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Study of a low power dissipation, miniature laser-pumped rubidium frequency standard*

Liu Guo-Bin(刘国宾)[a)b)], Zhao Feng(赵 峰)[a)], and Gu Si-Hong(顾思洪)[a)†]

[a)] *Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan* 430071, *China*

[b)] *Graduate School, Chinese Academy of Sciences, Beijing* 100080, *China*

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This paper studies a miniature low power consumption laser-pumped atom vapour cell clock scheme. Pumping ^{87}Rb with a vertical cavity surface emitting laser diode pump and locking the laser frequency on a Doppler-broadened spectral line, it records a $5\times10^{-11}\tau^{-1/2}$ ($\tau < 500$ s) frequency stability with a table-top system in a primary experiment. The study reveals that the evaluated scheme is at the level of 2.7 watts power consumption, 90 cm^3 volume and $10^{-12}\tau^{-1/2}$ short-term frequency stability.

Keywords: laser-pumped atom clock, laser frequency stabilization, rubidium vapour cell clock
PACC: 3280B, 4262, 3335H

1. Introduction

In modern society, atomic clocks have been widely used to provide standard time. Among all kinds of atomic clocks, the spectral-lamp pumped rubidium cell clock (SLRC) is most used due to its small size and low power consumption. However, there are still many potential customers of atomic clocks who cannot afford the size and power consumption. Developing a smaller atomic clock of lower power consumption is an important goal in the atomic clock industry.

The optical pumping source, the spectral lamp, represents a considerable part of the power and volume of a SLRC, and its long warm-up time also restricts the SLRC starting time. Since the appearance of the laser in the 1960s, and particularly semiconductor lasers in the 1970s, intensive research interests have been made to develop a laser-pumped atom vapour cell clock (LPAC) in which the spectral lamp is replaced with a laser diode.[1,2]

Good characteristics of the laser improve the atomic clock in several respects: an intensive coherent light source with a narrow spectral bandwidth improves pumping efficiency by at least one order of magnitude; the easily controlled laser intensity effectively controls background noise. Pumping by a laser, we can improve the frequency stability of the atomic clock by at least one order of magnitude. Several realized LPACs have reached good frequency stability. For instance, with a sub-MHz bandwidth extended cavity diode laser, a LPAC realized in Mileti's group has achieved frequency stability of $5 \times 10^{-13}\tau^{-1/2}$.[3]

However, an ideal monochromatic light causes a light shift in a different way, i.e. besides amplitude fluctuation, the laser frequency fluctuation affects the absorption lineshape and thus causes a light shift eventually. The problem makes laser frequency stabilization an important task for an LPAC. Although there are only a few apparatus locking the laser frequency to a Doppler-broadened spectral line,[4,5] in most LPACs an independent reference system including an independent atom vapour cell is employed to lock the laser frequency to a Doppler-free line;[1] this scheme costs extra volume and power consumption.

On the other hand, if the laser frequency can be properly stabilized without an extra reference system, LPACs are promising to achieve considerably smaller and lower power consumption atomic clocks. Our work is to exploit the potential of LPACs in this direction.

2. Principle and experimental setup

The experimental setup is shown in Fig.1: a vertical-cavity surface emitting laser (VCSEL) is chosen as the pumping laser, a precision current source

*Project supported by National Natural Science Foundation of China (Grant Nos 10574141 and 10675162).
†E-mail: shgu@wipm.ac.cn

(Keithley Model 6220) drives the VCSEL with about 1.2 mA DC current in the experiment. When its temperature is stabilized at about 70 °C the VCSEL emits 794.7 nm laser light with 0.17 mW, which excites the $5S_{1/2}F = 1 \rightarrow 5P_{1/2}$ transition of ^{87}Rb to build up a population inversion between the ground hyperfine states of ^{87}Rb.

The laser was collimated via a set of lenses to a parallel beam of diameter 10 mm, which lessens the influence of an inhomogeneous light intensity distribution on signal broadening.[1] A photocell detector was used to detect the laser interacting with atoms. The laser bandwidth of the VCSEL is about 100 MHz and no step of narrowing bandwidth was arranged in the experiment. The laser frequency was locked to the $5S_{1/2}F = 1 \rightarrow 5P_{1/2}$ Doppler-broadening absorption line as in our previous works.[6,7]

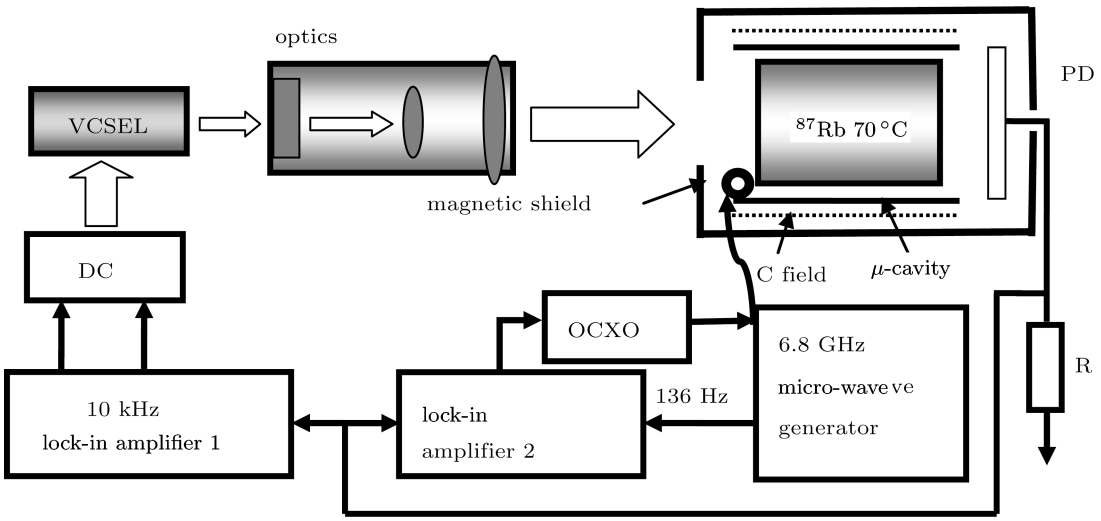


Fig.1. Experimental setup of the laser-pumped rubidium frequency standard. DC: precision current source, optics: optical attenuator, lens etc; PD: photodetector; R: I–V transform resistance.

An oven-controlled crystal oscillator (OCXO) provided a 10 MHz signal as the input to a microwave generator (Agilent E8257D), wherein a 6.8 GHz microwave was synthesized and coupled through a dielectric ring into the microwave cavity to build up a microwave field which drives the magnetic dipole transition between hyperfine ground states.

In order to generate a negative feedback signal to stabilize the laser frequency, a 10 kHz AC current provided by lock-in amplifier 1 in Fig.1 was superposed on the injection DC current of the VCSEL, a differential curve of the Doppler-broadened $5S_{1/2}F = 1 \rightarrow 5P_{1/2}$ absorption spectral line was demodulated with reference to 10 kHz by phase sensitive detection (PSD) using the same lock-in amplifier. The differential voltage signal was transformed to current as an error signal mixed into the VCSEL injection current to stabilize the laser frequency.

In a similar way, the microwave was modulated at 136 Hz within the microwave generator which also sent out a 136 Hz reference to lock-in amplifier 2 in Fig.1. The negative feedback voltage was obtained with lock-in amplifier 2 and fed back to OCXO to stabilize the microwave frequency.

^{87}Rb atoms and buffer gas of a mixture of CH_4 and N_2 were sealed in a $10\times\phi10$ mm glass cell, and the temperature of the cell was stabilized at 70°. The buffer gas improves atomic clock performance mainly by three effects: suppressing the pumping effect due to ^{87}Rb spontaneous emission[8] which reduces population inversion between hyperfine ground states; squeezing the microwave transition linewidth by means of the Dicke effect,[9] reducing temperature-dependent frequency drift with a proper ratio between CH_4 and N_2 such that they shift the microwave frequency in opposite direction as the temperature changes.[10,11]

Our laboratory-patented miniature TE_{011} mode

microwave cavity was used in the experiment;[12] its resonant frequency was finely turned to the clock transition frequency and a Q-value of 400 was measured. A solenoid wrapped around the cavity provided about 10^{-5} T magnetic field, which selects out $m_{\rm F} = 0$ ground states as clock states via the Zeeman shift and provides an axis of quantization for magnetic dipole transition.

The sample cell is magnetically shielded by a 0.5 mm thick single layer permalloy.[13] The temperature of the VCSEL and the sample cell are separately controlled with homemade servo circuits, which can achieve 5‰ (increment of controlled temperature ÷ increment of environment temperature) controlled accuracy.

3. Results and discussion

Figure 2 is the PSD differential curve corresponding to ^{87}Rb atomic absorption spectra recorded in the experiment. When the laser frequency was locked by the differential signal, the frequency drift range was decided by measuring the fluctuation of the error signal and it was concluded that the laser frequency was confined within ±50 MHz corresponding to the centre of the Doppler-broadening absorption spectrum.

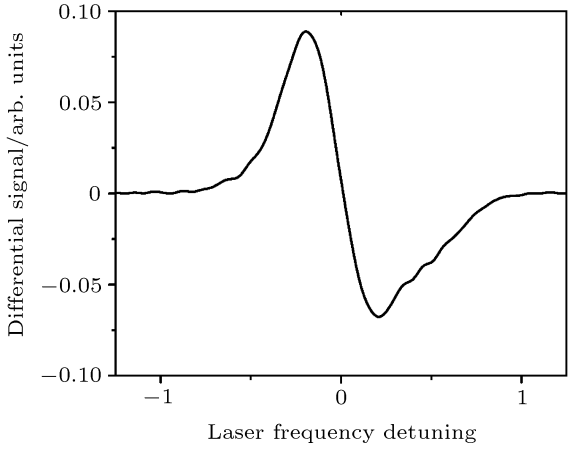


Fig.2. Laser frequency stabilizing error signal obtained with PSD.

The linewidth of the clock transition in our experiment is 680 Hz (full width at half maximum); Fig.3 shows its differential curve. In the PSD a modulation frequency of 136 Hz is chosen which depresses best the 50 Hz coupling noise, and the modulation depth is 160 Hz which leads to the best S/N of the PSD signal. Both parameters are decided through optimizing experimental data.

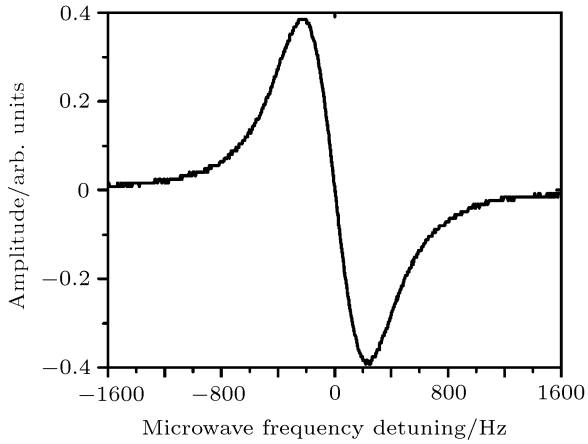


Fig.3. Microwave frequency stabilizing error signal obtained with PSD.

The clock output frequency is compared with a hydrogen maser (CH1-75A, Institute of Electronic Measurements, Russia). Fig.4 shows measured results of typical short-term stability.

From Fig.4 it is seen that a stability of $5\times10^{-11}\tau^{-1/2}$ has been achieved for $\tau < 500$ s. After 500 s the frequency stability begins to depart from the white noise limit; we believe that is mostly caused by the different long-term fluctuations of OCXO and the equipment used in the experiment.

From our study on passive coherent population trapping (CPT) atomic clocks, frequency stability is very sensitive to temperature fluctuations, especially that of the VCSEL. In our design of this LPAC scheme, the VCSEL and sample cell should be sealed in a temperature-controlled closed physics package, while for the convenience of arranging different conditions to study various behaviours, they were mounted in their independent systems and separated by a certain interval in the experiment. An 'open' side had to be left for the laser beam in both systems, each with only a piece of glass to separate it from the environment. The VCSEL and cell suffered considerably from environment temperature fluctuations. From the thermal sensors that were not mounted exactly at the 'open' side, we know that temperatures were controlled within 5‰, but what the cell and VCSEL received must be worse.

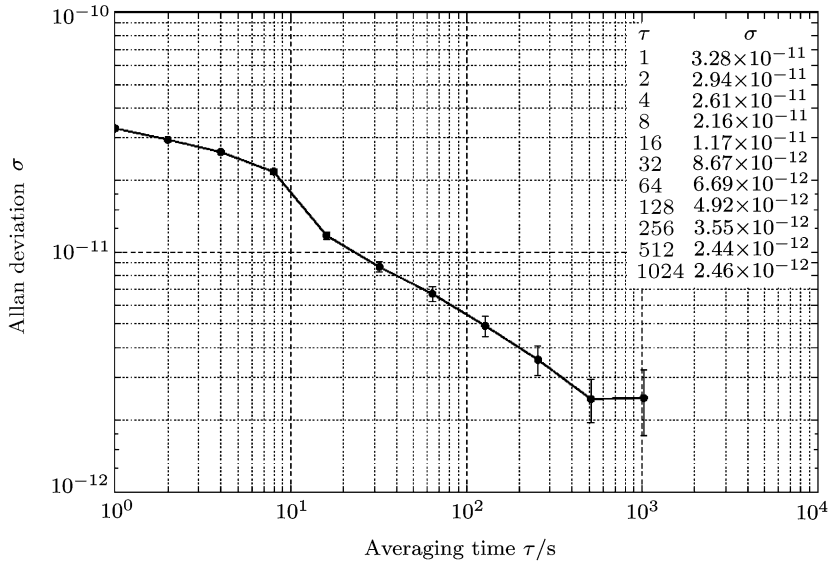


Fig.4. Measured short-term stability with our laser-pumped rubidium frequency standard.

Similarly, an opening was also left in the magnetic shielding structures; thus the sample cell endured relatively strong electromagnetic radiation and stray static fields, which are also important sources that deteriorated frequency stability.[13]

These problems will be much eliminated when the VCSEL and sample cell are integrated into a closed physics package. From our experience and previous study on a rubidium clock, especially a CPT atomic clock with the same VCSEL,[6] we are confident that the short-time frequency stability will be improved by about one order of magnitude.

Concerning the light shift, we find that frequency jitters of narrow bandwidth laser affect short term stability seriously so that Doppler-free frequency locking is commonly chosen, while with a 100 MHz bandwidth laser interacting with thermal atoms, the detected optical signal jittering effects will be mostly erased. Slow frequency drift, which is more related to middle-term frequency stability, might leave more influence, while its effect on frequency stability not only relates to the locking range of frequency, but the laser bandwidth as well. Experimental study proved that expanding the bandwidth by frequency modulation, and the light shift effect can be much reduced.[14] Comparing with the 5 MHz locking range of the 0.1 MHz bandwidth laser,[15] we find that a 100 MHz range should not be bad with a 100 MHz bandwidth laser.

In SLRC, the spectral lamp works at a temperature of about 140 °C and it also generates strong radio frequency field conditions, so that a certain volume has to be arranged for shielding the radiation field and dispersing extra heat. Replacing the lamp with a laser diode not only reduces watt=level spectral-lamp power consumption to the milliwatts level, but also eliminates the volume related to radiation and overheating. When no power and volume are used to stabilize laser frequency, such as the way studied in this work, the LPAC is expected to considerably reduce in size and power consumption.

In the experiment, the microwave cavity size is $30\times\phi18$, and laser beam divergence angle is 23.5°. When we apply these parameters into the designed scheme, the size of the physics package will be $35\times\phi18$ (the VCSEL is 2 mm outside the cavity to provide the cell with a $\phi9$ pumping beam). Inside the package, the temperature of cell and VCSEL are controlled together at 70 °C, where VCSEL provides the right wavelength laser. We have studied the power consumption of the same size physics package with a CPT atomic clock, at 25 °C environment temperature. It consumed 0.9 watt when it was wrapped in a 5 mm thick polyurethane foam heat preservation layer. We have also designed a mixed digital–analogue circuit, which is similar to the circuit used in our CPT atomic clock;[16] its power consumption budget is 1.8 watts.

From all these studies we are confident that it would not be difficult to realize a LPAC of 2.7 W power consumption and 90 cm^3 volume with a 0.9 W, 40 cm^3 physics package. With the application of technologies such as 'system in package', the size and power consumption can be considerably further re-

duced.

4. Conclusion

A small low power consumption laser-pumped atom vapour cell atomic clock scheme is studied and experimentally tested. Pumping ^{87}Rb with a vertical cavity surface emitting laser diode and locking the laser frequency on a Doppler-broadened spectral line, we have recorded a $5\times10^{-11}\tau^{-1/2}$ (τ500 s) frequency stability with a table-top system in a primary experiment. The study reveals that the evaluated scheme is at the level of 2.7 watts power consumption, 90 cm^3 volume and $10^{-12}\tau^{-1/2}$ short-term frequency stability. With application of advanced technologies such as 'system in package' etc, further reductions in the power consumption and volume are expected. Besides size and power consumption, the short warm-up of the LPAC is also an important advantage to many customers. With great demand for small low power consumption atomic clocks from the market, the LPAC will find extensive applications.

References

[1] Vanier J 2007 *Appl. Phys.* B **87** 565

[2] Lewis L L and Feldman M 1981 *Proc. 35th Ann. Freq. Control Symp.* p612

[3] Mileti G, Deng J Q, Walls F L, Lowe J P and Drullinger R E 1996 *Proc. IEEE Int. Frequency Control Symp.* p1066

[4] Hashimoto M and Ohtsu M 1987 *IEEE J. Quantum Electronics* **23** 446

[5] Chantry P J, Liberman I I, Verbanets W R, Petronio C F, Cather R F and Partlow W D 1996 *Proc. IEEE Int. Freq. Control Symp.* p1002

[6] Du R C, Chen J H, Liu C Y and Gu S H 2009 *Acta Phys. Sin.* (in Chinese, accepted for publication)

[7] Liu G B, Du R C, Liu C Y and Gu S H 2008 *Chin. Phys. Lett.* **25** 472

[8] Happer W 1972 *Rev. Mod. Phys.* **44** 169

[9] Dicke R H 1953 *Phys. Rev.* **89** 472

[10] Wang Y Q, Wang Q J, Fu J S and Dong T Q 1986 *The Theory of Frequency Standards* (Beijing: Science Press) (in Chinese) p378

[11] Xia B H, Zhong D, An S F and Mei G H 2004 *Chin. J. Magnetic Resonance* **21** 41 (in Chinese)

[12] Mei G H, Zhong D, An S F, Liu J T and Huang X R 2001 *Miniaturized Microwave Cavity for Atomic Frequency Standard* U S Patent No.6 225 870 B1

[13] Dong L, Zhang L, Dou H P, Yin W B and Jia S T 2008 *Chin. Phys.* B **17** 152

[14] Zhu M and Cutler L S 2000 *Proc. Precision Time and Time Interval* p311

[15] Mileti G, Deng J Q, Walls F L, Jennings D A and Drullinger R E 1998 *IEEE J. Quantum Electronics* **34** 233

[16] Chen J H, Du R C, Lv L Q, Gan N, Li Y Y, Ma H, Liu C Y and Gu S H 2008 *Proc. China. Freq. Control Symp.* p135 (in Chinese)