A Downsized Microwave Cavity for the Rubidium Vapor Cell Frequency Standard

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Abstract: **We describe the design of a miniature microwave cavity for the rubidium vapor cell frequency standard with an integrated filter-absorption cell. The three-dimensional simulation and mechanical structure of a dielectric-loaded cavity operated in the TE_{111} mode is also presented. As a result of this compact design, the physics package volume is reduced to 38 cm^3, and the resulting size of the whole device is 216 cm^3 (3.7cm×7.7cm×7.6cm).**

Key word: Rubidium vapor cell frequency standard; Downsized microwave cavity; Quality factor; Filling factor

Introduction

Among the various atomic frequency standards, the rubidium frequency standard (RFS) offers the best combination of frequency stability, size, weight, lifetime and cost for many commercial and military applications, especially for the vehicle, marine, airplane and satellite.

Up to now, the frequency stability of on-board miniature RFS has already been close to that of miniature cesium frequency standard, but the size of RFS is much less than that of the cesium frequency standard.

We have developed a miniature RFS with the size is of about 220 cm^3.

The compact design of the RFS includes the miniaturization of the physics package and electronics. The techniques of the downsized physics package involve mainly the usage of an integrated filter-absorption cell and reduction of the size of the microwave cavity. This paper focuses on the design and development of the downsized microwave cavity of RFS. The miniature cavity-cell assembly based on the compact microwave cavity is also presented.

Main Features of the Microwave Cavity

The microwave cavity is used essentially for two purposes: providing the microwave field interrogating the ^{87}Rb atom in the cell and using as the band-pass filter for the microwave frequency multiplier and mixer.

To satisfy the requirements of the miniature rubidium frequency standard, the microwave cavity designer should take four factors into account. Firstly, it is necessary to generate the microwave magnetic field parallel to the quantization axis in the microwave resonant region. Secondly, the quality factor of the cavity is appropriately chosen. Thirdly, the resonant frequency of the cavity is close to 6834MHz, corresponding to the clock transition between the hyperfine levels (F=1, m_F=0), and (F=2, m_F=0). Last, the cavity size should be as small as possible.

The Cavity Mode

The choice of a proper cavity mode is

important in realizing a downsized cavity. The microwave cavity for the RFS is usually operated in three modes: TE_{011}, TE_{111} and TE_{101} [1]. Among the existing cavities, the quality factor of cavity operated in the TE_{011} mode is maximal, and the region where the microwave magnetic field intensity is strongest is just the center of the light-microwave resonance in the integrated cell, so the filling factor is highest. Unfortunately, this mode at the rubidium resonance frequency of 6834MHz requires a minimum diameter of about 70mm, and it is impossible to substantially reduce this size by a dielectric filling. And TE_{011} mode is not the dominant mode of a cylindrical cavity resonator. Therefore, this type of cavity is not suited to the cavity miniaturization. The case of the rectangular cavity operated in mode TE_{101} is slightly different from other cavities since a dielectric slab is inserted along one of its sides in order to eliminate the variation of the stimulating field along the X-axis. The dimension of this cavity is minimal among the three mode cavities, but the filling factor is so small, that it is rarely used in the RFS.

Considering both the filling factor and the size of the cavity together, we select the cylindrical cavity operated in the mode TE_{111}, which is the dominant mode of a cylindrical cavity resonator.

Design of the Downsized Cavity

So far, two kinds of cavities have been used in the miniature RFS: magnetron-type cavity and dielectric-loaded cavity. The former includes the magnetron cavity, the slotted tube cavity and the loop-gap cavity etc. To miniaturize the size of the cavity, the inductive-capacitive structure is adopted in the magnetron cavity and the slotted tube cavity to adjust widely the resonance frequency. For example, in the magnetron cavity, the inductive-capacitive structure is a tubular one formed by a set of electrodes that are coaxial and equally spaced. The gaps between the electrodes are called slots. Electrodes act as inductors and slots act as capacitors. According to the magnetron theory, the resonance frequency is mainly determined by the inductance and the capacity of the inductive-capacitive structure because the latter parameters influence the distribution and intensity of the magnetic field in the region of the integrated cell. The geometric structure of electrodes and slots are then very critical to the resonance frequency of the cavity. Therefore, this kind of cavity has a complicated structure and high manufacturing cost [2].

Considering the reasons mentioned above, we choose a dielectric-loaded cavity operated in the mode TE_{111}. The relationship between the average dielectric constant ε_r , the cavity length *l*, cavity radius *a*, and resonance frequency *f* of the cylindrical cavity without the cell and holes is expressed as [3]

$$\frac{\varepsilon_r \mu_r f}{c} = (\frac{1}{2l})^2 + (\frac{1}{3.41a})^2 \qquad (1)$$

Where $\mu_r = 1$ and $c = 3\times10^8 m/s$.

Figure 1 shows the variations of the radius *a* versus the length *l* of the cavity with different value ε_r at the resonance frequency of 6834MHz.

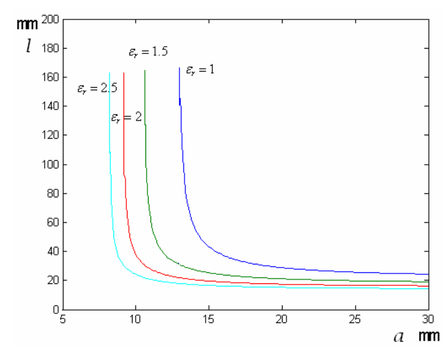

Figure 1 Variations of the cavity radius *a* versus the cavity length *l* with different value ε_r at the resonance frequency of 6834MHz

From Figure 1 we can see that a cavity with a volume of 10 cm^3 at the resonance frequency of 6834MHz is expected to be realized by selecting the cavity-loaded dielectric with of ε_r 2.5 in the whole cavity. While the cavity of a RFS must contain an integrated cell, the value of the dielectric ring between the cavity body and the integrated cell should be larger than 2.5. Besides fairly larger value of ε_r , the cavity-loaded dielectric material should possess: lower dielectric loss and better coefficient of heat conductivity.

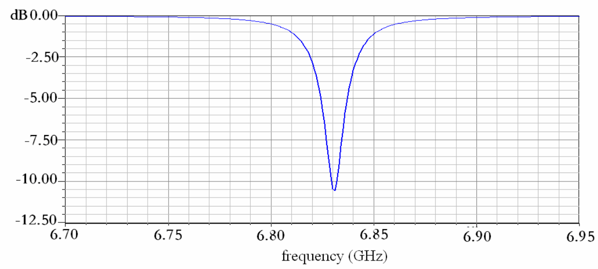

Figure 2 Simulation of the cavity response

Given the values of electrical parameters and the shapes of the dielectric ring and the integrated cell we have obtained the distribution of microwave magnetic field in the cavity and the cavity response through a high frequency three-dimensional numerical simulation and experiments. When the internal diameter of the cavity is 20 mm and the length is 26 mm, the quality factor is about 450 at the resonant frequency of 6.83GHz (shown in Figure 2).

Figure 3 and Figure 4 show the simulation results of microwave magnetic field in the cavity. It can been seen that the distribution of the microwave magnetic field in the cavity is very similar to the TE_{111} mode, the microwave signal is injected into the cavity by a microwave coupling loop, and the direction of the microwave magnetic field is almost parallel to the direction of static magnetic field, which meets the requirement of the system.

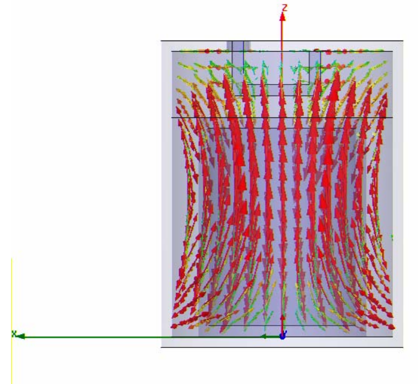

Figure 3 Distribution of microwave magnetic Field

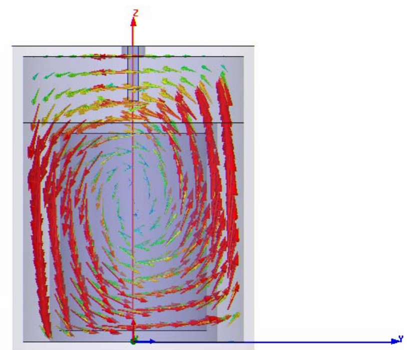

Figure 4 Distribution of microwave magnetic Field

Figure 5 shows the schematic diagram of the miniature cavity-cell assembly based on the downsized microwave cavity. From Figure 5, we can know that the miniature cavity-cell adopts two-cell scheme. The photocell is installed on the inner surface of the upper cap. To realize frequency multiplier in the resonance cavity, the step recovery diode (SRD) for frequency multiplication is installed the upper cap. One terminal of SRD is connected with the RF signal (90MHz) and the synthesizer signal (5.3125MHz), and the other is linked to the ground through the coupling loop, accordingly, the microwave interrogation field can be established in the cavity. The C-field coil is surrounded on the outer surface of the cavity body, the magnetic shield is installed at the outside of the cavity, and the transistor used as a heating component is fixed at the top of the magnetic shield. To ensure good mechanical and thermal stabilities, the cavity body, the dielectric ring and the integrated cell are linked up tightly, the magnetic shield, the cavity cap and the cavity body are fasten together.

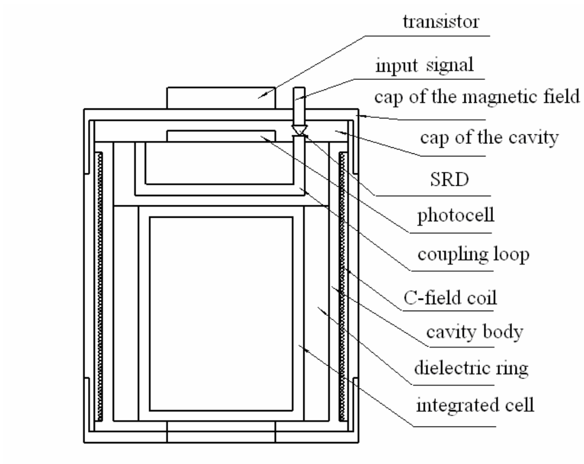

Figure 5 Schematic diagram of the cavity-cell assembly

The whole size of the physics package, which contains the cavity-cell assembly, the rubidium-lamp exciter and the quartz oscillator, is reduced to 38 cm^3 (the 7.2cm length, and 2.6 cm diameter).

Conclusion

Through the dielectric-loaded cylindrical cavity operated in the mode TE111, a miniature cavity-cell assembly has successfully developed. As a result, the size of the whole device is 3.7cm(H) ×7.7cm (L)× 7.6cm(W)(216cm3 volume). At the same time, the short-term stability is superior to $3\times E\text{-}11/\sqrt{\tau}$ through adjusting and optimizing the other parameters of the physics package and the electronics.

Reference

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