Investigation on Physics Package with Slotted-tube Microwave Cavity for Rubidium Atomic Frequency Standard

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Abstract—**In this paper, a unique physics package using slotted-tube cavity for rubidium atomic frequency standard has been described, including its structure, characteristics and performances. Due to the advantages of high cavity Q factor, large microwave filling factor, stable light intensity and so on, the physics package has obtained a high signal-to-noise ratio. The test results suggest that RAFS using this physics package has achieved an excellent short-term frequency stability of 1.2E-12 / $\tau^{1/2}$ (1s≤τ≤100s).**

I. INTRODUCTION

Ten years ago, a new type of magnetron microwave cavity [1] for atomic frequency standard was invented in our laboratory, and it was named as the slotted-tube cavity [2]. Based on this microwave cavity, we developed a compact physics package for rubidium atomic frequency standard (RAFS).

The paper will describe investigations on this novel physics package (PP), including its structure, characteristics and performances. We'll discuss PP signal-to-noise ratio (SNR), and its affect to RAFS frequency stability. In order to improve RAFS stability, we'll search the approaches to enhance physics package SNR.

Our physics package is mainly composed of cavity-cell assembly, spectral lamp, microwave frequency multiplier, C-field coil, magnetic shield and temperature controller. The cavity-cell assembly employs a patented slotted-tube microwave cavity, and uses the separated filter technique (SFT). This cavity-cell assembly has a number of merits, such as compact structure, low temperature coefficient (TC), low light shift, as well as high SNR.

We have made a lot of investigations and experiments on the physics package. The test results suggest that RAFS using this physics package has realized short-term frequency stability of 1.2E-12 / $\tau^{1/2}$ (1s≤τ≤100s).

II. STRUCTURE OF PHYSICS PACKAGE.

The novel physics package of RAFS is mainly composed of cavity-cell assembly, spectral lamp, microwave frequency multiplier, C-field coil, magnetic shield and temperature controller. Fig. 1 illustrates the structure of physics package, which excludes the module of C-field current supply and temperature controller circuit for the sake of simplification. The core element of PP is cavity-cell assembly, therefore we firstly will describe the structure of cavity-cell assembly.

A. The Cavity-cell Assembly

The cavity-cell assembly adopts a patented slotted-tube microwave cavity, and uses the separated filter technique [2]. The structure of cavity-cell assembly is shown in Fig.2. The whole assembly consists of many parts, including a cylindrical cavity body, a slotted-tube, a dielectric ring, an absorption cell, a filter cell, a top cap, a photocell, a coupling loop, a step recovery diode, two thermistors, a heating transistor and C-field coil.

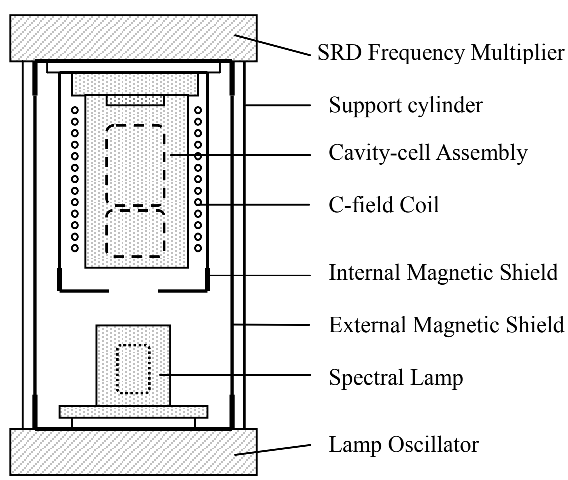

Fig.1. Physics package with slotted-tube cavity drawing

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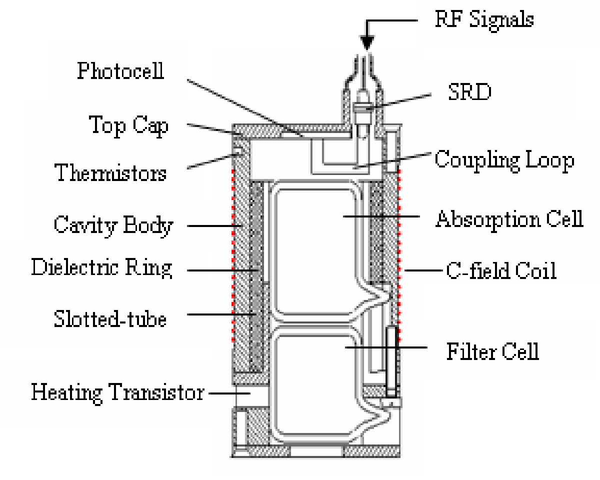

Fig.2. Cavity-cell assembly drawing

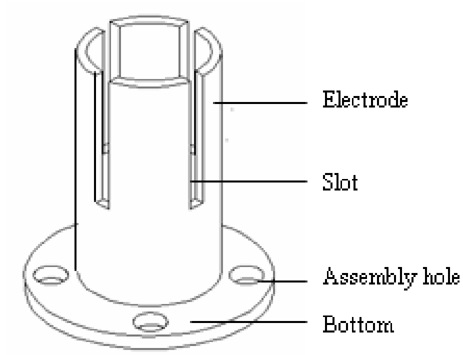

Fig.3. Slotted-tube drawing

The slotted-tube is a tubular structure shown in Fig.3. On the upper part of the structure there are four equally spaced slots. The slotted-tube and the bottom cap of the cavity are made as a whole. The slotted-tube is fixed to the cavity body through the screws. The dielectric ring is inserted between the slotted-tube and the cavity body. Although dielectric ring itself is not necessary to construct the cavity, but it can increase the effective volume, thus reduce the actual volume of the cavity. The absorption cell is filled with ^{87}Rb isotope and some buffer gases, while the filter cell is filled with ^{85}Rb isotope and buffer gas of argon. Both cells are inserted into the slotted-tube. In order to realize a good mechanical and thermal stabilization, the cavity body, the dielectric ring, the slotted-tube and the two glass cells are designed and assembled together tightly.

The photocell is adhered to the inner surface of the top cap, it is used as a photo detector. The coupling loop and a step recovery diode (SRD) are also installed on the top cap. They are used to input RF signals and to realize microwave frequency multiplication.

The cavity-cell assembly can work well under the temperature of 66～70℃, therefore it needs some kind of heating and temperature controlling device. A power transistor is installed on the bottom of slotted-tube, used as a heater. Two thermistors are embedded in the upper wall of cylindrical cavity body, one is for temperature control, and another is for temperature test.

The C-field coil is reeled on outer surface of the cavity body, providing a homogeneous magnetic field with direction parallel to the axis of cavity.

B. The Spectral Lamp

The spectral lamp is a RF-discharge lamp for optical pumping in the RAFS. Its RF-exciter is a typical Clapp oscillator, operating around frequency of 110MHz, and providing a RF-exciting power of 0.5W via a coupling inductor which is rolled on the bulb. The lamp bulb is filled with ^{87}Rb isotope and noble gas of argon. The working temperature of lamp is about 132℃. The voltage and current of lamp oscillator are carefully regulated, it can produce a stable RF-exciting power to yield a consistent light intensity. The lamp operates in a good spectral mode, so-called ring-mode, providing a stable emission spectrum.

C. The Microwave Frequency Multiplier

The microwave frequency multiplier (MFM) is a typical SRD high-order harmonic frequency multiplier to complete 76th frequency multiplication from 90MHz to 6840MHz, meanwhile it also plays a role of frequency mixer to make frequency subtraction between 6840MHz and 5.3125MHz. Finally it will produce 6834.6875MHz microwave field in the cavity for exciting Rb atom hyperfine transition.

The input coupling, matching, and SRD bias circuits of MFM are located in the screen chamber, over the cavity-cell assembly. Since the step recovery diode (SRD) is sensitive to temperature, it is installed on the top cap of cavity, there it can benefit from stable temperature environment of the cavity.

The microwave frequency multiplier has no independent resonating cavity, but shares the same slotted-tube cavity with Rb atom transition microwave resonator. It will also benefit from low temperature coefficient (TC) of the cavity frequency, yielding a stable 6834.6875MHz microwave signal.

III. MAIN PERFORMANCES

A. Stability and Signal-to-Noise Ratio

The time-domain frequency stability of the passive RAFS can be expressed as following:

$$\sigma_y(\tau) = \frac{k}{(\nu_0 / \Delta\nu) \bullet SNR} \tau^{-1/2}$$

Where $\sigma_y(\tau)$ is the Allan deviation, ν_0 is ^{87}Rb hyperfine transition frequency of 6834.6xxxMHz, $\Delta\nu$ is the transition line-width, *SNR* is the signal-to-noise ratio of the physics package, k is a constant coefficient of 0.1～0.2, while τ is the sample average time [3] [4].

Usually, for a conventional gas-cell RAFS, the reasonable line-width $\Delta\nu$ is of the order of about 400Hz. Therefore, the stability $\sigma_y(\tau)$ is primarily determined by *SNR* when τ is given. It's obvious that increasing *SNR* will make the stability of RAFS to be improved.

As a type of magnetron microwave cavity, the slotted-tube cavity also has a microwave field distribution of the quasi H_{011} mode. One of the advantages of the H_{011} cavity is high Q factor. According to experimental test results, the loaded Q factor of slotted-tube cavity can reach a considerable value of 400～450.

Another feature of the slotted-tube cavity-cell assembly is that it can obtain a large microwave filling factor. Our investigations show that the microwave filling factor depends on the number of slots of the slotted-tube cavity.

The slot number was taken as 4 in the prototype design of our physics package, as shown in Fig.3. Both theoretical analyses and experimental measurements have suggested that increasing the slot number will lead filling factor to get larger.

At present our cavity-cell assembly has employed the cavity with slot number of 8. This change results in that stability of RAFS is significantly improved. It is because the larger microwave filling factor is, the more atoms will participate in microwave transition, thus the SNR is enhanced, and the stability can be improved finally.

B. Light Shift and Temperature Coefficient

Light shift (LS) and temperature coefficient (TC) are the most significant factors that affect the long-term stability of a RAFS. Here TC refers to the fractional frequency change of a RAFS caused by cavity temperature change. The SFT design of the physics package enables us to deal with the gas parameters of absorption cell and filter cell separately, and buffer gas pressures in both cells can be optimized for the minimum LS and TC. The test results of

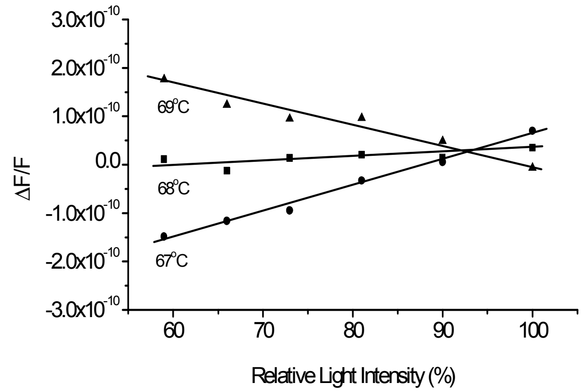

Fig.4. Test results of the LS and TC experiments

LS and TC experiments are shown in Fig.4. Each curve in Fig.4 refers to a different cavity temperature. The cross point of the 3 curves implies that there exists a condition in which the frequency of the RAFS is not sensitive to cavity temperature and light intensity. This condition corresponds to the cavity temperature of about 68°C, and the relative light intensity of 90%, and it is so-called zero light shift (ZLS) point. Further analyses and calculations indicate that under this condition, LS is 7E-12 / 10%, and TC is 1.5E-11 / °C. The TC is obtained in the cavity temperature region of 67～69 °C [5].

IV. STABILITY TEST AND ANALYSIS

To evaluate performance of the developed physics package, we have tested the short-term frequency stability of a RAFS which employed the physics package. The measured results of Allan deviation are showed in Fig.5. It shows that short-term stability of 1.2E-12 / $\tau^{1/2}$ (1s≤τ≤100s) has been achieved. This excellent stability performance of

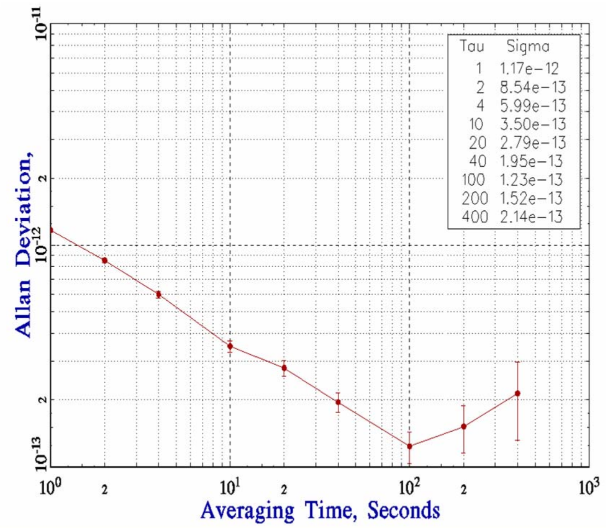

Fig.5. Short-term stability of RAFS with developed physics package

RAFS is due to high SNR of the developed physics package. The reference source in the stability test is an ultra-stable 8607 BVA crystal oscillator. The 8607 crystal oscillator has outstanding short-term stability of 1E-13 for sample times of 1s～100s. While, its stability will become worse for sample times of $\tau \geq 100$s, due to aging of itself, and this is the main cause of the RAFS stability test result declining for $\tau \geq 100$s in Fig.5.

Further investigations on the physics package with slotted-tube cavity are going on. There will be potential for improving its performance. First, the microwave filling factor of cavity still can be enlarged by increasing the slot number properly. Second, the spectrum of pumping light might be purified by installing an optical filter between lamp and cavity-cell assembly, then reducing the shot noise of photodetector signal. Both the improving measures described above will possibly enhance the SNR of the whole physics package, therefore the RAFS could obtain more excellent frequency stability.

In addition, we will pay more attention to the performance of RAFS long-term stability. It will require that we have to optimize LS and TC of the physics package more carefully. Of course, the treatments of the electronics of RAFS are also very important. We hope that RAFS using the developed physics package could achieve the long-term frequency stability of 5E-14 ($\tau \geq 10000$s), or even better.

V. CONCLUSION

We have made a lot of investigations and experiments on the unique physics package with slotted-tube cavity. Due to various advantages of high cavity Q factor, large microwave filling factor, stable light intensity, good lamp spectral mode and so on, the physics package has obtained a considerable high SNR.

The test results suggest that RAFS using this physics package has realized short-term frequency stability of 1.2E-12 / $\tau^{1/2}$ ($1s \leq \tau \leq 100s$), it could be a good candidate for high performance RAFS. Nevertheless, we believe that the physics package SNR can be further optimized through some feasible improvements. It is worth expecting that the short-term frequency stability of our RAFS will reach the level of ＜1E-12 / $\tau^{1/2}$ ($1s \leq \tau \leq 100s$) in the near future.

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