A High-stability Compact Optical System for Integrating Sphere Cold Atom Clock

Xiumei Wang, Jin He
Shen Zhen SoC Key Laboratory
PKU-HKUST Shen Zhen-Hong Kong Institution
Shenzhen 518000, P. R. China
frankhe@pku.edu.cn

Yunjia Wang, Wenming Wang, Yifei Wang, Shiguang Li, Weili Wang, Guodong Liu, Xi Zhu, Chengyuan Zhang, Yanjun Chen, Liang Wang, Yaxuan Liu, Lianshan Gao
Time and Frequency Center
Beijing Institute of Radio Measurement and Metrology
Beijing 100857, P. R. China
13301028378@163.com

Jingbiao Chen
State Key Laboratory of Advanced Optical Communication Systems and Networks, Institute of Quantum Electronics, Department of Electronics
Peking University
Beijing 100871, P. R. China
jbchen@pku.edu.cn

***Summary*—A high-stability compact optical system is proposed for integrating sphere cold atom clock. Both an extended cavity diode laser with linewidth of about 50 kHz and a distribution feedback Bragg laser are applied as laser sources. The frequency of the former is locked with high frequency stability of the 10^{-13} level between 1~10^4s averaging time. A new scheme of laser frequency stabilization and shift is realized and the laser power is stabilized to the 10^{-5} level between 1~10^4s averaging time. The reasonable arrangement of the optical paths enables a compact system with a total size of 500mm×500mm×200mm.**

Keywords—cold atom clock, optical system, laser stabilization, compactness

I. INTRODUCTION

With the development of engineering, the high stability and compactness of laser cooling and absorption appear to be one of the main challenges in the development of transportable or satellite borne quantum instruments with cold atoms [1]. Many efforts have been made both in laboratories and industry to find the elegant solutions for the highly stable and compact optical system [2-5], taking into account various constraints: laser frequency and power stabilization, laser linewidth, laser frequency shift, integration, etc. The integrating sphere cold atom clock (ISCAC) [6] is the next-generation satellite borne atomic clock, whose prototype has exhibited excellent results: a short-term frequency stability of $3\times10^{-13}\tau^{-1/2}$ and a preliminary long-term frequency stability of 8.6×10^{-16}. However, its optical system determines the technical performance and engineering characteristics, such as cold atom temperature, cold atom total number, frequency stability, volume, weight, power consumption, etc. So it is necessary to achieve a high-stability compact optical system to realize the engineering products for space in the future.

Here we show a high-stability compact optical system for ISCAC with cesium atoms which offers the required beams for diffusing laser cooling, atom state preparation and clock signal detection. The compact optical system is composed of an extended cavity diode laser (ECDL) and a distribution feedback Bragg (DFB) laser with high laser frequency and power stability. Two sides of the optical system are covered by optical components reasonably, and the total size of the optical system is 500mm×500mm×200mm.

II. BRIEF DESCRIPTION OF THE OPTICAL SYSTEM

A. Principle

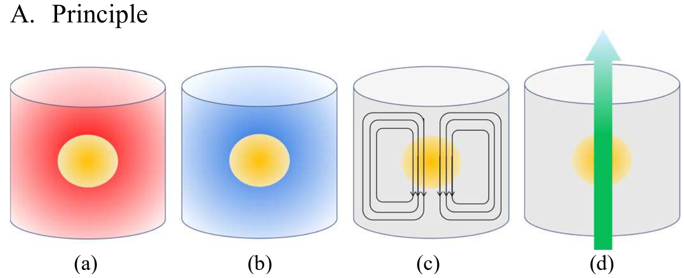


Fig. 1. The operation process of ISCAC, (a)laser cooling, (b)state preparation, (c)microwave interrogation, (d)clock signal detection

As shown in Fig. 1, the operation process of ISCAC includes diffuse laser cooling, state preparation, microwave interrogation and clock signal detection, which occur at the same place inside the cylindrical microwave cavity. Thanks to the special process, a huge reduction of the physics package volume down to a few liters can be realized. During the process, there are four laser beams, cooling, repumping, pumping, and probe beams. The diffuse lights for laser cooling (cooling and repumping light) and state preparation(pumping light) are produced by the reflection of the laser light at the inner surface of the microwave cavity and the cold atoms should be stored in the cavity with a high vacuum.

TABLE I. THE REQUIREMENT OF LASER BEAMS IN THE OPTICAL SYSTEM FOR ISCAC WITH CESIUM

Parameters	**Cooling**	**Repumping**	**Pumping**	**Probe**
Power/mW	~200	~20	~1	~0.002
Energy level of D2 line	4→5’	3→4’	4→4’	4→5’
Detuning	~-3Γ	0~0.5Γ	0~0.5Γ	0~0.5Γ
Polarization	free	free	free	Circular
Duration time	~50ms	~50ms	~1ms	~5ms

In the above process of ISCAC with cesium, the requirement of laser beams in the optical system is shown in

Table.1. The four laser beams are at constant frequencies, and their characteristics should be realized in our optical system.

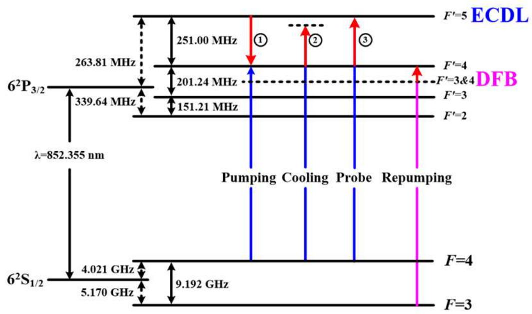


Fig. 2. The scheme of laser frequency stabilization and shift

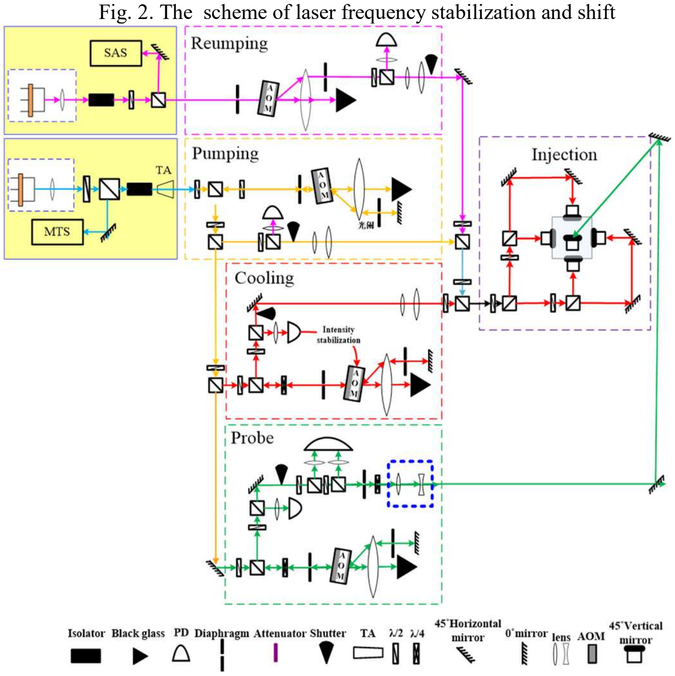


Fig. 3. The scheme of optical path

To minimize the number of laser sources and simplify the laser frequency shift processes, a new laser frequency stabilization and shift scheme is proposed, as shown in Fig. 2. Both an ECDL and a DFB laser allow us to realize the required beams. The ECDL has been specially developed with a narrow linewidth, which offers the pumping, cooling and probe beams. The frequency of this laser is locked to the cesium D2 line F=4 →F'=5 by modulation transition spectroscopy (MTS), and then it's shifted to form the frequency of the above-mentioned three beams sequentially. Firstly, the pumping beam (resonance of D2 line F=4→F'=4) is formed by the negative frequency shift from the locked frequency of the ECDL. Secondly, the cooling beam (red-detuning of D2 line F=4→F'=5) is formed by the positive frequency shift from the pumping beam. Thirdly, the probe beam (near resonance of D2 line F=4→F'=5) is also formed by the positive frequency shift from the pumping beam. The DFB laser offers the repumping beam, whose frequency is locked to the cesium D2 line F=3→F'=3&4 by saturated absorption spectroscopy (SAS). The repumping beam is formed by the positive frequency shift from the DFB laser, because its frequency is resonant with D2 line F=3→F'=4. Fig.3 shows the scheme of the optical path with four laser frequency shift processes realized by acoustic-optical modulators (AOMs), which meet all the requirements of the clock.

B. Architecture

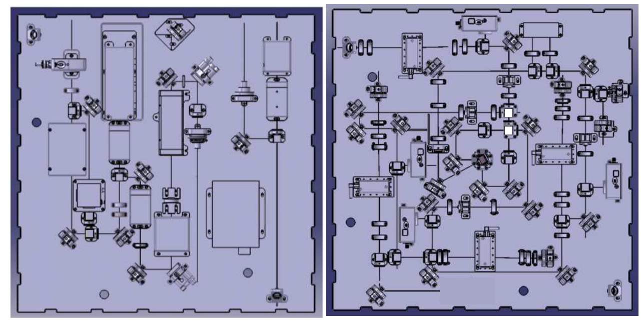

(a) (b)

Fig. 4. Two sides of the optical system, (a) bottom, (b)top

As is shown in Fig.4, the optical components are arranged on the two sides of the optical system reasonably. The bottom side is covered by the optical path of laser sources, and the top side is covered by the optical path of laser frequency shifts and injection. The total size of the optical system is 500mm×500mm×200mm, which is the consequence of the minimum laser sources, the simplified laser frequency shift processes, the smart arrangement of optical paths, and the sparing use of optical components. This compact architecture has been established completely, and the bottom side of the established architecture is shown in Fig.5.

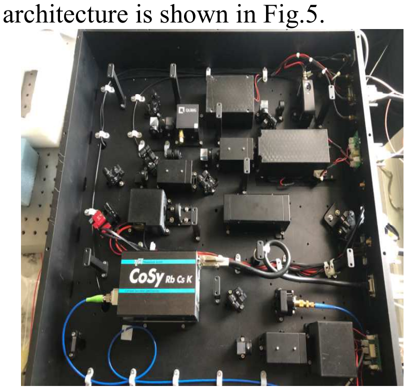


Fig. 5. The bottom side of the established architecture

III. SUBSECTION OF THE OPTICAL SYSTEM

A. Laser source with high frequency stability

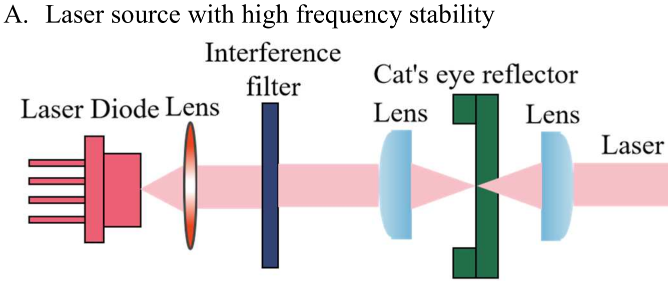
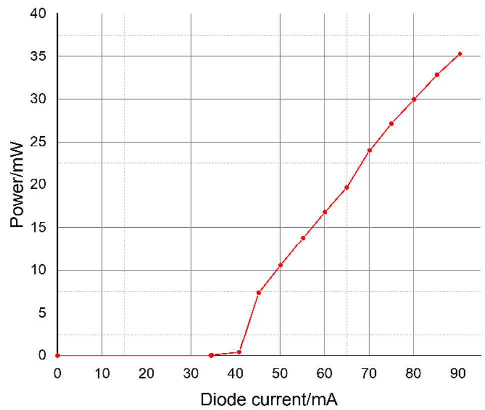
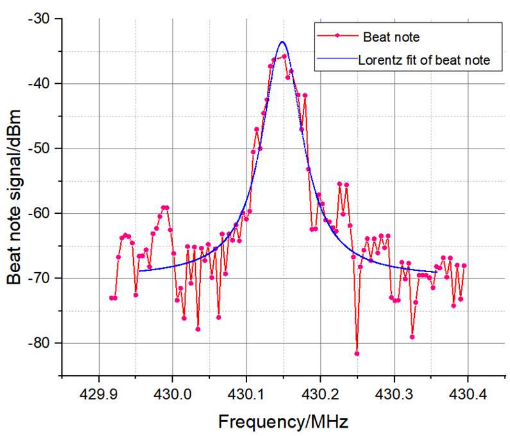


Fig. 6. The scheme of ECDL

In our optical system, both an ECDL and a DFB laser are applied as laser sources. The former offers the beams for laser cooling, state preparation, and clock signal detection, which is more important than the latter and necessary to be specially developed with high frequency stability. As shown in Fig. 6, the ECDL is built with a narrow-band interference filter, whose cavity is composed of a cat's eye mirror and the rear surface of the laser diode. The interference filter is installed in the middle of the cavity to realize the wavelength selection. All the optical elements are integrated and the length of the cavity is 73 mm. By optimizing the feedback, the characteristic of the laser allows us to frequency lock the laser source without any problem.



(a)

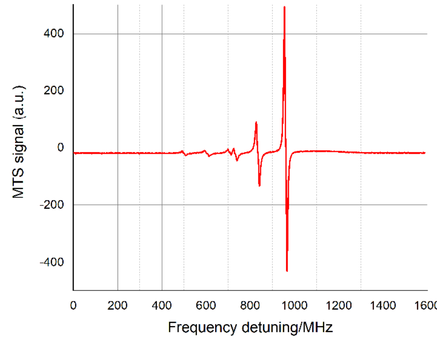


(b)

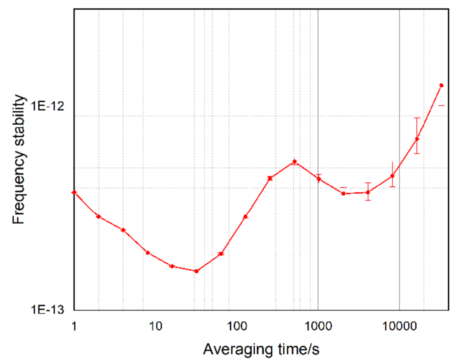
Fig. 7. The optical characteristic of ECDL, (a) Output power versus diode current, (b) frequency beat-note signal of our laser with another ECDL

As shown in Fig. 7, the output power of the ECDL after one optical isolator up to 35mW has been measured with a diode current of 90mA, which is enough to be amplified. Besides, the frequency beat-note signal of our laser with another ECDL shows that the laser frequency noise is suppressed effectively, and the linewidth of about 50 kHz is realized.

According to the scheme of laser frequency stabilization and shift shown in Fig. 2, the frequency of the ECDL should be locked to the cesium D2 line F=4→F' =5 by MTS. The MTS optical path is also integrated into our optical system and the obtained signal on the D2 line is shown in Fig. 8(a). As shown in Fig.Fig. 8(b), the laser frequency is stabilized on the cesium D2 line F=4→F' =5 and the frequency stability is achieved to the 10^{-13} level between 1~10^4s averaging time by self comparison within about 60 hours.



(a)



(b)

Fig. 8. The frequency signal and stability of ECDL with MTS, (a) the scanned MTS signal of the D2 line of cesium, (b) the frequency stability

B. Laser beam with high power stability

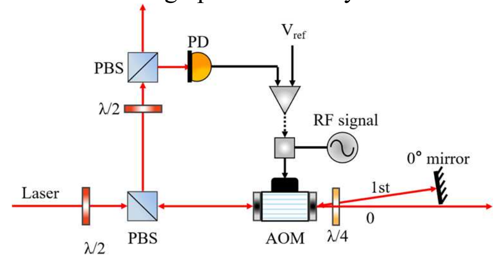


Fig. 9. Experimental setup stabilizing the cooling laser power

Fig. 9 shows the experimental setup stabilizing the cooling laser power with an acoustic-optical modulator (AOM). The laser beam passes through the AOM, and the position of the AOM is set to optimize the first-order diffraction beam for the near max diffraction efficiency. The first-order beam diffraction is picked up by a 0° mirror and turned back for the second pass-through of the AOM. Some of them are reflected by a PBS and monitored by a PD in the in-loop. The in-loop signal of the PD is compared to a reference voltage issued from a voltage reference with low noise and low drift. After the comparison, the error signal shows the difference between the PD signal and the voltage reference and it will be applied to the diffraction efficiency of AOM.

As shown in Fig. 10, the cooling beam power stability is 10^{-5} level between 1~10^4s averaging time within about 60 hours by adjusting the diffraction efficiency of AOM, which is 1~2 orders of magnitude better than the fluctuation of the laser output power. This method can also be applied to three other beams to achieve this level.

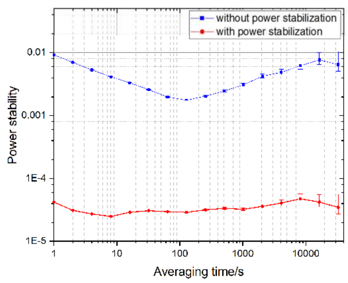


Fig. 10. The Allan variance of continuous power locking in about 60 hours(with and without stability)

C. Balance detection process

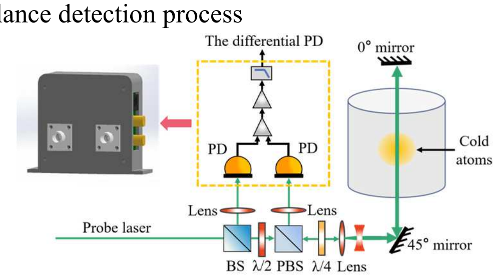


Fig. 11. Experimental setup for balance detection

As shown in Fig. 11, the clock signal is detected by a differential photodetector (PD) for the balance detection process. In this process, the probe beam is separated into two beams by a beamsplitter (BS). One beam is detected by the differential PD, and the other beam is injected into the physical package to be absorbed by the cold atoms. The latter is reflected by a 0° mirror and turned back to be also detected by the differential PD. This process can detect the background and the transmission probe beam simultaneously, and the difference between them is the pure cold atom absorption signal. In this signal, the noise from the background probe beam is removed effectively,which means the clock signal in our optical system will be more precise. In the optical system, the differential PD has been established, whose size is 50mm×50mm×20mm and opto-eletronic characteristics are tested in the lab.

D. Compact optical arrangement

Fig. 12. The special compact optical arrangement at the center

In our optical system, the diameter of all mirrors is φ12.7mm and the light height is 15mm, which are fixed by the special miniaturized metal support with screws on the Aluminum bench with reliability. Using these optical components, the optical path is arranged from the periphery to the center, and the required beams are introduced to the physical package at the center. However, due to the large spot of the probe beam and limited space, the optical path at the center have to be integrated and the special compact optical arrangement is shown in Fig. 12. The light height of the probe beam is increased from 15 mm to 35mm and the mirror size of other beams is decreased from 12.7mm to 6mm. Thanks to this special arrangement, all the required beams are introduced to the physical package vertically without any problem.

IV. Conclusion

In conclusion, we present a high-stability compact optical system for ISCAC with high laser frequency and power stability, whose total size is 500mm×500mm×200mm. The optical system has been established completely. In the future, it will be validate and improved to be more stable and compact.

Acknowledgments

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