REVIEW

Review of chip-scale atomic clocks based on coherent population trapping*

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Research on chip-scale atomic clocks (CSACs) based on coherent population trapping (CPT) is reviewed. The background and the inspiration for the research are described, including the important schemes proposed to improve the CPT signal quality, the selection of atoms and buffer gases, and the development of micro-cell fabrication. With regard to the reliability, stability, and service life of the CSACs, the research regarding the sensitivity of the CPT resonance to temperature and laser power changes is also reviewed, as well as the CPT resonance's collision and light of frequency shifts. The first generation CSACs have already been developed but its characters are still far from our expectations. Our conclusion is that miniaturization and power reduction are the most important aspects calling for further research.

Keywords: chip-scale atomic clock, coherent population trapping

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1. Introduction

The research on chip-scale atomic clocks (CSACs)[1,2] has been a very active field for more than ten years. More and more researchers from institutes, universities, and industrial companies are becoming interested in this field, and theoretical and experimental studies are continually published. As a result, the CSACs' size, power consumption, and stability have been continually improved[3,4] in the last decade. Many expected that if the atomic clocks with chip scale can be driven by a battery, this form of miniaturized low consumption atomic clock will be suitable for a large variety of commercial handheld battery-operated instruments, such as global positioning systems (GPS) receivers, navigators, and other general instruments and equipment that require a built-in source for the standard frequency. This kind of microscale atomic clock has the potential to take the lead in a wide variety of application fields.

People first considered producing CSACs because the coherent population trapping (CPT)[5–7] phenomenon appeared to be feasible for driving microscale atomic clocks. So far, almost all CSAC research has been based on the CPT phenomena. One key advantage of this CPT technology is the possibility of significantly minimizing an atomic clock's physical size and power consumption.

The first atomic clock was invented in the 1950s. Since then, miniaturization and power reduction have together been the main focus of research, as this directly affects the range of applications for atomic clocks. During half a century of progress, scientists made the atomic clocks smaller and smaller. By the end of the last century, the smallest atomic clocks were utilized in airplanes, space shuttles, and even satellites for navigation and positioning. Yet they were still too big and consumed too much power for broader applications in everyday electronics. At the dawn of this century, people were working to make new and improved battery-driven atomic clocks that were much smaller than the traditional atomic clocks. Based on the theory behind the CPT, scientists predicted that both the size and the power consumption of atomic clocks could be significantly reduced.[8–10]

Coherent population trapping (CPT) was first observed in 1976.[6] It occurs when a three-level Λ style atomic states system is excited by two coherent laser fields (Fig. 1). When the laser fields are resonant with the transitions from the ground state's hyperfine levels to the excited state, an interference takes place in the coherent excitation process and no atoms are excited.[11] So all atoms are trapped in the ground state. In CPT atomic clocks, the two laser fields are usually generated through a radio frequency (RF) modulated vertical cavity surface emitting laser (VCSEL) and penetrate an Rb or Cs vapor cell.[12] Then a phase locking loop will lock the two laser fields' frequency difference, actually locking the RF frequency, to the CPT resonance to obtain the atomic standard frequency. The main advantage of the CPT atomic clocks compared to the traditional atomic clocks is the absence of a microwave cavity, enhancing the clock by allowing substantial reductions in size, power, and cost while maintaining the stability.

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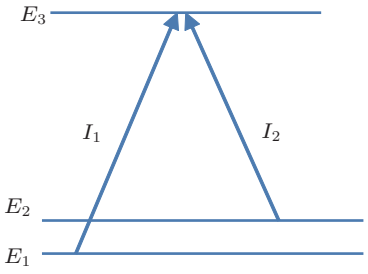


Fig. 1. (color online) Λ mode atomic states system.

Note that the performance (instability is about 10^{-11}) of the CPT atomic clocks is several orders of magnitude worse than that of the atomic fountain clocks. The advantages of the CPT systems, therefore, lie mainly in the potential for reduced size, power consumption, and cost. In addition, their long-term stability will be about three orders of magnitude better than that of the crystal oscillators.

In the first decade of this century, researchers conducted substantial theoretical and experimental research on the CPT atomic clocks aimed at miniaturization and power consumption reduction. In 2004, a National Institute of Standards and Technology (NIST) group released their smallest physics package of the CPT atomic clock. Based on their experimental results and theoretical analysis, they predicted that the physics part could be smaller than 10 mm^3, and the total power budget could be less than 30 mW.[13] It is well known that the electrical circuit itself can be easily reduced to a very small size; therefore, it is expected that the CSAC will eventually be about 1 cc in volume, and can be driven by a battery.

Based on the theoretical and experimental research, the manufacturing process of the CPT atomic clocks also saw great developments. From the related technical reports published, we can see that most research groups use the micro-electro-mechanical system (MEMS) processing techniques for the miniaturization of the physics package and alkali vapor cells.[14–16] The cells are made by sandwiching a silicon wafer with a hole between two glass wafers.[17,18] Alkali atoms, along with the appropriate buffer gases, are sealed in the space between the glass wafers. The inside volume of the cell may vary from one mm^3 to a few ten mm^3.

A vertical cavity surface emitting laser[19–21] is used in most CSACs because of its low power requirements (typically < 2 mW), high modulation efficiency, and the availability of single-mode devices at 852 nm and 894 nm for Cs and at 795 nm for the Rb D1 line.

For the typical CSAC, the MEMS technology is used to fabricate the optics and integrate them with the cell and the VCSEL. For saving power and efficiently controlling the temperature, the physics part is entirely sealed in a vacuum shell and magnetically shielded. In the commercial products, the shells' sizes are about 1 cm,[22–24] so they can be plugged directly into the main circuit board. The total power consumption of the CPT clocks is greatly reduced from several watts to around a hundred milliwatts. In 2010, Symmetricom published their first commercial CSAC, with a volume of 16 cm^3, a power consumption of 120 mW, and a shortterm frequency instability better than 2×10^{-10}. The performance data of small atomic clocks are very good already, but their size and power consumption still have not reached the threshold for the CSACs to be widely used. Many groups from different countries are working toward the goal of making a real chip-scale atomic clock.

In 2008, Teledyne Scientific, Rockwell Collins, and Agilent demonstrated their compact, low-power atomic clock, which has a volume less than 1 cm^3, a power consumption below 30 mW, and an Allan deviation better than 1×10^{-11} (1 hour).[25]

Since there is increasing interest in CSACs based on the CPT, many new theoretical and experimental studies are being published constantly. This review paper will summarize the important progresses and achievements in this area and organize them in four sections: CPT signal improvement, atom and buffer gas selection, miniaturization and power saving, and the stability and CPT resonance shift. We hope this informational review will be helpful for researchers in this field.

2. Research on CPT signal improvement

In the past ten years, theoretical and experimental research on the CPT atomic clocks[26,27] increased greatly. The CSACs are based on the CPT phenomenon, and so far, there is still no other technology that can replace it. Most of the research on CPT atomic clocks seeks methods to improve the CSACs' performance, which include increasing the contrast and narrowing the resonance line widths of the CPT resonance,[28,29] comparison of the D1 and D2 lines,[30] adopting the Ramsey method,[31] etc.

This CPT phenomenon takes advantage of the first two hyperfine components of the ground state (which have very narrow transition line widths) because they have long lifetimes and $m_{\mathrm{F}} = 0$ is the magnetic-field-insensitive ground state for both. For CPT's applications in CSACs, there are two important parameters: the CPT resonance contrast and its line width. The contrast is defined as the change in transmitted power due to the CPT effect. Usually it is the CPT peak value divided by the absorbed power peak value.

A variety of different excitation schemes, such as the D1 or D2 line excitation,[32] the σ^+ & σ^- field configuration,[33] and the push–pull method, have been proposed. The purpose is to obtain better CPT contrast and line width.

Several groups have studied the Rb and Cs D1 and D2 excitation.[34–37] Their research results demonstrate the excitation of the D1 and D2 transitions of thermal ^{85}Rb vapor. The

excitation of the D1 line results in a resonance contrast almost one order of magnitude larger than that in the excitation of the D2 line and the resonance width is narrower, which is in agreement with the theoretical expectations.[30]

The difference between the two excitation lines is caused by the excited-state hyperfine structure (see Fig. 2). The $P_{1/2}$ excited state has only two hyperfine levels, and both of them contribute to the coherence preparation. The $P_{3/2}$ excited state of the D2 line has four excited-state hyperfine levels, and only two of them couple to the ground state. The other two levels do not contribute to the CPT, however they do reduce the lifetime of the coherent dark state. This will increase the CPT resonance width and decrease its contrast.

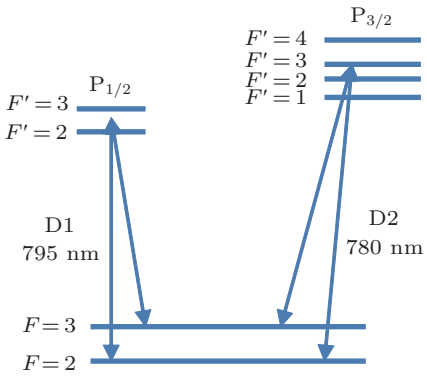


Fig. 2. (color online) ^{85}Rb D1 and D2 lines.

Their study shows that the CPT atomic clocks using the D1 transition may expect a significantly better performance than those using the D2 line. For the same reason, no matter whether the atom is ^{85}Rb, ^{87}Rb, or ^{133}Cs, the performance will be improved nearly tenfold for the CPT frequency standard when the D1 line rather than the D2 line is used. Therefore, most research groups choose the D1 line for their CPT atomic clocks. Although a few groups have tried the Cs D2 line, it is mainly because the 852 nm VCSELs are much cheaper than 795 nm (for Rb D1) and 894 nm (for Cs D1) VCSELs, and have good qualities. The reason is 850nm VCSELs have been produced for and widely used in optical communications for a long time.

To achieve the high contrasts and narrow resonance line widths needed for the applications of the CPT-based atomic frequency standards, several groups show that generating the CPT with a combination of σ^+ & σ^- light fields[33,36] overcomes the atom extreme states trap problem.[37]

In the case of a conventional CPT interrogation with a bichromatic circularly polarized light field, the signal amplitudes will be limited by the loss of atoms toward the extreme Zeeman sublevels $|F,\ m_F = \pm F\rangle$ through optical pumping (Fig. 3). The atoms which are accumulated in those states cannot contribute to the CPT signal. This occurs because there is only σ^+ or σ^- laser field wherein the spin is equal to 1 or -1, the atoms are pumped to the extreme Zeeman sublevels, and no light field can excite them out of the states. Obviously if both σ^+ and σ^- laser fields are present, the problem will be overcome.

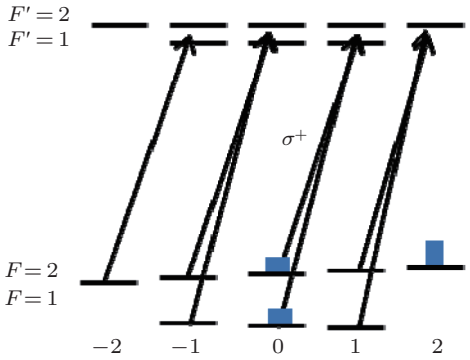


Fig. 3. (color online) ^{87}Rb D1 line under σ^+ pump.

Unfortunately, the bichromatic circularly polarized σ^+ and σ^- fields both have a beat wave frequency that is equal to the two hyperfine ground ($m_F = 0$) states' separation. If they are in phase, the CPT will be killed by the reverse effect of the two bichromatic circularly polarized laser fields. So we cannot prepare the CPT by using a linearly polarized laser field even though we know it can be divided into two bichromatic circularly polarized σ^+ and σ^- light fields, because the two beat waves will be in phase. Theoretically, to obtain a better CPT signal, the σ^+ and σ^- light field beat waves have to be out of phase; in other words, they must have a π phase difference when they interact with the atoms to generate the CPT.[33]

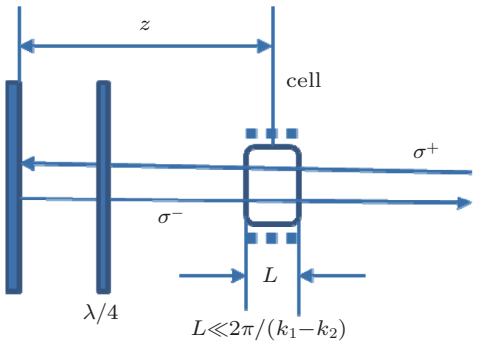


Fig. 4. (color online) Circularly polarized σ^+ laser beam going through an atomic cell and a $\lambda/4$ wave plate, reflected by a mirror and going through the $\lambda/4$ wave plate again, becoming a σ^- laser beam, where $Z = (2n+1)\pi/(k_1 - k_2)2$.

Three typical methods have been proposed to achieve the σ^+ & σ^- pump idea when the size of the atom cell is much smaller than the beat wave length ($L \ll 2\pi/(k_1 - k_2)$, k_1 and k_2 are the wave vectors). The beat wave length is about 10 cm for ^{85}Rb and 4.4 cm for ^{87}Rb. As shown in Fig. 4, we may reflect the laser beam which goes through a $\lambda/4$ wave plate two

times to obtain left circularly polarized light from right circularly polarized light. The beat wave phase delay between the two penetrations through the atom cell is equal to $(2n+1)\pi$, or the optical path is $2Z=(2n+1)\pi/(k_1-k_2)$. For ^{85}Rb, it will be about 5 cm. Some typical works have been done by three cooperating groups.[33,37] Their works demonstrate that the σ^+ & σ^- method can significantly improve the CPT signal.

In 2006, Shah *et al.* proposed and demonstrated a scheme to implement the σ^+ & σ^- configuration.[38] Two independent VCSELs are mounted one next to the other with the laser fields' polarization directions perpendicular to each other. The two laser fields pass through a $\lambda/4$ wave plate, then go through the atom cell together. A combination of σ^+ & σ^- light fields is produced by modulating the two lasers separately with a π phase difference.[38]

The advantage of this scheme is that it does not need space for the optical path of the phase delay, so it can be easily miniaturized. In 2007, they proposed another method called fourwave mixture,[39] which can significantly increase the contrast, but the required configuration is difficult to miniaturize.

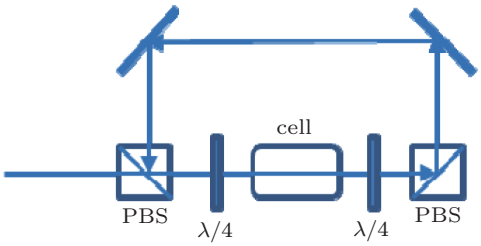


Fig. 5. (color online) The σ^+ & σ^- scheme of Gu's group.

In 2012, Gu's group proposed another scheme,[40] as illustrated in Fig. 5. The bichromatic circularly polarized fields reach a $\lambda/4$ wave plate after going through the cell and become a linearly polarized light, which is reflected by a second PBS. After being reflected by the mirrors, they go back to the first PBS and become coupled back to the input light. The optical path allows the laser beam to achieve a $(2n+1)\pi$ phase delay, and the polarization direction is perpendicular to the incident light. After going through the first $\lambda/4$ wave plate again, a σ^+ & σ^- field with a suitable phase delay will be obtained. This method can also improve the CPT signal contrast, but it makes the optical system more complicated and needs more room for the optical path.

Taichenachev *et al.*[41] and Kazakov *et al.*[42] proposed to obtain CPT resonances with a bichromatic linearly polarized light (lin||lin field) on the D1 line of ^{87}Rb. They demonstrated that two Λ schemes can be formed with two pairs of ground-state hyperfine sublevels simultaneously: $|F=1,\ m_F=-1\rangle$, $|F=2,\ m_F=1\rangle$ and $|F=1,\ m_F=1\rangle$, $|F=2,\ m_F=-1\rangle$ coupled with the common excited states $|F'=1,\ m_F=0\rangle$ (Fig. 6(a)). If the contribution of the nuclear spin to the Zeeman splitting is negligible, the two-photon resonance frequencies ($|F=1,\ m_F=-1\rangle$, $|F=2,\ m_F=1\rangle$ and $|F=1,\ m_F=1\rangle$, $|F=2,\ m_F=-1\rangle$) will both be equal to the frequency of the 0–0 resonance formed on $|F=1,\ m_F=0\rangle$, $|F=2,\ m_F=0\rangle$.

Watabe *et al.*[43] proposed another lin||lin field method for obtaining high-contrast coherent population trapping signals on the Cs D1 line. The high-contrast signals were achieved by using a bichromatic linearly polarized light. In this excitation scheme, a laser beam with linear polarization is transmitted through a vapor of cesium atoms in a magnetic field parallel to the beam direction. Therefore, both σ^+ and σ^- transitions are excited. Two two-photon resonances of Λ type are formed involving two pairs of ground-state hyperfine sublevels: $|F=3,\ m_F=-1\rangle$, $|F=4,\ m_F=1\rangle$ and $|F=3,\ m_F=1\rangle$, $|F=4,\ m_F=-1\rangle$ (Fig. 6(b)). Both Λ schemes are excited through the common excited state $|F'=3,\ m_F=0\rangle$.

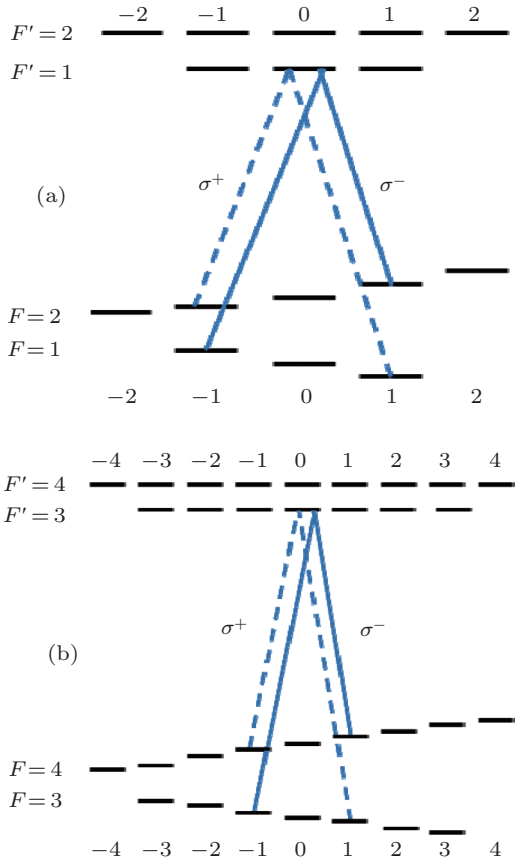


Fig. 6. (color online) Excitation schemes with a lin||lin field on the D1 line of (a) ^{87}Rb and (b) Cs.

No CPT resonance on the ground-state hyperfine sublevels with $|F,\ m_F=0\rangle$, $|F+1,\ m_F=0\rangle$ is excited in the lin||lin configuration, because the different components of the circularly polarized light are in phase and interfere destructively with the CPT effect.[44]

Their experiments demonstrated that a high-contrast dark resonance can be obtained with a lin||lin light field excitation

scheme for the D1 line of either Cs or ^{87}Rb. In those cases, we need to choose the common excited state as $|F' = 3\rangle$ for Cs and $|F' = 2\rangle$ for ^{87}Rb. This is the necessary condition of this scheme, so that the excited state level should be distinguishable; it limits the atoms that can be used and limits the buffer gas pressure.

Jau *et al.*[45,46] proposed to improve the CPT resonance's contrast with a push–pull pumping method. They AM-modulate the laser field to generate the pulses of right circular polarization alternating with pulses of left circular polarization. The pulses propagate along the direction of the magnetic field in an alkali atomic cell, and are separated by half of the period of the 0–0 transition. Since the CPT signals with AM light are nearly independent of the gas pressure, the push–pull method works for a wide range of conditions, including atomic beams with almost no collisions and atoms in buffer gases with pressures of many atmospheres. They qualitatively demonstrated that in this case, no matter what the initial states of the atoms are, nearly all of the atoms will eventually be pumped into the superposition.

Based on the push–pull scheme, they have obtained higher contrasts and narrow resonance line widths of CPT. They measured a 30% contrast for the push–pull CPT resonance. In 2007, they achieved the push–pull method in a mode-locked laser cavity,[46] and the mode separation frequency was equal to the ground state hyperfine separation frequency, obtaining a much stronger signal.

The push–pull method can greatly improve the CPT signal, so it has great potential in atomic clocks and related fields. However, it may not be suitable for the CSAC because extra room is required for the phase delay or the laser cavity.

For CSACs, as the size of the vapor cell is reduced, the lifetime of the ground-state coherence becomes shorter due to the collisions between the atoms and the cell walls. So the buffer-gas pressures have to be increased, which tends to broaden the CPT line width. Knappe *et al.* studied this topic.[47] They designed an experiment and measured the CPT line width as a function of the laser intensity for various cell sizes. In the experiment, they used two surface separations to simulate the different cell sizes, and used Ne as the buffer gas. Their experimental results show that smaller cell sizes require higher buffer-gas pressures to optimize the CPT line width. Since a higher pressure reduces the CPT resonance contrast, we need a higher laser intensity to compensate for it.

The Raman–Ramsey fringes method,[48] which is familiar to researchers in the atomic clock research field, is used to improve the frequency resolution. Several groups[49–51] have proposed to use the Ramsey method on CPT atomic clocks to narrow the CPT resonance spectral widths. They observed the Raman–Ramsey fringes with laser pulses.[52,53] According to their research results, when this method is used, the CPT resonance spectral widths are no longer limited by the optical saturation and collision effects: they depend only on the free evolution time between the two pulses. A fringe width below 100 Hz and a frequency instability of 7×10^{-13} are reported.[54]

In 2008, a Peking University (PKU) group[55] proposed a full band modulation (FBM) method, in which the laser is modulated at the full ground state hyperfine splitting frequency. Before that, half band modulation (HBM) was widely used in implementing the CPT atomic clocks. Using the FBM, we can adjust the intensity ratio of the two laser fields to increase the CPT signal contrast as well as reduce the line width. Compared with the traditional HBM, when the FBM is used, the two pump lasers' intensities can be balanced. The best CPT signal is achieved when the intensities of the two laser fields are equal. When the HBM is used, the intensity ratio of the two sidebands cannot be controlled. If the intensity ratio of the two laser fields is far from 1, and the intensity of one laser field is lower, optical pumping appears, and most atoms are pumped to one of the hyperfine splitting ground states. This will decrease the CPT resonance contrast and increase the CPT line width because the atoms can escape from the ground state coherence through one-photon absorption.

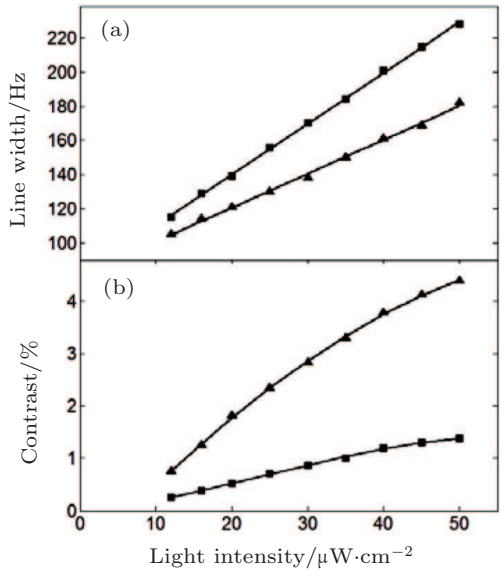


Fig. 7. (a) Line width and (b) contrast of CPT resonance as a function of light intensity under FBM (triangles) and under HBM (squares).[55]

Using the FBM allows us to easily adjust the intensity ratio of the two laser fields by changing the RF power. Therefore, the CPT signal quality under the FBM is better than that under the HBM. Figure 7 shows the width and the contrast of the CPT resonance under HBM and FBM. It can be seen that using the FBM results in a larger contrast and a narrower width. From the figure, it is estimated that the ratio of contrast to width under the HBM is only about 1/4 of that under the FBM.

In 2009, the PKU group proposed a new scheme to implement the chip scale atomic clock based on the detuning coherent population trapping (DCPT) transient oscillation phenomenon.[56] It is proved that when a square wave laser pulse is transmitted through an alkali cell and the atoms have a typical Λ system, the laser fields' different frequencies are detuned from the CPT resonance by a few kHz, and the laser power will have a damping oscillation.[57] Also, the oscillating frequency is exactly equal to the frequency detuning from the atomic hyperfine splitting. Therefore, we can directly measure the frequency detuning and then compensate the output frequency of the microwave oscillator to obtain the standard frequency. By this method, we may further simplify the structure of the CPT atomic clock and make it easier to digitize and miniaturize.

3. Atom and buffer gas selection and micro-cell fabrication

Another very important issue for the CSAC is the selection of working atoms and buffer gases. Many research groups have carried out experiments with different atoms to make CSACs based on the CPT phenomena. Most of them chose ^{87}Rb[58–60] or ^{133}Cs,[61,62] and a few groups used ^{85}Rb.[63] From their research reports, we can see that all the atoms used in the CPT atomic clocks have their own advantages and disadvantages.

Many researchers chose ^{87}Rb as the working atom for the CPT atomic clocks because ^{87}Rb has a long history as the atom for the conventional atomic clocks, and it has performed very well. For the CPT atomic clocks, researchers demonstrated that the D1 line can provide a good CPT resonance. Usually nitrogen, neon, and argon were selected as the buffer gases.

In 2005, an NIST group reported their comparison of Cs D2 and Rb D1 lines using different buffer gases[64] and different cell fabrication techniques. Their results showed that for long-term frequency stability, rubidium with neon and argon as the buffer gases has the best performance under their particular process for making the micro size cell.

Since they did not experiment on the Cs D1 line, from those early experimental results, we still cannot tell which alkali is better for the CPT atomic clocks. Actually, very few groups did the experiment on the Cs D1 line before 2005, because it was difficult to find 894 nm VCSEL laser diodes for the experiment. However theoretically, we expect the Cs D1 line to provide a good performance for the CSAC.

In recent years, more and more groups did CPT clock research with both the Cs D1 line[65] and the Cs D2 line.[66] For the commercial CPT atomic clocks, Symmetricom chose Cs as the working atom for their CSAC, and their product parameters for stability and power consumption look very good. From this commercial product, we can see that Cs performs very well for the CSAC. Compared with Rb, the Cs D1 line has a lower work temperature and a higher transition frequency, which together are good for CSAC stability and power conservation.

Some groups have also studied the Cs D2 line,[67] which take advantage of the fact that the 852 nm VCSELs are much cheaper than 894 nm or 795 nm VCSELs and have good quality and a long service life. The laser quality is very important for the CSAC, even though some reports show that the D2 line is not as good as the D1 line for the CPT atomic clocks.

So far, most research groups have chosen the ^{87}Rb or the ^{133}Cs D1 line to implement the CPT atomic clocks. In contrast, the PKU group chose the ^{85}Rb D1 line.[63] As we all know for ^{85}Rb, the two ground states transition frequency is only 3.035 GHz, which is less than half of the two ^{87}Rb ground states' transition frequency (6.8 GHz). This is a disadvantage for the stability of the atomic clocks. But for the CPT atomic clocks, ^{85}Rb has its own advantage in that it is easy for full band modulation (FBM),[54] so it can reduce the effect of light shift (Fig. 8).

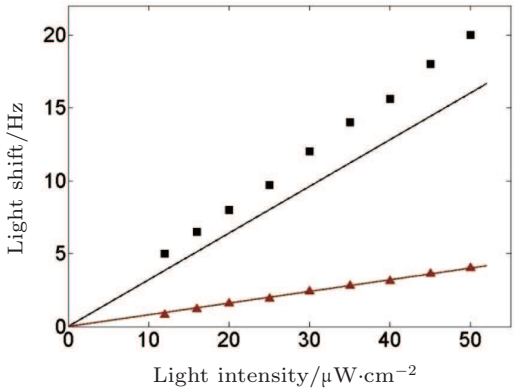


Fig. 8. (color online) Frequency shift of CPT resonance as a function of light intensity under FBM (triangles) and under HBM (squares). The solid curves are theoretical results.[55]

From our theoretical and experimental results, we can see that the light shift of frequency under FBM is only 1/4 of that under HBM. This result can be easily explained, as the off-resonance light is far from the resonance in the FBM. From this point of view, the light shift under FBM in ^{85}Rb is almost the same as that under HBM in ^{87}Rb. If the FBM is applied to ^{87}Rb, the light shift will be only 1/4 of that under HBM. Another advantage of ^{85}Rb is that by the FBM, it can easily balance the intensities of the two pump laser fields, which will benefit stability and reduce the RF power consumption.

Since the CSAC has more strict volume and power consumption requirements, the buffer gases will play a more important role, therefore the buffer gas selection will be more important than in traditional atomic clocks. When the volume is smaller than 1 cm^3, it will be very difficult to find enough room to isolate the cell from temperature changes of the environment. Therefore, if the CPT resonance can be insensitive

to the temperature, it will be very helpful for the CSAC to achieve a higher stability and reduce the power consumed to control the temperature. Several groups have researched on buffer gases[68,69] including nitrogen, argon, neon etc. In order to reduce the dependence of the clock's frequency stability on the temperature stability of the atoms, a mixture of different buffer gases is used to reduce the rate of frequency shift. The basic idea is to use two buffer gases that produce opposite shift ratios. In 2008, the PKU group experimentally demonstrated that by optimizing the buffer gases' pressure and pressure ratio,[70] the temperature shift ratio of the CPT resonance can be substantially reduced (Fig. 9).

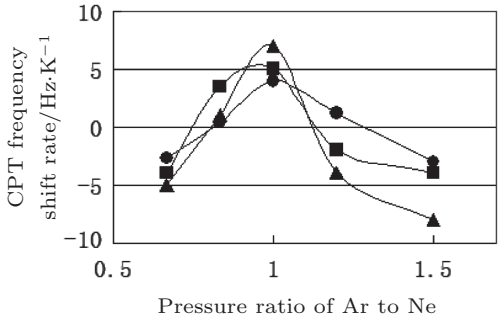


Fig. 9. Frequency shift ratios for different buffer gas ratios and pressures. Circles correspond to group 1 cells with total buffer gas pressure 50 kPa. Squares correspond to group 2 cells with total buffer gas pressure 100 kPa. Triangles correspond to group 3 cells with total buffer gas pressure 150 kPa.[70]

It can be seen in Fig. 9 that the three curves have similar bell shapes, and the frequency shift ratios clearly have a strong relationship with the pressure ratio of Ar to Ne. This is because the two buffer gases produce opposite shift ratios. From the figure, we can clearly see that the frequency shift ratio crosses the zero line at two points on each curve. We can therefore optimize the buffer gas pressure to decrease the shift ratio to approximately zero.

In 2011, we demonstrated that by optimizing the buffer gas pressure and the light intensity, it is possible to substantially reduce the temperature frequency shift ratio of the CPT resonance.[71] When the collision shift ratio is less than 0.3 Hz/K, adjustments in the light intensity can make the collision shift and the light shift cancel each other, allowing the frequency shift ratio to be minimized to near zero. Reducing the temperature sensitivity is crucial for the long-term stability of the CSACs, and very important for their miniaturization. Therefore, the selection and optimization of buffer gas always receives special attention from researchers.

Atom vapor cell fabrication is also an important technology. For the traditional Rb atomic clocks, people usually use glass cells, however it is difficult to make them very small due to the limit of the fabrication technique. For the CSAC, the alkali vapor cell has to be as small as a few mm^3, and preferably made on a chip. Therefore, most groups made the cell with a sandwich structure[64,72] utilizing the manufacturing techniques of MEMS. For filling the cell, there are two typical methods. In the first method, chemical reactions are used. A stable alkali compound is put in the cell. When sealing the cell or afterward, it is heated[73] or laser-irradiated to induce a chemical reaction[74,75] that generates the alkali and the buffer gases. The second method is directly injecting liquid alkali and the buffer gases into the cell and then sealing the cell.[64] The entire fabrication process should be finished in a high vacuum system. For sealing the microscale cells, the anodic bonding technique is widely used. The cell's internal shape is also designed in various styles[76] to achieve better results. In addition, since the cell windows for a CPT atomic clock do not need very good optical quality, some groups use the glass cells[60] even though they cannot be made very small. The advantages are that it is a well-known technology and it is easy to fill the alkali and buffer gases.

4. Miniaturization and power reduction

Miniaturization and power saving are the most important research fields of the CSAC. Since the CSACs are usually not as stable and reliable as the traditional rubidium atomic clocks, if we do not significantly shrink their volume and reduce their power consumption, they will hardly replace the traditional frequency standard in the application fields.

Five years ago, several groups and companies made the first generation of small CPT atomic clocks. The volumes were 40–100 cm^3, and the power consumptions were about 3–5 W. However, most of these products were not well suited to the potential markets, as their sizes and power consumptions were still similar to those of the small traditional rubidium atomic clocks.

For commercial success, CSACs' volume and power consumption should be at least one order of magnitude smaller than those of the traditional rubidium atomic clocks, meaning that the volume has to be smaller than 10 cm^3 and the power consumption should be smaller than 100 mW.

For volume reduction, the atomic cell can be made only a few cubic millimeters;[59,64] with MEMS techniques, we can make the physics part within a few tens of mm^3. There are many research works to improve the contrast and narrow the CPT line width, however, most of them stopped at the experiments, because more space is required in the CPT atomic clock to implement those particular methods. Even the methods can improve the stability of the CPT atomic clocks, for CSACs, the miniaturization is more important than stability.

For example, the σ^+ & σ^- pump scheme usually requires extra space for the phase delay and makes the system complicated. Even it can improve the stability, it is still not suitable in making real CSAC products. The push–pull scheme has the same problems. There are some methods, which may not need

additional space, such as the lin||lin excitation,[43] the pulsed Raman–Ramsey Fringes generation,[77] and the two VCSEL idea;[38] however, they make the system complicated, and are very difficult to use in the commercial CSAC.

For the CSAC, techniques that benefit volume reduction and power saving are always more appealing to practical researchers. Buffer gas selection and pressure optimization are always important, because they have the potential to reduce the volume and the power consumption, and simultaneously improve the performance of the CPT clocks. From 2008 to 2011, we reported our research on buffer gas optimization.

As we can see in Fig. 10, from 35 °C to 43 °C, the frequency shift ratio is approximately zero. A buffer gas optimization method can be used if we can expand the low shiftratio region enough that we do not need to control the temperature, or only need to control the temperature roughly within an 8° range. It will be very helpful for CSAC miniaturization, power reduction, and stabilization.

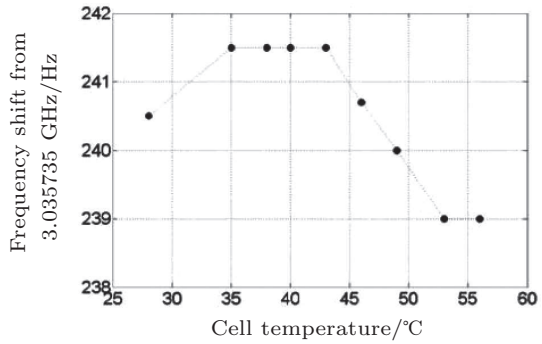


Fig. 10. Frequency shift of CPT resonance as a function of cell temperature.[71]

Theoretically, if we keep the temperature shift of frequency within 0.1 Hz in the entire working temperature region, then we can make a CSAC with no temperature control or thermal isolation part and still have a reasonable stability. This would allow us to shrink the CSAC's volume dramatically and reduce the power consumption.

As we have said, besides the volume reduction, power saving is also very important for the CSAC. In the first generation of CPT atomic clocks, for high stability, people used an oven controlled crystal oscillator (OCXO) to generate the RF signal. With the OCXO, the clocks are more stable but need at least a few watts of power for operation – an intolerable level in the commercialization of CSACs. To save power, some research groups used local oscillators (LO),[78] while some selected a temperature compensated crystal oscillator (TCXO) or a voltage-controlled oscillator (VCO)[79,80] as the RF source.

The LO has advantages for the CSAC in that it consumes very little power (less than 5 mW)[81,82] and is small in size. Simultaneously, the LO's disadvantage is that the free run stability is not as good as the commercial TCXOs and OCXOs. Figure 11 is a LO stability plot made by the PKU group. The short term stability is better than CU and NIST reported data,[78] but still one or two orders shy of the typical TCXO for the CPT atomic clock. If we add a temperature control and thermal isolation package, the stability may be improved, but the volume and power consumption would also be increased, which is not what we want in the CSACs. TCXOs' advantages are that they have better free run short term stability (frequency instability 10^{-11} s^{-1}), low power consumption,[27] and small volume.

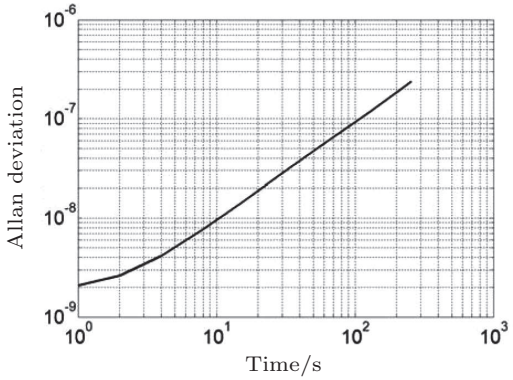


Fig. 11. LO (made by PKU group) free run stability.

An application specific integrated circuit (ASIC) has been used as the control circuit for the CSACs by almost all researchers. Clearly, this will significantly save power and reduce the volume. Technically speaking, the electronic control circuit can be integrated into a microchip. So for CSAC miniaturization and power saving, the key problems are the physics part and the RF generation part. Therefore, we have mainly reviewed the research about these parts in this section.

5. Frequency stability and CPT resonance shift

Usually, the CPT resonance is sensitive to the temperature, the phenomenon called temperature shift, which directly influences the frequency stability of the CSACs. Therefore, the temperature control and a thermal insulation system are essential to the CSACs. But these systems require increases in the size of the physics package and the power consumption. For solving this problem, researchers have paid more and more attention to reducing the temperature sensitivity of the CPT resonance.

The buffer gases[83] play a very important role in the temperature sensitivity of the CPT. We all know that the buffer gas is needed in the atomic cell because slowing down the diffusion of atoms reduces the line width of the CPT resonance and prevents the wall relaxation.[84] But the collisions between buffer gas atoms and alkali atoms causes the collision shift, which influences the stability of the CPT atomic clock. The atomic hyperfine frequency may be shifted as a result of these collisions, because the collisions perturb the wave function of

the rubidium atoms, influencing the hyperfine constant. Perturbations are sensitive to the temperature, and although the cell is thermally isolated and temperature controlled, residual temperature drifts still limit the long-term stability of the CPT atomic clocks. Roughly linear shift ratios, from several Hz/K to tens of Hz/K, are observed in rubidium.[70]

Controlling the temperature drift within an acceptable range presents a challenge and may put stringent requirements on the temperature stability of the physics package of a CPT atomic clock, especially after miniaturization. This may increase engineering-related constraints in the manufacture of the CPT clocks and may require an increase of the size for thermal isolation. As we discussed in the last section for reducing the dependence of the atomic clock frequency stability on the temperature stability of the atoms, a mixture of different buffer gases is used. In the case of rubidium, Ar–N_2 and CH_4–N_2 have been of particular interest because the nitrogen produces the required fluorescence quenching while the other partner is used to decrease the temperature coefficient.[85,86] Ar–Ne is another choice for rubidium clocks.[64,70]

Figure 12 shows a comparison of the typical shift ratios of the CPT resonance with the buffer gas Ar–Ne. In Fig. 12(a), the temperature shift ratio is negative, and in Fig. 12(b), it is positive. This indicates that we may optimize the buffer gas pressure to decrease the shift ratio, as we discussed in the last section (Fig. 10).

A follow-up study has shown us that the shift ratio cannot equal zero. The temperature shift ratio will decrease when the buffer gases are adjusted toward the zero point, but when the shift ratio is smaller than 0.3 Hz/K, the frequency shift with the temperature will no longer be monotone. We made a group of cells in which the buffer gases pressure and ratio are designed close to the two shift ratio crosszero points (Fig. 9). The frequency shift ratios of these cells mostly fall within the range of -0.5 Hz/K to 0.5 Hz/K. Figure 10 shows the CPT resonance frequency shift as a function of the cell temperature for a special cell. In this cell, from 35 °C to 43 °C, the frequency shift ratio is approximately zero. When the temperature is below 35 °C, the shift is positive; when the temperature is higher than 43 °C, the shift is negative (Fig. 10). We cannot obtain an ideal zero temperature shift. But this result also tells us that if we use this cell in a CPT clock and keep the cell temperature between 35 °C and 43 °C, the temperature shift will be less than 0.1 Hz, and the frequency instability will be kept in the 10^{-11} region. This performance may meet the basic requirements for commercializing CSACs.

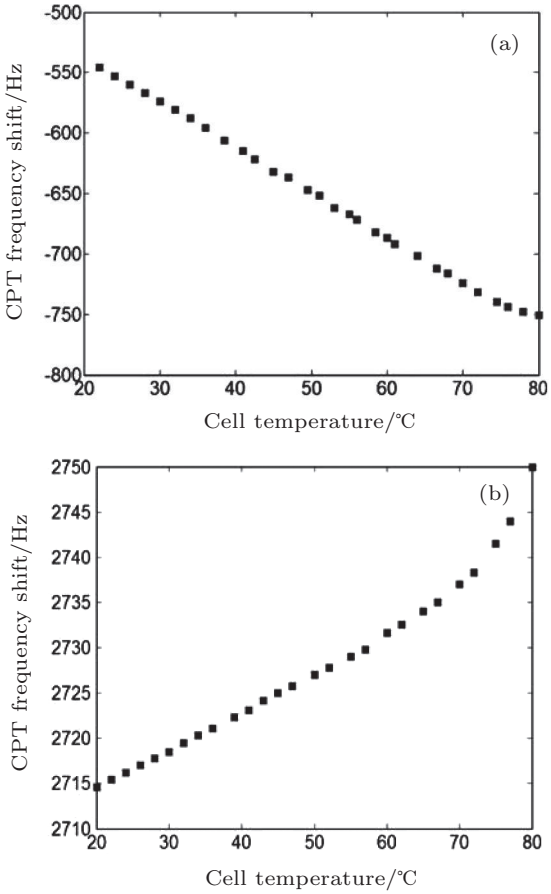


Fig. 12. Frequency shift of CPT resonance as a function of cell temperature for two typical Rb vapor cells: (a) temperature shift ratio is negative, (b) temperature shift ratio is positive[70]

Here we can give a qualitative explanation of the experimental results. Several factors can affect the CPT resonance shift, and two of them are related to the temperature. One is the collision shift which is caused by collisions between buffer gases and the rubidium atoms. As the temperature change is directly related to the atoms' velocity, the collision shift is sensitive to the temperature. The other one is the light shift; usually it is related to the pump laser bands' intensity. In the alkali cell, the light absorption by atoms decreases the laser intensity, and the alkali density is determined by the cell's temperature, so the average light intensity is related to the cell temperature.

At low temperatures (< 20 °C), the collision shift increases linearly with increasing temperature and the light shift decreases exponentially with increasing temperature. We can describe the total temperature shift with the equation[71]

$$\nu_t = \delta P_0 (T - T_0) - \frac{\kappa}{2} D I_0 e^{\alpha(T-T_0)} + C, \qquad (1)$$

where ν_t is the total temperature shift, the first term is the collision shift, the second term describes the light shift, and C is a constant. When the contribution of the buffer gas collision to the frequency shift ratio is large for example several Hz/K or tens of Hz/K, the contribution of the light shift to the total frequency shift ratio can be neglected (Fig. 12). When the

collision shift ratio is less than 0.3 Hz/K, it becomes comparable to the light shift ratio, which then cannot be neglected. In Fig. 10, the positive frequency shift ratio below 35 °C is dominated by the buffer gas collision. The negative frequency shift ratio above 43 °C is mainly influenced by the light shift. In the range from 35 °C to 43 °C, the two effects are canceled, and the net frequency shift ratio is approximately zero.

We have repeated this experiment with other cells, and the experimental data are in good agreement with the theoretical curve (Fig. 13). It can be seen from Fig. 13 that the frequency shift ratio is influenced by both light intensity and temperature. We can adjust the frequency shift ratio by adjusting the light intensity and choosing a suitable operating temperature, minimizing the temperature coefficient of the resonance frequency shift. In addition, if the shift canceling temperature range can be extended across the full range of the operating temperature, the need for a temperature control system is eliminated. This is very important for our final goal of making an atomic clock on a single small chip.

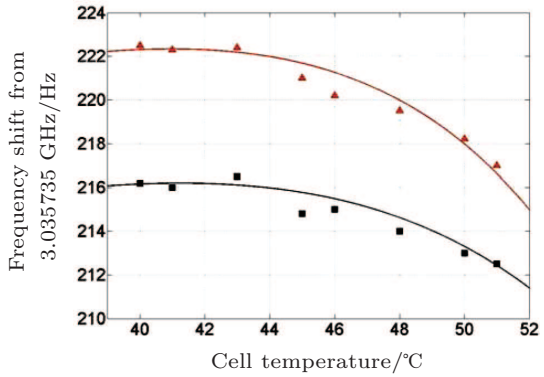


Fig. 13. (color online) Frequency shift of CPT resonance as a function of cell temperature under different light intensities: squares: 50 μW/cm^2, triangles: 100 μW/cm^2.[71]

To improve the stability, Zhu[87,88] believed that the light shift plays a very important role. He proposed an optical pumping method to reduce the light shift (AC Stark shift), using multiple excited state energy levels to cancel the net light shift. The collision-broadened line width in the optical transition is used to reduce the resultant laser frequency detuning. By using this method, his preliminary results showed an improved short term stability of a small-cell CPT atomic clock, and the clock frequency was less sensitive to laser frequency detuning, laser power, and microwave power.

Other groups have proposed to achieve higher stability by optimizing the buffer gas and adjusting the microwave power.[89–91] The microwave power changes the total laser intensity as well as the intensity ratio between respective sidebands. It was demonstrated that an appropriate index of modulation for the pump VECSL can mutually cancel out the light shifts affected by the resonant and the off-resonant optical sidebands.[92,93] If we lock the modulation power to a value where the light shift contributions to the clock frequency vanish, there is no doubt that the stability of the CPT resonance will be improved. It has been demonstrated that tuning the microwave power to this point will make the light shift independent of the laser power level. In addition, by adjusting the cell size and the buffer gas pressure, it was theoretically and experimentally demonstrated that within a certain temperature range, the CPT resonance has a very low sensitivity to the temperature and the buffer gas pressure.[94] Combining those methods, we can solve the laser aging problem and relax the constraints on the accuracy control of temperature and buffer gas filling. Those are very important to the CSAC, not only for performance, but also good for reliability and service life.

All the methods reviewed in this section have advantages and disadvantages. The PKU group method has a wider working temperature range but requires locking the laser power. The last method discussed makes the CPT resonance insensitive to the laser power, the buffer gas pressure and the temperature, but it requires keeping the microwave power and the working temperature within relatively small ranges. An important difference between different methods of microwave modulation is that the PKU group uses full band modulation[95] and most other groups use half band modulation. Combining the above methods to improve the CSAC performance is one possibility for future researches.

6. Conclusion

In this paper we have reviewed both theoretical and experimental studies of the CSAC. Most of the researches are based on the CPT phenomenon, which allows us to shrink the size and reduce the power consumption of atomic clocks. The final goal is to develop a low cost, battery driven microscale atomic clock that is roughly 1 mm^3 in volume so that more applications will be possible,[96,97] as it would improve the performance of any instrument that requires a frequency standard, such as wireless communications, global positioning, and network synchronization.

It should be noted that this paper does not include research works on CPT masers[98–100] or active CPT atomic clocks. The reason is that a CPT maser must have a cavity. Therefore, its size cannot be smaller than the cavity size, which is limited by the working wavelength. This precludes the possibility of sufficient miniaturization of CPTs for the CSAC, which is our main objective.

The research on the CSAC has been ongoing for over ten years. Microscale atomic clock research is gradually shifting from theoretical and experimental researches to practical product development. Before 2005, most of the researches focused mainly on the basic principles,[101–103] the miniaturization of the physics package,[104–106] and new methods to improve the

CPT resonance signals. More recently, CSAC researchers' attention has gradually shifted to the study of stability, reliability, and service life.

So far, the smallest CPT atomic clock's size and power consumption remains one order of magnitude shy of the goal proposed at the beginning of this research ten years ago. It is extremely difficult for today's CSACs to replace the traditional small atomic clocks and crystal oscillators in potential applications. Reducing the volume to fit on a single chip is very important for the future of the CSAC. Therefore, further technical and theoretical breakthroughs are needed for CSACs' miniaturization and power reduction. To achieve this goal, there are a few research issues that require our attention. First is minimizing the temperature sensitivity to relax the requirement for thermal isolation and temperature control (Section 5). Second is the methods for improving the CPT signal contrast and narrow the linewidth, such as the lin||lin method and the Raman–Ramsey fringes with pulses, they have been reviewed in Section 2. We also reviewed some effective methods for increasing the CPT contrast and reducing the linewidth, which have the potential to improve the performance of the CPT atomic clocks, but would increase the volume or the power consumption. Most of these methods are very difficult to apply in CSACs unless we find a way for them to benefit the miniaturization and the power. We also need to pay attention to the new scheme for non-CPT atomic clocks based on the detuned coherent population trapping (DCPT) oscillation[56,107] clocks, which directly read the ground state transition frequency as the standard frequency, no longer need the phase locking loop, and have good reliability, good potential for miniaturization, and good prospects for power reduction. The scheme shows us another way to approach CSACs, indicating that the CPT might not be the best way to make a practical CSAC.

The CSAC unquestionably has great potential in the frequency standard field. But for reaching the goal, to achieve real CSAC, we still await further theoretical and technical breakthroughs.

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