, mainly focuses on optically pumped Cs beam clocks. Email: 1210407534@qq.com.
Contact author: MA Jie (1979-), male, associate researcher, M.S. degree, mainly focuses on optically pumped Cs beam clocks. Email: mj@ntsc.ac.cn.
Supervisor: ZHANG Shou-gang (1966-), male, researcher, Ph.D. degree, mainly focuses on quantum frequency standard. Email: szhang@ntsc.ac.cn.

Received: Nov.6, 2017; **Accepted**: Dec.19, 2017

atomic clocks, laser cooling, laser pumping and atom interferometer[1-3]. Generally, laser is locked at the frequency of the cycling transition $6S_{1/2}$, $F=4\rightarrow 6P_{3/2}$, $F=5$ of Cesium (Cs)[4]. Saturated absorption frequency stabilization as an available technology is widely applied to lock the frequency of laser. Optically pumped Cs beam clock makes the state selection by means of optical methods other than magnetic state selection[5-7]. It is a potential frequency standard in the extensive engineering applications. The preparation efficiency of atomic state could be improved by the optical pumping. The frequency stabilized laser is the foremost device for optically pumped Cs beam clock[8-10].

Frequency stability of the optically pumped Cs beam clocks is closely related to the stability of the laser. The pumping efficiency of the Cs atom depends on the purity of the laser. The number of the un-pumped atoms will increase when poor laser is used to pump Cs atom in the pumping region of the Cs beam tube. The fluorescence signal produced in the detecting region could be influenced by the atoms retained in the $F=4$ level of the ground state of the Cs atom. The Signal-to-Noise Ratio (SNR) of Ramsey signal used to lock the quartz crystal oscillator and the accuracy of the atomic clock could become poor. The stability of the optically pumped Cs beam clock could be improved when the frequency stabilized laser with excellent property is utilized to irradiate Cs atoms[11].

Observatoire de Neuchâtel (ON) has developedoptically pumped space Cs atomic resonator with only one optical frequency[12]. ON, Thales and the SYRTE Observatoire de Paris have joint-developed space Cs atomic clock with the Distributed Bragg Reflector (DBR) laser at 894nm[13]. Peking University has developed the frequency stabilized laser locked by fluorescence signal for the optically pumped Cs beam clock[9]. National Time Service Center (NTSC) of Chinses Academy of Sciences has developed the saturated absorption frequency stabilization laser for engineering optically pumped Cs beam clock[7].

The laser device used in optically pumped Cs beam clock should have the ability to emit two laser lights, simultaneously. One of them is the pumping laser with the stabilized frequency, the other is the detecting laser with the stabilized frequency which has the frequency shift, 250 MHz, with pumping laser. Besides, in order to promote the miniaturization of the optically pumped Cs beam clock, the volume of the laser device should be reduced as much as possible[14]. The Doppler-free Saturation Absorption Spectrum (SAS) as reference signal has higher SNR [9]. But, the setup, especially light path, of this saturated absorption frequency stabilization is complex and it is against the miniaturization and engineering of the equipment, especially aerospace application. The simplified saturated absorption frequency stabilization, only with a pumping laser and a probing laser, can overcome the shortcomings mentioned above. The polarization directions of the two lasers are parallel to each other in this setup[15]. However, the SNR of the traditional SAS and the peak value of the reference signal are lower. The amplitude and the SNR of the reference signal could be increased by adjusting the polarization directions of the two probing lasers.

In this paper, a compact frequency stabilized laser used in optically pumped Cs beam clocks, which could simultaneously output two lasers, is reported. The dependence of the reference signal amplitude on the polarization directions of the two probing lasers is described and the comparison of two different mechanisms is made. We suggest a concise saturated absorption frequency stabilization method that produce higher reference signal compared with simplified saturated absorption frequency stabilization and has simpler setup compared with Doppler-free saturated absorption frequency stabilization setup.

1 Principle and experiment

A simplified interaction diagram of the Cs beam tube and laser used in the optical pumped Cs beam clock is shown in Fig. 1. The direction of light beams is perpendicular to the direction of atomic beam. The atomic beam sprays out from the collimator of a Cs oven. Before interacting with the detect laser, the atomic beam has passed through the pumping and microwave area. In the pumping area, Cs atoms are pumped to the $6S_{1/2}$, $F=3$ level through the $6S_{1/2}$, $F=4\rightarrow 6P_{3/2}$, $F=4$ transition by the pumping laser. In the microwave area, Cs atoms are transferred to the $6S_{1/2}$, $F=3$, $m_F=0$ by the microwave tuned to 919 263 177 0 Hz. In the detecting area, the atoms in the $6S_{1/2}$, $F=4$ level is detected by the detecting laser turned to $6S_{1/2}$, $F=4\rightarrow 6P_{3/2}$, $F=4$ transition line. The fluorescence emitted by the atomic spontaneous radiation is collected by fluorescence collector, and then the Ramsey is produced by Photo

Diode (PD). The laser produced by the Distributed Feedback (DFB) diode laser is locked in the $6S_{1/2}$, $F=4 \rightarrow 6P_{3/2}$, $F=5$ transition line. The laser beam is separated by the Polarizing Beam Splitter (PBS). One laser beam serves as the pumping laser while the other laser beam serves as the detecting laser. And, the frequency of the pumping laser is shifted 250 MHz by the Acoustic Optical Modulator (AOM).

The laser produced by the DFB diode lasercould be stabilized by using the SAS device. The generation mechanism of SAS can be described by the theory of velocity selective optically pumping. The Doppler-free SAS can be understood by the combined effects of the velocity-selective optical pumping, the saturation and the resonant light pressure[16-17]. The traditional SAS can be obtained by the concise saturated absorption frequency stabilization system without the other probing laser. The amplitude of the reference signal produced by the cycling transition $6S_{1/2}$, $F=4 \rightarrow 6P_{3/2}$, $F=5$ of Cs depends on the probabilities of transitions corresponding to the pumping laser, the probing laser and the spontaneous emission from the $6P_{3/2}$, $F=5$ by the pumping laser, respectively.

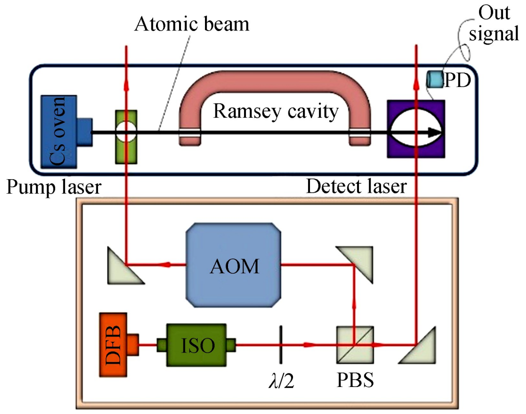


Fig.1 Interaction diagram of the laser and Cs beam tube

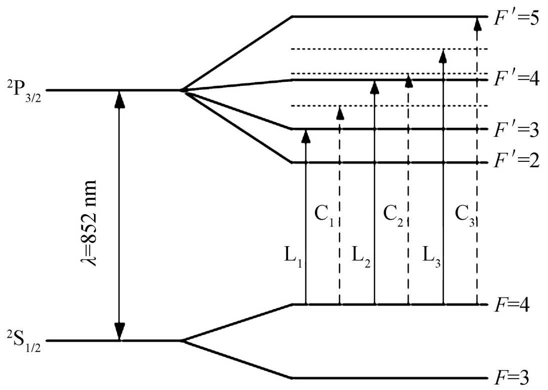


Fig.2 Diagram of hyperfine energy level involved in Cs D_2 line

As the Fig. 2 shows, there are 3 peaks involved with principal resonances and 3 peaks involved with cross-over resonances in the Cs D_2 SAS. The solid lines (L_1, L_2, L_3) indicate principal resonances and the dotted lines (C_1, C_2, C_3) indicate cross-over resonances. The transition probability amplitudes of the stimulated emission are proportional to the transition probability amplitudes of the spontaneous emission, shown in Fig. 2, in the interaction of laser and Cs atoms.

The amplitude of the reference signal is given by[5]

$$\Psi \propto |\eta_p|^2 \cdot |\eta_b|^2 \cdot [-\delta_{sp} + |\eta_{sp}|^2/\Gamma] \tag{1}$$

where $|\eta_p|^2$ is the transition probability corresponding to the pumping laser, $|\eta_b|^2$ is the transition probability corresponding to the probing laser and $|\eta_{sp}|^2$ is the transition probability of spontaneous emission from the $6P_{3/2}$, $F=5$ by the pumping laser. Kronecker's δ symbol indicates the depopulation of the $6S_{1/2}$, $F=4$ induced by the pumping laser. $|\eta_{sp}|^2/\Gamma$ shows the branching ratio of the spontaneous emission from the $6P_{3/2}$, $F=5$ and indicates augmentation of the $6S_{1/2}$, $F=4$ populations.

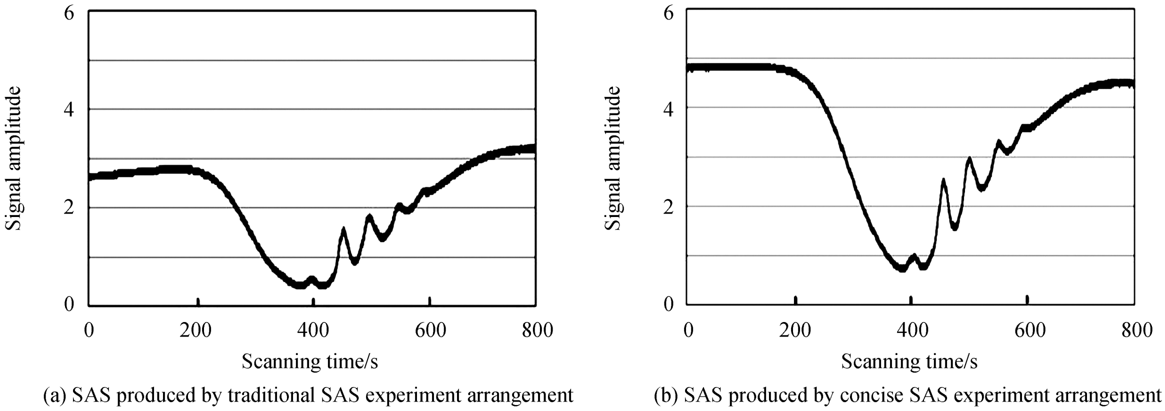
The amplitude ofthe reference signal produced by Cs $6S_{1/2}$, $F=4 \rightarrow 6P_{3/2}$, $F=5$ transition could be improved by adjusting the polarization directions pumping laser and the probing laser. Fig. 3(a) shows the interaction between the pumping laser and the probing laser in the traditional SAS experiment. The polarization directions of the two lasers are parallel to each other. Fig. 3(b) shows the interaction between the pumping laser and the probing laser in the concise SAS experiment. The polarization directions of the two lasers are perpendicular to each other. The direction of magnetic field is parallel to the polarization direction of the pumping laser. The temperature variation amplitude of the DFB could be limited in the 1mK when the laser is locked.

(a) Diagram of traditional SAS experiment arrangement

(b) Diagram of concise SAS experiment arrangement

Fig.3 Comparison of traditional SAS experiment with concise SAS experiment arrangement

The SAS, as theFig. 4 shows, is produced by the traditional simplified SAS setup and the concise SAS setup, respectively. The measurement is carried out when the laser is turned to the 852nm at room temperature. The frequency of the scanning signal imported to the laser is 12 Hz. The laser power and the magnification times of the signal-amplifier are unchanged. As the Fig. 4 shows, there is a clear distinction in the peak amplitude of reference signal which is produced by the cycling transition $6S_{1/2}$, $F=4\rightarrow 6P_{3/2}$, $F=5$ between Fig. 4(a) and (b). The peak amplitude of reference signal of Fig. 4(b) is much bigger than that of Fig. 4(a). It is because of the changes of the probabilities of transitions corresponding to the pumping laser and the probing laser, which is caused by the changes of polarization of the pumping laser and the probing laser.



(a) SAS produced by traditional SAS experiment arrangement (b) SAS produced by concise SAS experiment arrangement

Fig.4　SAS signal amplitude versus scanning time

The SNR of the reference signal shown in Fig. 4(b) is improved by the increase of the peak amplitude of reference signal. The noise, introduced into the frequency stabilization circuit, could be reduced greatly with the same restriction of supply voltage when the reference signal is used to lock the frequency of laser. Futhermore, the slope of the error signal, used to correct the supply current of the laser, could be improved to make laser locked more quickly. Therefore, the stability of the frequency stabilized laser, locked by this reference signal, could be improved.

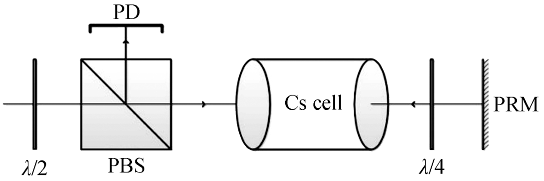


Fig.5　Designed concise saturated absorption frequency stabilization light path

As the striking features mentioned above, we design the concise saturated absorption frequency stabilization light path as Fig. 5 shows. The combination of the PBS and the λ/2 wave plate is used to adjust the laser power of the pumping laser. PD is used to detect the laser power of the probing laser. The λ/4 wave plate is used to adjust the polarization direction of the probing laser. The reflectivity of the Partially Reflecting Mirror (PRM) is 10% to light at 852 nm. The pumping laser shoots into the Cs cell through the λ/2 wave plate and the PBS. The polarization direction of the probing laser, adjusted by the λ/4 wave plate, is perpendicular to the polarization direction of the pumping laser. The probing laser reflected by the PRM is reflected to the PD and the SAS is obtained. In order to reduce the volme of experimental arrangement, the elements with small size is used in the experiment. The dimensions of the Cs cell are $L=25$ mm and $\phi=16$ mm. The diameter of the used lens is 12.7 mm and the dimension of the PBS is 12.7 mm ×12.7 mm×12.7 mm.

Fig. 6 shows the concrete structure of the designed laser device. To achieve the requirements for the optically pumped Cs beam clock, the frequency stabilization diode laser can emit two lasers at the same time. As shown in Fig. 6, a DFB serves as a light source, operating at 852 nm with a 2 MHz line-width. The collimating lens and cylinder lenses are used to collimate laser . An optical Isolator (ISO) is used to prevent the optical feedback from the saturated absorption setup and the main output of the system. By using a combination of a half-wave plate and a PBS, a variable part of the laser power is divided for spectroscopy, and then a light beam shoots into SAS light path system, as Fig. 5 shows, while the other laser beam shoots into the next half-wave plate and PBS. The laser beam is split into two beams. One of the light beams is reflected by mirror and shoots into the concave lens and convex lens. By using a combination of a concave lens and convex lens, a laser with expanded spot is formed. It shoots into the detecting area of the optically pumped Cs beam clock to detect atoms in the $6S_{1/2}$, $F=4$ level. The other light beam shoots into the AOM and the laser frequency is shifted 250MHz by AOM. It shoots into the pumping area of the optically pumped Cs beam clock to pump atoms to the $6S_{1/2}$, $F=4$ level through the $6S_{1/2}$, $F=4 \rightarrow 6P_{3/2}$, $F=4$ transition.

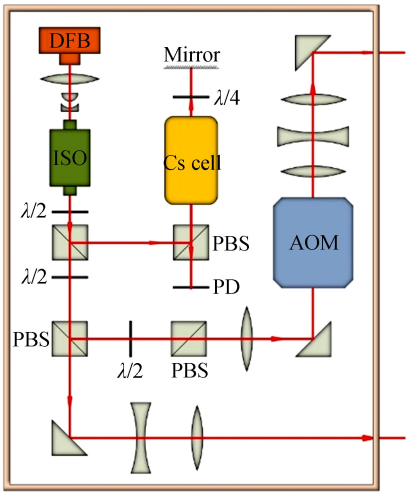


Fig.6 Composition diagram of the frequency stabilized laser device used in optically pumped Cs beam clock

The signal generator controlled by Micro-program Control Unit (MCU) outputs reference signaland modulating signal . A 2 5 kHz sinusoidal modulating signal is added to the laser injection current and inputted into laser and SAS optical part. The SAS signal is amplified by pre-amplifier and inputted into mixer where it is mixed with ref signal. There is only the reference signal produced by the cycling transition $6S_{1/2}$, $F=4 \rightarrow 6P_{3/2}$, $F=5$ of Cs when the supply current of the laser and the scanning current are appropriately adjusted, respectively. The laser could be locked in the reference frequency of the cycling transition $6S_{1/2}$, $F=4 \rightarrow 6P_{3/2}$, $F=5$ of Cs after inputting the error signal, produced by mixing the reference signal with the modulating signal, into the Proportion Integration Differentiation (PID) which stabilizes the supply current of the laser.

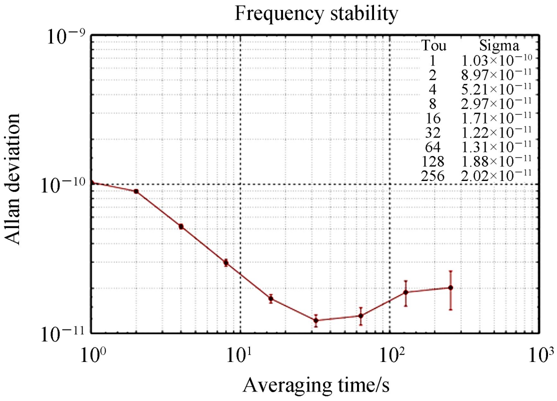


Fig.7 Measured frequency stability of frequency stabilized laser

The frequency stabilityof the laser, locked at the frequency of the cycling transition $6S_{1/2}$, $F=4 \rightarrow 6P_{3/2}$, $F=5$ of Cs, is measured by mixing it with the laser, locked at the frequency of the crossover transition $6S_{1/2}$, $F=4 \rightarrow 6P_{3/2}$, $F=4$ and $F=5$ of Cs. This two lasers are both locked by concise saturated absorption frequency stabilization setup. The measured frequency stability of the frequency stabilized laser is shown in Fig. 7. The Allan deviation is 1.03×10^{-10} at 1s and reaches the minimum value 1.31×10^{-11} at 64s. The frequency stability is 1.88×10^{-11} at 100s. The designed frequency stabilized laser has worked for about one and a half years without losing lock.

2 Discussion

The property of the compact frequency stabilized laser meets the requirement of the miniaturized optically pumped Cs beam clock[18-20]. The laser is a portable device. It could be widely used in engineering application. It is small and the dimension of the laser device is 36.5 cm×15 cm×5 cm. In order to improve the anti-seismic property of the laser device, optical elements are installed on the baseboard milled from a whole piece of aluminum. Furthermore, the automatic frequency stabilization laser is a more useful device. Self-recovery capacity and the ability of automatic peak-seeking are added to the laser. However, the quality of the laser spot is poor, which impacts the laser-atom interaction in the Cs beam tube. It needs to be improved in the experiment.

Laser is sensitive to the displacement caused by the vibration of the optical element. The simplification of the light path is beneficial to improve anti-vibration character of the frequency stabilization system. The structure of the concise saturated absorption frequency stabilization setup is compact. It can be set up when only a $\lambda/4$ wave plate is introduced into the traditional simplified saturated absorption setup. However, the SNR of the reference signal produced by the concise saturated absorption frequency stabilization setup is higher than the reference signal produced by the traditional simplified saturated absorption frequency stabilization setup. In addition, its setup is simpler compared with Doppler-free saturated absorption frequency stabilization. Therefore, the concise saturated absorption frequency stabilization setup will have better anti-vibration performance compared with Doppler-free saturated absorption frequency stabilization setup. The compact setup is beneficial to the miniaturization and engineering of the saturated absorption frequency stabilization.

The concise saturated absorption frequency stabilization light path is installedon the mounting plate, milled by aluminum block. The anti-vibration character of the light path could be improved and it contributes to the engineering of this technology. Pony-size optical elements are employed to enhancing the miniaturization of the setup. The frequency stability of the laser, locked by the concise saturated absorption frequency stabilization setup, is improved for the increase of the peak amplitude of the reference signal. But, the frequency stability starts to turn bad on 64s. It is due to the temperature variation of Cs cell. The long-term stability could be improved by adding temperature control on Cs cell.

The distinction between the traditional SAS and the Doppler-free SAS is whether or not it has the Doppler background. Structurally, Doppler-free saturated absorption light path has three laser beams and the traditional saturated absorption light path has two lasers. The principle of the Doppler-free SAS mentioned in Refs. [5-6] could be applied to the traditional SAS. The probabilities of transitions corresponding to the pumping laser, the probing laser and the spontaneous emission from the excited state vary with the polarization of the pumping laser and the probing laser. The peak amplitude of the reference signal could be increased by adjusting the polarization directions of the pumping laser and the probing laser. Magnification times of signal could be reduced to introduce less noise into the frequency stabilization system. The frequency stability of the stabilized laser locked by the system could be improved. The frequency stability is measured by beating frequency of two lasers locked by employing the same way of frequency stabilization. This method could give a better view of the result of a measurement.

The interaction mechanism of the laser in the concise saturated absorption frequency stabilizationsetup also could be used in the Doppler-free saturated absorption frequency stabilization experiment at 852nm under lab conditions. It only needs to introduce a $\lambda/2$ wave plate to change the polarization direction of the probing laser. The peak amplitude of the reference signal, produced by the transition $6S_{1/2}$, $F=4 \rightarrow 6P_{3/2}$, $F=5$ of Cs could be increased and the frequency stability of laser locked by the Doppler-free saturated absorption frequency stabilization system could be improved according to the principle.

Except for the electrical parameters of the frequency stabilization circuit, some optical elements parameters could be optimized to improve the experiment results. In the experiment, the intensity of the probing laser, the pressure of buffer gas in the Cs cell, the diameter of the laser beam and the size of Cs cell could be adjusted to improve the amplitude of the signal and the frequency stability.

3 Conclusion

We present a compact frequency stabilized laser used in optically pumped Cs beam clocks, which could simultaneously output two lasers. The frequency of the laser is stabilized in the $6S_{1/2}$, $F=4 \rightarrow 6P_{3/2}$, $F=5$ transition line of Cs by the concise saturated absorption frequency stabilization device. The peak amplitude of the reference signal is increased by adjusting the polarization direction of the pumping laser and the probing laser. The frequency stability of the laser locked by the frequency stabilization system could be improved by increasing the amplitude of the reference signal. The frequency stability of the designed laser is satisfied with the requirement of stability of the optically pumping Cs beam clock. Through experimental measurements, the SNR of Ramsey signal used to lock the quartz crystal oscillator is about 1.0×10^4 when the designed laser is used in the optically pumped Cs beam clocks. The compact setup could contribute to the miniaturization and engineering of the optically pumped Cs beam clocks.

References

[1] CHEN Jing-biao, ZHU Cheng-jin, WANG Feng-zhi, *et al*. A new pumping-probing scheme for the optically pumped cesium beam frequency standard[J]. *Chinese Physics Letters*, 2001, **18**(1): 16-17.

[2] GHEZALI S, LAURENT PH, LEA S N, *et al*. An experimental study of the spin-exchange frequency shift in a laser-cooled cesium fountain frequency standard[J]. *Europhysics Letters*, 2007, **36**(1): 25-30.

[3] MORETTI D, FELINTO D, TABOSA J W R. Collapses and revivals of stored orbital angular momentum of light in a cold-atom ensemble[J]. *Physical Review A*, 2009, **79**(2): 718-722.

[4] DURFEE D S, SHAHAM Y K, KASEVICH M A. Long-term stability of an area-reversible atom-interferometer sagnac gyroscope[J]. *Physical Review Letters*, 2006, **97**(24): 240801-240804.

[5] LEE H S, BAEK K J, KWON T Y, *et al*. Velocity distribution and second-order Doppler shift in an optically pumped cesium beam frequency standard[J]. *IEEE Transactions on Instrumentation & Measurement*, 2002, **48**(2): 492-495.

[6] SANG E P, LEE H S, SHIN E, *et al*. Generation of a slow and continuous cesium atomic beam for an atomic clock[J]. *Journal of the Optical Society of America B*, 2002, **19**(11): 2595-2602.

[7] LI Xiao-feng. Research on the key technology of small optically pumped cesium beam frequency standard[D]. Beijing: University of Chinese Academy of Sciences, 2015.

[8] SHI Hao, MA Jie, LI Xiao-feng, *et al*. Simulation and design of fluorescence collector[J]. *Chinese Physics Letters*, 2016, **33**(9): 094205.

[9] WANG Qing, DUAN Jun, QI Xiang-Hui, *et al*. Improvement of laser frequency stabilization for the optical pumping cesium beam standard[J]. *Chinese Physics Letters*, 2015, **32**(5): 054206.

[10] HAAMSH. Corrections for second-order doppler shift and cavity phase error in cesium atomic beam frequency standards [J]. *IEEE Transactions on Instrumentation & Measurement*, 2007, **23**(4): 509-514.

[11] HISADOME H, KINARA M.Design of stabilized laser for optically pumped atomic frequency standards[J]. *Electrical Engineering in Japan*, 2001, **136**(2): 31-37.

[12] LECOMTE S, HALDIMANN M, RUFFIEUX R, *et al*. Performance demonstration of a compact, single optical frequency Cesium beam clock for space applications[C]. In proceedings of Frequency Control Symposium, 2007 Joint with the 21st European Frequency and Time Forum. IEEE International, 2007, 1127-1131.

[13] HERMANN V, GAZARD M, BERTHOUD P, *et al*. OSCC project: A space Cs beam optically pumped atomic clock for Galileo[C]. In proceedings of Frequency Control Symposium, 2007 Joint with the 21st European Frequency and Time Forum, 2007, 77-80.

[14] SALLOT C, BALDY M, GIN D, *et al*. $3 \cdot 10^{-12}\ \tau^{-1/2}$ on industrial prototype optically pumped cesium beam frequency standard[C]. In the proceeding of Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum, 2003, 100-104.

[15] ZHANG Xian, HUANG Kai-kai, XU Hao, *et al*. A compact setup of SAS for diode laser frequency stabilization[J]. *Chinese Physics Letters*, 2012, **29** (7): 74206-74209.

[16] IM K B, JUNG H Y, OH C H, *et al*. Saturated absorption signals for the Cs D_2 line[J]. *Physics Review A*, 2001, **63** (3): 222-224.

[17] MAGUIRE L P, MESE E, SCHOLTEN R E, *et al*. Theoretical calculation of saturated absorption spectra for multi-level atoms[J]. *Journal of Physics B Atomic Molecular & Optical Physics*, 2006, **39**(12): 2709-2720.

[18] WANG Xi, WANG Yong, DUAN Li-na, *et al*. LD side-pumped passive mode-locked: YAG laser with semiconductor saturable absorption mirror[J]. *Acta Photonica Sinica*, 2015, **44**(7): 0714001.

[19] HASEGAWA A, FUKUDA K, KAJITA M, *et al*. Accuracy evaluation of optically pumped primary frequency standard CRL-O1[J]. *Metrologia*, 2004, **41**(4): 257-263.

[20] WANG Meng-yu, JIN Xue-ying, WANG Jing, *et al*. Analysis of the pound-drever-hall frequency stabilization technique based on a whispering gallery mode optical microsphere cavity[J]. *Acta Photonica Sinica*, 2017, **46**(7): 0706003.