Study on the Effect of Excitation Circuit of Spectral Lamp on the Temperature Coefficient of Physics Package of Rubidium Atomic Clock

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Abstract. As one of the important factors affecting the long-term frequency stability of Rubidium atomic frequency standards (RAFS), the temperature coefficient has a great influence on the performance of RAFS. The temperature coefficient of physics package has an important influence on the temperature coefficient of rubidium atomic clock. The instability of temperature is often the most important error term of RAFS. The variation of temperature to several degrees means a month’s aging. As an important part of rubidium atomic clock physics package, the Lamp Excitation Circuit directly affects the voltage adaptation area and temperature coefficient of Rubidium gas cell physics package. In order to satisfy the long-term frequency stability and adapt extraterrestrial environment, we propose the improvements of Lamp Excitation Circuit in physics package of Rubidium Atomic Clock, since minute current change of Lamp Excitation Circuit are mapped onto the clock’s long-term frequency stability, and the stabilization of the lamp excitation circuit has the potential to significantly improve the RAFS’ long-term frequency stability and temperature coefficient. We demonstrate that the temperature coefficient of physics package can be reduced obviously by improved Lamp Excitation Circuit. Suggesting that performance of the RAFS could be improved greatly further.

1. Introduction

The lamp-pumped Rubidium Atomic Frequency Standard (RAFS) is the most widely used atomic clock in the world[1]. In the past decades, with the continuous development, RAFS is arguably the “workhorse” of atomic timekeeping in space; it has a very good long and short-term stability[2], excellent performance and low radiation sensitivity. Its longevity in space extends to decade[3,4], and Rb atomic clocks are attractive candidates for space programs due to their small size, low weight, and low power consumption[5]. It uses the transition frequency between the ground state ⁵²S¹/² of ⁸⁷Rb atom and two hyperfine Zeeman sub-levels F=1, mF=0 and F=2, and mF=0 to discriminate the frequency. The crystal excitation frequency is locked in this transition frequency through a frequency-locked loop.

The principle block diagram of passive atomic frequency standard is shown in figure 1. RAFS is essentially a frequency-locked loop, in which the physics package (PP) is equivalent to quantum frequency discriminator[1]. It includes lamp excitation circuit, ⁸⁷Rb lamp, filter cell, absorption cell,
photo detector, magnetic shield, C-field coil and temperature control system. The physics package generates transition spectral lines and converts the difference between the excitation signal frequency and the center frequency of the spectral line into a discriminator signal. The light emitted by the spectral lamp filters the $^{87}\text{Rb}$ atom in the absorber cell at the ground state superfine level $F=1$ to the $F=2$ level, which causes the number of particles to be reversed. The crystal excitation frequency is synthesized by frequency doubling to obtain the microwave excitation signal similar to the frequency of the above transition spectral line, which excites the atom from the ground state superfine level $F=1$ to the level $F=2$ level. $F = 2$, $mF = 0$ to $F = 1$, $mF = 0$ level transition[6], when the transition occurs, the light intensity through the absorption cell detected by the photocell becomes weaker, which is the detection signal of light. The photometric signal is input into the circuit system to produce the correction signal of crystal excitation, which can lock the crystal excitation frequency to the atomic transition frequency. From the working principle of the rubidium atomic frequency standard, it can be seen that the stability of the rubidium spectral lamp directly affects the stability of the atomic transition spectral line frequency. The stability of lamp excitation circuit is one of the important factors affecting the stability of rubidium spectral lamp. Therefore, how to improve the stability of lamp excitation circuit, then improve the stability of spectral lamp, and ultimately reduce the temperature coefficient of physics package becomes a key issue. Finally, by analyzing and improving the lamp excitation circuit, and testing the performance under atmospheric and vacuum conditions, the testing results is helpful to optimize the temperature coefficient and improve the long-term stability of rubidium-loaded clocks in the application of space.

Figure 1. Basic Block Diagram of a Passive atomic frequency standard.

2. Rubidium gas cell physics package
As the core component of rubidium gas cell atomic frequency standards, the physics package mainly consists of lamp excitation circuit, $^{87}\text{Rb}$ lamp, filter cell, absorption cell, photo detector, magnetic shield, C field coil, cavity and oven temperature control system. The physics package mainly plays the role of frequency discriminator, providing a stable frequency and narrow line width atomic resonance absorption line. By comparing the frequency of the microwave excitation signal with the atomic transition spectrum, the output discrimination signal of physics package is then conducted by phase-sensitive detecting, so that the output frequency of the crystal excitation is locked to the central frequency of the transition spectrum. As shown in figure 2, the light beam from the lamp finally gets to the rubidium absorption cell, placed in the microwave cavity, as to deplete the population of $F=1$ level and build a population inversion between the $F=1$ and $F=2$ levels of $^{87}\text{Rb}$ ground state[7]. The excitation circuit is used to generate the excitation frequency, and the rubidium lamp is used to emit ultra-fine level spectrum a and b lines, and the filter cell is used to remove the hyperfine component of the a lines and retain b lines[8]. The absorption cell is used to reverse the number of ground-state particles, pumping $^{87}\text{Rb}$ F1 ground-state atoms to F2 level (F1→ F2). The photo detector converted the optical signal through the absorbed cell into electrical signals and supplied to the servo system; the C-field is used to fine-tune the transition frequency of $^{87}\text{Rb}$ and exclude them from the phase-locked loop capture band by sensitivity of the non-clock transition signals to the C-field. The magnetic shielding is mainly used to shield the influence of the geomagnetic field and the spatial stray magnetic field on the
transition frequency of rubidium clock atoms in the PP, in order to obtain the best SNR (signal to noise ratio). The filter cell and absorption cell are separately temperature controlled[9,10].

![Figure 2. Rubidium gas cell physics package.](image)

3. Lamp excitation circuit

3.1. Traditional Lamp excitation circuit

One of the important components of the Physics Package is Rb lamp. The Rb lamp consists of electrode less Rb bulb and a lamp exciter[11]. Rubidium spectrum lamp is a kind of electrodeless discharge lamp by using high frequency excitation applying to the rubidium atomic gas. The lamp excitation circuit provides a radio frequency between 100MHz and 150MHz for the rubidium spectrum lamp. The rubidium lamp emits pumping light under the excitation.

Considering the stability of lamp excitation circuit, we ultimately choose the Clapp oscillator which is an improved Three-point capacitance oscillator. the feedback coefficient and frequency stability of the excitation will be affected slightly when the external environment changes. The circuit principle is shown in figure 3(a) and (b). L3 is the coupling coil around the rubidium lamp, and $C_{ce}$ is the interelectrode capacitance between the emitter and collector of transistor.

![Figure 3. The principle chart of the spectral lamp excitation circuit.](image)

From the alternating current path shown in figure 3(b), it can be seen that the excitation frequency of the circuit is as follows:

$$f_0 = \frac{1}{2\pi\sqrt{L_1C_{ce}}}$$

(1)

Considering the transistor equivalent output capacitance $C_{ce}$, the total capacitance $C_e$ of the oscillating circuit is:

$$\frac{1}{C_e} = \frac{1}{C_{ce}} + \frac{1}{C_1} + \frac{1}{C_2}$$

(2)

Reaction coefficient $F$ is:
Because the junction capacitance of the transistor and $C_2$ are parallel, when capacitance $C_c$ values is larger, the frequency of the exciter circuit will not affected by the junction capacitance. In addition, $C_{ce}$ and $C_2$ are both larger than $C_1$, so the oscillating frequency mainly depends on $C_1$ and $I_0$.

Equation (3) shows that the feedback coefficient will not be influenced when the excitation frequency is changed by adjusting $C_1$ values. In addition, because $f_0$ is almost independent of the transistor equivalent input capacitance and output capacitance, it improves the frequency stability.

3.2. Improvement of Lamp Excitation Circuit

The main problem of Clapp circuit is that the excite current is affected by the temperature sensitivity of the transistor. Considering that the transistor is an active device, the working state and the output of the lamp will be changed when the temperature of the excite circuit or the surrounding environment changes which is mainly the change of light intensity and spectrum distribution.

Zero drift is usually called as temperature drift, the main cause of zero drift is variation of transistor parameters caused by temperature. Therefore, in order to restrain this temperature drift, we adopt temperature compensation measurement in traditional lamp excite circuit. The improved schematic diagram of the lamp excitation circuit is shown in figure 4.

![Figure 4. Improved lamp excitation circuit.](image)

There are two main measurements to restrain the temperature drift. One is to introduce the DC negative-response into the circuit as to add the resistance $R_3$ and $R_4$ in series at the emitter of the transistor. When the temperature increases, the collector current of transistor ($I_C$) increases, and then the emitter current of transistor ($I_E$) increases correspondingly. Therefore, the resistance $R_3$ and $R_4$ increase accordingly. Because $U_{BO}$ basically remains constant and $U_{BE} = U_B - U_E$, the $U_B$ will decrease which leads to a dropping of the base current $I_B$ and $I_C$. As a result, the increase of collector current with temperature almost equal to the decrease of base current. therefore, $I_C$ and $U_{CE}$ are basically unchanged. Similarly, when the temperature decreases, each variable changes in the opposite direction, $I_C$ and $U_{CE}$ are basically unchanged.

The other method is to adopt the temperature compensation by using thermal elements to offset the temperature drift, in which a diode is connected in the bottom of the base circuit, and the temperature compensation is carried out by using the forward characteristics of the diode. When the temperature increases, collector current increases, and then emitter voltage $U_E$ increases. On the other hand, the dropped voltage of diode inevitably decreases, and then $U_B$ decreases. As a result, $U_{BG}$ decreases and collector current $I_C$ decreases.

4. Expeiment

4.1. Current Test
The traditional lamp excitation circuit and the improved lamp excitation circuit are tested separately at different temperatures. The lamp voltage is set to be 17V and 19V respectively. The test results are shown in Figure 5(a) and (b).
As shown in figure 5(a) and (b), the black and red line respectively show the trend of the current changing with temperature in traditional circuit and the improvement of the lamp excitation circuit. It can be seen that the slope of the red curves is obviously smaller than that of black. The current temperature sensitivity of the improved lamp excitation circuit has been significantly improved.

4.2. the lamp voltage test

Test frequency accuracy is conducted by changing the lamp voltage starting from 19V with an decreased step of 0.5V. The black and red line in figure 6 shows the trend of voltage adaptation zone in the original lamp excitation circuit and the improved lamp excitation circuit. The lamp voltage adaptive zone test data are shown in table 1.

![Figure 5. (a) Lamp Voltage 17V (b) Lamp Voltage 19V](image)

Table 1. Debugging record of lamp voltage adaptive zone.

| Voltage change | 19V-18V | 18V-17V | 17V-16V | 16V-15V | 15V-14V | 14V-13V |
|----------------|--------|--------|--------|--------|--------|--------|
| Original circuit | 2.27E-11 | 2.599E-11 | 2.926E-11 | 3.630E-11 | 4.409E-11 | 6.824E-11 |
| Improved circuit | 1.540E-11 | 1.300E-11 | 1.740E-11 | 2.190E-11 | 2.930E-11 | 3.500E-11 |
| promote | 7.32E-12 | 1.30E-11 | 1.19E-11 | 1.44E-11 | 1.48E-11 | 3.32E-11 |

It can be seen from figure 6 that the test curve of lamp voltage adaptation zone becomes flat by adding temperature compensation measurement to the original lamp excitation circuit. It can be seen from Table 1 that the change of frequency stability corresponding to each 1V lamp voltage decreases between 7.32E-12/V and 3.32E-11/V. It can be concluded from the test that the lamp voltage adaptation zone improves obviously with the improvement of lamp excitation circuit. The test results show that the lamp voltage adaptation zone has a direct impact on the temperature coefficient of the physics package. When the test results of lamp voltage adaptation zone become smaller, the
temperature coefficient of physics package decreases obviously, which is helpful to improve the temperature coefficient of rubidium clock and further enhance the long-term frequency stability of rubidium clock.

4.3. temperature coefficient

The temperature coefficient[12] of PP has an important influence on the temperature coefficient of and long-term stability of rubidium atomic frequency standards (RAFS).

The temperature coefficient of PP was tested by changing the temperature of vacuum tank. Test temperature coefficient of physics package is conducted by changing the temperature of vacuum tank, which starts from 32°C with each step of 2°C.

The temperature coefficient test curve of physics package of original lamp excitation circuit and improved lamp excitation circuit is shown in figure 7 and figure 8 respectively. The experimental results of the improved temperature coefficient of physics package in original and the improved circuit are shown in Table 2.

![Figure 7. temperature coefficient of PP](image1)

![Figure 8. temperature coefficient of PP](image2)

Table 2. debugging record of temperature coefficient of physics package.

| Temperature change | 32°C-34°C | 34°C-36°C | 36°C-38°C | 38°C-40°C |
|--------------------|-----------|-----------|-----------|-----------|
| Original           | -5.11E-12/°C | -5.25E-12/°C | -5.11E-12/°C | -4.93E-12/°C |
| improved           | -4.42E-12/°C | -4.80E-12/°C | -4.09E-12/°C | -4.23E-12/°C |
| promote            | 6.90E-13/°C  | 4.50E-13/°C  | 1.02E-12/°C  | 7.00E-12/°C  |

As can be seen from the above table, the temperature coefficient of the physics package in each temperature section decreases. The temperature coefficient decreases by 6.90E-13/°C when temperature of the vacuum tank rises from 32°C to 34°C. The temperature coefficient decreases by 4.50E-13/°C when the temperature of vacuum tank rises from 34°C to 36°C. The temperature coefficient decreases by 1.02E-12/°C when temperature of the vacuum tank rises from 36°C to 38°C. The temperature coefficient decreases by 7.00E-13/°C when temperature of the vacuum tank rises from 38°C to 40°C.
5. Conclusion
The improved lamp excitation circuit can obviously improve the temperature coefficient of the physics package of the rubidium clock, and the influence of temperature on the frequency stability of the physics package is reduced, which is helpful to improve the temperature coefficient and long-term frequency stability of the whole rubidium clock. The lamp oscillation circuit has a great influence on the temperature coefficient of the physics package, to reduce the temperature coefficient of the physics package and then improve the frequency stability of rubidium clock. A new improved lamp excitation circuit has been proposed by analyzing the principle of the lamp excitation circuit. The rationality and feasibility of the improved circuit are proved by the experiment of lamp voltage adaptive zone and temperature coefficient of the physics package. Through the specific experimental, it is shown that the lamp excitation circuit has a great influence on the voltage adaptation zone and temperature coefficient of the physics package. The improved circuit in this paper can help to improve the performance of the physics package, and can be applied for improving the temperature coefficient and long-term frequency stability of the rubidium atomic clock.

References
[1] Hao Q, Li W, He S, et al. A physics package for rubidium atomic frequency standard with a short-term stability of $2.4 \times 10^{-13} \tau^{-1/2}$[J]. Review of Scientific Instruments, 2016, 87(12):123111.
[2] Dupuis R T, Lynch T J, Vaccaro J R. Rubidium Frequency Standard for the GPS IIF program and modifications for the RAFSMOD Program[C]// IEEE International Frequency Control Symposium. IEEE, 2008.
[3] Camparo J C, Hagerman J O, Mcclelland T A. Long-term behavior of rubidium clocks in space[C]// European Frequency & Time Forum. IEEE, 2012.
[4] V.Formichella, J. Camparo, and P. Tavella, On-orbit GPS RAFS lamp light variations: Statistics of lamp light jump. in Proc. 2017 Precise Time and Time Interval Meeting, ION PTTI 2017 (The Institute of Navigation, Manassas, VA, 2017)pp.291-298
[5] Camparo J C, Moss S C, Lalumondiere S D. Space-system timekeeping in the presence of solar flares[J]. IEEE Aerospace and Electronic Systems Magazine, 2004, 19(5):3-8.
[6] Camparo J C. The Rubidium Atomic Clock and Basic Research[J]. Physics Today, 2007, 60(11):12.
[7] Dingjan J, B. Darquié, Beugnon J, et al. A frequency-doubled laser system producing ns pulses for rubidium manipulation[J]. Applied Physics B (Lasers and Optics), 2006, 82(1):47-51.
[8] Camparo J C, Mackay R. Spectral mode changes in an alkali rf discharge[J]. Journal of Applied Physics, 2007, 101(5):27-1022.
[9] W J Riley,"A Rubidium clock for GPS", in proceedings of the 13th Precise Time and Time Interval (PTTI) Applications and Planning Meeting (1982)
[10] Li W, Kang S, Ming G, et al. Demonstration of a Physics Package with High SNR for Rubidium Atomic Frequency Standards[C]// China Satellite Navigation Conference (CSNC). 2013.
[11] Singh S, Ghosal B, Saxena G M. A New Rb Lamp Exciter Circuit for Rb atomic clocks and Studies on, Transition from Ring to Red mode[J]. Physics, 2010.
[12] Feng H, Cui J Z, Tu J H. An Enhanced Physics Package Used in Rubidium Atomic Frequency Standards[J]. Applied Mechanics and Materials, 2014, 687-691:3179-3182.