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Citation: Chin. Phys. B . 2019, 28(7): 070602. **doi:** 10.1088/1674-1056/28/7/070602
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Development of the integrated integrating sphere cold atom clock*

Ming-Yuan Yu(于明圆)[1,2], Yan-Ling Meng(孟艳玲)[1], Mei-Feng Ye(叶美凤)[1], Xin Wang(王鑫)[1,2], Xin-Chuan Ouyang(欧阳鑫川)[1,2], Jin-Yin Wan(万金银)[1], Ling Xiao(肖玲)[1], Hua-Dong Cheng(成华东)[1,†], and Liang Liu(刘亮)[1,‡]

[1] *Key Laboratory of Quantum Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai* 201800, *China*
[2] *Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing* 100049, *China*

(Received 28 February 2019; revised manuscript received 8 April 2019; published online 12 June 2019)

We develop an integrated integrating sphere cold atom clock (ISCAC), which mainly consists of physical package, laser system, microwave source, and electronics. This compact system is more stable and reliable than the previous version. The experimental results show that the short term frequency stability of $5.4\times10^{-13}\tau^{-1/2}$ and 2.9×10^{-15} at 1-day integrating time are achieved.

Keywords: integrating sphere cold atom clock, physical package, laser system, frequency stability

PACS: 06.30.Ft, 42.50.–p, 32.30.–r **DOI:** 10.1088/1674-1056/28/7/070602

1. Introduction

Atomic clocks are used in many different fields, such as navigation, time keeping, and fundamental physics research.[1,2] Consequently, many kinds of atomic clocks have been developed, such as chip-scale atomic clock,[3] hydrogen maser,[4] pulsed optical pump atomic clock (POP) based on vapor cell,[5,6] microwave Hg ion clock,[7,8] integrating sphere cold atom clock,[9,10] atomic fountain,[11–13] and optical clock.[14–16] Although atomic fountains are the contemporary primary frequency standard and an ultra-high precision of 10^{-19} is achieved for the optical clock,[14] the compact microwave atomic clocks play an important role in global positioning systems due to their small size and good frequency stability.

Atomic beam slowing by diffuse light was an early proposal made by Wang,[17] and the diffuse laser cooling and slowing of Na atomic beams were first demonstrated by Ketterle *et al.*[18] The diffuse light cooling atoms directly from an atomic vapor background was then realized by Guillot *et al.*[19] and Cheng *et al.*[20] The compact cesium clock (HORACE) has been developed and the short-term stability of $2.2\times10^{-13}\tau^{-1/2}$ (τ is the integration time in seconds) and 3×10^{-15} at the integration time of 10^4 s were achieved.[9,21] We developed a similar compact atomic clock, an integrated integrating sphere cold atom clock (ISCAC), with rubidium atoms. The ISCAC is designed for onboard and space applications. It has good performance, especially in microgravity, because the lifetime of cold atoms in space is nearly one order longer than that on earth. Recently, the long term frequency stability of 2×10^{-15} has been reached for the principle prototype of the ISCAC.[10,20,22]

This paper mainly introduces the latest progress of the integrated ISCAC. The principle of the ISCAC is described in Section 2. The experimental set-up, mainly including the physical and optical systems, is introduced in Section 3. Section 4 describes the experimental result. Then, the experimental result is analyzed in Section 5. Finally, the conclusion is drawn in Section 6.

2. Principle

The ISCAC is a cold atom clock based on the diffuse light cooling and operated at a POP scheme. The cooling light is injected into the microwave cavity and reflected by the inner surface of the cavity, whose diffuse reflectivity is about 97%, and the diffuse light cooling of the ^{87}Rb vapor is performed inside the microwave cavity, which locates in the ultra-high vacuum cavity. After the laser cooling phase, the cold atoms populate in the states $|F=2,m_F=0,\pm1,\pm2\rangle$, and are then pumped to the states $|F=1,m_F=0,\pm1\rangle$ by an optical pumping pulse. The Ramsey microwave interrogation is performed to make the clock transition of $|F=1,m_F=0\rangle\rightarrow|F=2,m_F=0\rangle$. Finally, the population of the cold atoms in the state $|F=2,m_F=0\rangle$ is detected by an optical pulse. The time sequence of the ISCAC is shown in Fig. 1.

The Allan deviation can be used to evaluate the frequency stability of an atomic clock and expressed as[23]

$$\sigma_y=\frac{1}{\pi}\frac{\Delta\nu}{\nu_0}\frac{1}{C}\frac{1}{R_{\rm SN}}\sqrt{\frac{T_{\rm c}}{\tau}}, \tag{1}$$

*Project supported by the Youth Innovation Promotion Association of the Chinese Academy of Sciences and the National Natural Science Foundation of China (Grant Nos. 61875215, 61727821, and 11604353).

†Corresponding author. E-mail: chenghd@siom.ac.cn
‡Corresponding author. E-mail: liang.liu@siom.ac.cn

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where C and R_{SN} are the contrast[21] and signal-to-noise ratio of the Ramsey fringe, respectively; $\Delta\nu$ is the linewidth of the Ramsey fringe, ν_0 is the frequency of the clock transition, τ is the averaging time; and T_c is the cycle period of the clock. The relationship $\Delta\nu \sim 1/2T_f$ is satisfied, which means that the longer T_f corresponds to the narrower $\Delta\nu$, but the R_{SN} and C will decrease as T_f increases. However, there is a tradeoff between them. For the ISCAC, the lifetime of cold atoms, which is about 40 ms in the ground environment, is mainly determined by the free fall time of the cold atoms in the microwave cavity.[24] However, the lifetime of cold atoms can reach more than 200 ms in space, which corresponds to narrower linewidth of the Ramsey fringe. At the same time, the Dick effect[25] would be neglected. So the ISCAC would have better performance in a microgravity environment than on earth.

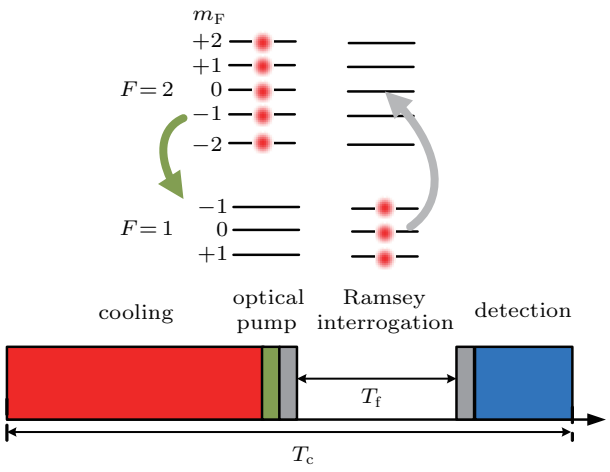


Fig. 1. Time sequence of the ISCAC.

3. Experimental setup

The ISCAC is mainly composed of four subsystems: physical package, laser system, microwave source, and electronics. Figure 2 shows the physical package. A cylindrical microwave cavity is designed for the diffuse light cooling and microwave interrogation. For the diffuse light cooling, the inner surface of the microwave cavity is coated to increase the diffuse reflectance at 780 nm, and the cooling light is injected into the microwave cavity by four 3-mm holes distributed centro-symmetrically in the undersurface of the cavity, which can make most of cold atoms distribute in the detection region.[26] For microwave interrogation, the 6.834 GHz signal is coupled into the cavity by a coupling loop installed in the middle of the cylinder, and the microwave cavity is operated in the TE_{011} mode with a quality factor about 22000. The microwave cavity is installed in the vacuum chamber with a volume about 1.5 L, in which the vacuum is maintained at 10^{-6}–10^{-7} Pa by two ion pumps. The biased magnetic field is about 0.6 μT and the stray magnetic field is less than 2 nT after shielding with three layers of μ-metal. The temperature stabilization is used to keep the microwave cavity working at the temperature of 34 ℃.

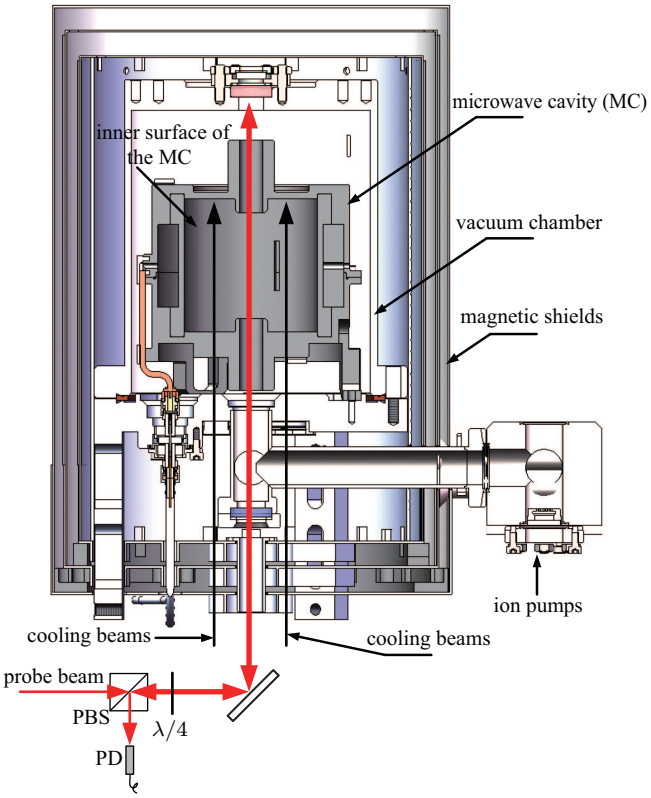


Fig. 2. The physical package of the ISCAC.

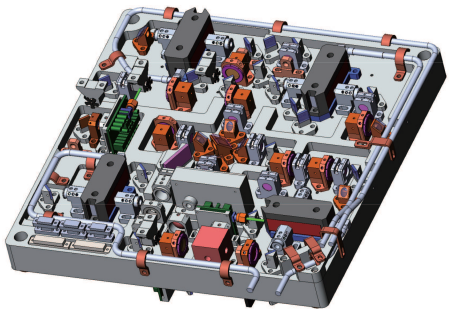


Fig. 3. The laser system of the ISCAC.

For future space-borne applications, the laser system must be developed with higher miniaturization and compactness. Figure 3 shows the compact laser system of the ISCAC. All the optical components are integrated on two sides of an aluminum baseplate with the dimensions of 300 mm×300 mm×20 mm. Three external cavity diode lasers are used to produce the cooling, repumping, pumping, and probe lights. Four acousto-optic modulators (AOM) are used to frequency-shift the light properly. The mechanical design and simulation of the optical bench are performed to optimize

the stability of the light paths. The lights are injected into the physical package in free space, which is different from the multimode fiber connection for the principle prototype of the ISCAC. This free space mode not only has higher laser injection efficiency but also has higher tolerance for the deformation of the optical bench. Figure 4 shows the integrated physical package and laser system. Furthermore, a miniaturized frequency synthesizer (FS) is also developed.[27] Its output frequency resolution is 0.71 μHz, and its output power range is from −87.41 dBm to −26 dBm with a resolution of 0.02 dB.

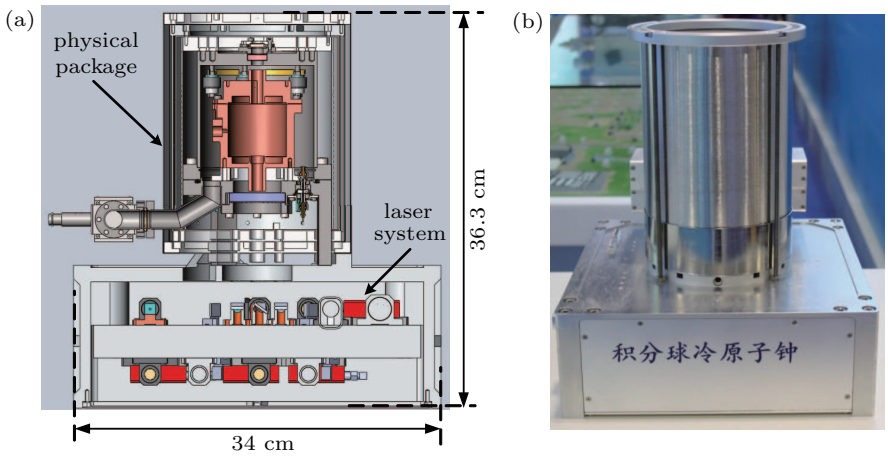


Fig. 4. (a) The integrated physical package and laser system (b) and its photo.

4. Experimental results

The time sequence of the clock is optimized first. The light switches based on the step motors are used and the extinction ratio better than 100 dB is achieved. The rotation of the step motor is controlled by a trigger voltage pulse. The delay time of the step motor is measured carefully. According to the measured results, we have optimized the time sequence and make sure that the light and microwave pulses are non-overlapping. Figure 5 shows the time sequence of the ISCAC. The cooling phase lasts for 55 ms, followed by an optical pump of 1.6 ms, then two microwave pulses with a duration of 1 ms separated by 24 ms are applied for the Ramsey microwave interrogation, and finally the population of cold atoms experiencing the clock transition is optically detected for 7 ms. The entire atomic clock operates with a period of 90 ms. In addition, the laser power stabilization and temperature control of the whole system are also optimized carefully. The optimized Ramsey fringe is shown in Fig. 6(a),

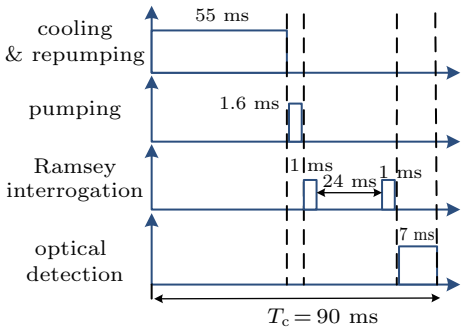


Fig. 5. The optimized time sequence of the clock operation.

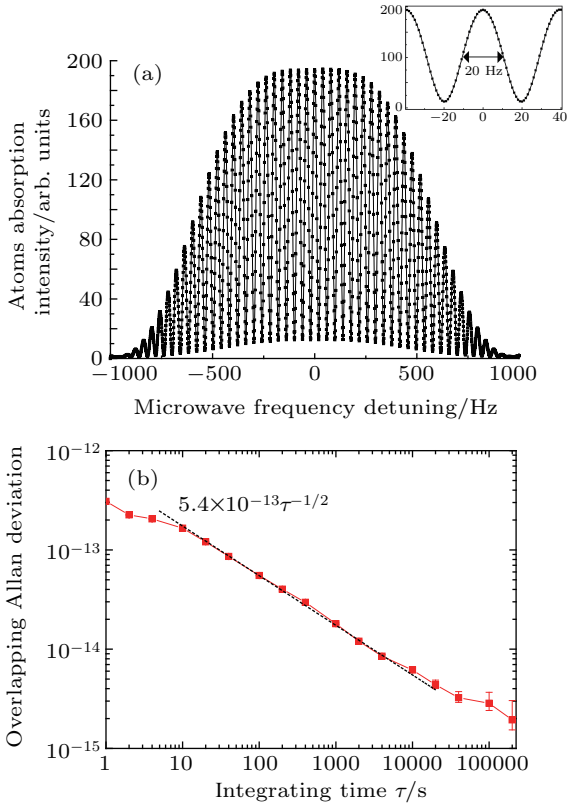


Fig. 6. (a) The Ramsey fringe. (b) The stability of the integrated ISCAC.

and the linewidth and signal-to-noise ratio (SNR) of the fringe are about 20 Hz and 518, respectively. The frequency stability of the ISCAC is measured with the three-cornered hat method[28] by comparing with two H-masers for about 11 days, the result is shown in Fig. 6(b). The short-term frequency stability is about $5.4 \times 10^{-13}\tau^{-1/2}$ (τ is the averag-

ing time), and the frequency stability of 2.9×10^{-15} at 1-day integrating time is achieved.

5. Discussion

The main limits of the short-term frequency stability of the ISCAC stem from the Dick effect, atomic shot noise, frequency and intensity fluctuations of the probe light (FM and AM noise),[9] and electronic noise. The noise budget of the system and the instabilities of the noise sources are shown in Table 1.

Table 1. Noise budget of the system and the instabilities of the noise sources.

Dick effect	$3.7 \times 10^{-13}\tau^{-1/2}$
FM & AM noise	$3.0 \times 10^{-13}\tau^{-1/2}$
Atomic shot noise	$0.83 \times 10^{-13}\tau^{-1/2}$
Quantum projection noise	$0.58 \times 10^{-13}\tau^{-1/2}$
Electronic noise	$2.1 \times 10^{-13}\tau^{-1/2}$
Total	$5.4 \times 10^{-13}\tau^{-1/2}$

According to the time sequence shown in Fig. 5, the number of detected atoms is about 1.2×10^7, so the short-term frequency instabilities caused by the atomic shot noise[9] and quantum projection noise[29] are about $0.83 \times 10^{-13}\tau^{-1/2}$ and $0.58 \times 10^{-13}\tau^{-1/2}$, respectively. The Dick effect is the main contribution to the frequency stability degradation. The performance of a homemade microwave frequency synthesizer is optimized and its estimated frequency stability degradation via the Dick effect[27,30] will be reduced to $1.8 \times 10^{-13}\tau^{-1/2}$. With future space application, when the free evolution time of the Ramsey interrogation increases to 100 ms, the frequency stability degradation caused by the Dick effect will be reduce to $0.72 \times 10^{-13}\tau^{-1/2}$. Since the absorption detection method is used here, the clock signal is very sensitive to the intensity fluctuation of the probe light.[9] The active power stabilization has been used to suppress the intensity fluctuation (AM) of the probe light, and the measured relative intensity noise (RIN) of the probe light is -110 dBc/Hz at the offset frequency of 1 Hz. The frequency stability degradation caused by the AM noise of the probe light is about $0.63 \times 10^{-13}\tau^{-1/2}$ and that caused by the FM noise is about $2.9 \times 10^{-13}\tau^{-1/2}$. The FM noise can be suppressed further by optimizing the frequency lock loop parameters (modulation frequency and loop gain).

6. Conclusion

In summary, we develop an integrated ISCAC and measure its frequency stability with a three-cornered hat method. After a preliminary optimization, the short-term frequency stability of $5.4 \times 10^{-13}\tau^{-1/2}$ and 2.9×10^{-15}at 1-day integrating time are achieved and further optimization is in progress. At the same time, we are currently developing an ISCAC for space application and in the near future we will obtain the new results.

References

[1] Kolkowitz S, Pikovski I, Langellier N, Lukin M D, Walsworth R L and Ye J 2016 *Phys. Rev. D* **94** 124043
[2] Abgrall M, Chupin B, De Sarlo L, Guena J, Laurent P, Le Coq Y, Le Targat R, Lodewyck J, Lours M, Rosenbusch P, Rovera G D and Bize S 2015 *C. R. Phys.* **16** 461
[3] Lacroute C, Reinhard F, Ramirez-Martinez F, Deutsch C, Schneider T, Reichel J and Rosenbusch P 2010 *Ieee Trans. Ultrason. Ferroelectr. Freq. Control* **57** 106
[4] Li J, Zhang J H, Bu Y N, Cao C Y, Wang W M and Zheng H F 2016 *2016 IEEE International Frequency Control Symposium (IFCS)* 30
[5] Lin H X, Deng J L, Lin J D, Zhang S and Wang Y Z 2018 *Appl. Opt.* **57** 3056
[6] Micalizio S, Calosso C E, Godone A and Levi F 2012 *Metrologia* **49** 425
[7] Chen Y H, She L, Wang M, Yang Z H, Liu H and Li J M 2016 *Chin. Phys. B* **25** 120601
[8] Prestage J D, Tu M R, Chung S K and MacNeal P 2008 *2008 IEEE International Frequency Control Symposium*, Vols. **1** and **2** 651
[9] Esnault F X, Holleville D, Rossetto N, Guerandel S and Dimarcq N 2010 *Phys. Rev. A* **82** 033436
[10] Liu P, Meng Y L, Wan J Y, Wang X M, Wang Y N, Xiao L, Cheng H D and Liu L 2015 *Phys. Rev. A* **92** 062101
[11] Guena J, Abgrall M, Rovera D, Laurent P, Chupin B, Lours M, Santarelli G, Rosenbusch P, Tobar M E, Li R X, Gibble K, Clairon A and Bize S 2012 *Ieee Trans. Ultrason. Ferroelectr. Freq. Control* **59** 391
[12] Santarelli C, Laurent P, Lemonde P, Clairon A, Mann A G, Chang S, Luiten A N and Salomon C 1999 *Phys. Rev. Lett.* **82** 4619
[13] Du Y B, Wei R, Dong R C, Zou F and Wang Y Z 2015 *Chin. Phys. B* **24** 070601
[14] Oelker E, Hutson R B, Kennedy C J, Sonderhouse L, Bothwell T, Goban A, Kedar D, Sanner C, Robinson J M, Marti G E, Matei D G, Legero T, Giunta M, Holzwarth R, Riehle F, Sterr U and Ye J 2019 arXiv:1902.02741[physics.atom-ph]
[15] Huntemann N, Sanner C, Lipphardt B, Tamm C and Peik E 2016 *Phys. Rev. Lett.* **116** 063001
[16] Bloom B J, Nicholson T L, Williams J R, Campbell S L, Bishof M, Zhang X, Zhang W, Bromley S L and Ye J 2014 *Nature* **506** 71
[17] Wang Y Z 1979 *National Symposium on Frequency Standards* (Chendu, China) p. 100
[18] Ketterle W, Martin A, Joffe M A and Pritchard D E 1992 *Phys. Rev. Lett.* **69** 2483
[19] Guillot E, Pottie P E and Dimarcq M 2001 *Opt. Lett.* **26** 1639
[20] Cheng H D, Zhang W Z, Ma H Y, Liu L and Wang Y Z 2009 *Phys. Rev. A* **79** 023407
[21] Esnault F X, Rossetto N, Holleville D, Delporte J and Dimarcq N 2011 *Adv. Space Res.* **47** 854
[22] Wang Y N, Meng Y L, Wan J Y, Yu M Y, Wang X, Xiao L, Cheng H D and Liu L 2018 *Phys. Rev. A* **97** 023421
[23] Ricehle D F 2005 *Frequency Standards: Basics and Applications*, Wiley, Darmstadt, p. 77–78
[24] Zhang W Z, Wang X C, Cheng H D, Xiao L, Liu L and Wang Y Z 2009 *Chin. Phys. Lett.* **26** 083703
[25] Audoin C, Santarelli G, Makdissi A and Clairon A 1998 *Ieee Trans. Ultrason. Ferroelectr. Freq. Control* **45** 877
[26] Meng Y L, Cheng H D, Zheng B C, Wang X C, Xiao L and Liu L 2013 *Chin. Phys. Lett.* **30** 063701
[27] Wang X M, Meng Y L, Wang Y N, Wan J Y, Yu M Y, Wang X, Xiao L, Li T, Cheng H D and Liu L 2017 *Chin. Phys. Lett.* **34** 063702
[28] Gunn L J, Catlow P G, Al-Ashwal, Hartnett J G, Allison A and Abbott D 2014 *IEEE Transactions on Instrumentation & Measurement* **63** 889–895
[29] Itano W M, Bergquist J C, Bollinger J J, Gilligan J M, Heinzen D J, Moore F L, Raizen M G, Winel and D J 1993 *Phys. Rev. A* **47** 3554
[30] Santarelli G, Audoin C, Makdissi A, Laurent P, Dick G J and Clairon A 1998 *Ieee Trans. Ultrason. Ferroelectr. Freq. Control* **45** 887