Study of Sapphire Loaded H-Maser in Shanghai Observatory

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Abstract— Sapphire loaded cavity for active H-maser was designed to minimize the mass and volume of the traditional active H-maser. The ability of sapphire loaded cavity to achieve self-oscillation was calculated. Then we made the experiment for sapphire loaded cavity in traditional H-maser as bed. The signal was found with oscillation power of −102.93 dBm while the beam flux is about 1.1 mA. For the temperature coefficient of sapphire loaded cavity is too high, the way to compensate the temperature-coefficient was studied. The region of "zero temperature coefficient point" was discussed.

1. INTRODUCTION

Nowadays with the development of SLR, VLBI etc, H masers as the most stable frequency sources readily available were used abroad. However traditional active H masers are heavy and large in size. Can't be used as mobile instruments. Sapphire loaded cavity can solve this problem efficiently. It can reduce the size and weight of the traditional active H maser without degrading the excellent stability of the traditional masers. Many analyses and different design were reported [1–3]. For many years, ShangHai Observatory was studying on active and passive H masers. The study on sapphire loaded H maser has just begun. We solved the Maxwell's equation for TE_{011} mode in sapphire loaded cavity calculated the Q, η' and temperature coefficient for the cavity, then we judged if it could achieve self- oscillation. With the sapphire loaded cavity we got a signal. To sapphire loaded cavity's high temperature coefficient problem we discussed the way to reduce the temperature coefficient. And we found the region to find "zero temperature coefficient".

2. THEORY ANALYSIS AND SIMULATION

The structure of the sapphire loaded cavity is as Fig. 1. We can solve the following Eq. (1) to determine the dimensions of the cavity for 1.42 G in TE_{011} mode. We need the optic axis of the sapphire crystal just parallel to Z axis. Then only the permittivity perpendicular to optic axis of the sapphire crystal could judge the frequency of the cavity for TE_{011} mode. The permittivity of sapphire crystal which perpendicular to optic axis is 9.36 (note $\varepsilon_r = 9.36$). We can write $\mathbf{a/b}$ as ρ_1. When the out side metal cavity size **a, h** was fixed, then by $\rho_1\mathbf{b}$ was fixed, For the cavity frequency was fixed, by Eq. (1) **c** was fixed. The whole cavity dimension was fixed.

$$\frac{\gamma_2\left[A_2 J_0\left(\gamma_2 b\right)+B_2 N_0\left(\gamma_2 b\right)\right]}{\left[A_2 J_1\left(\gamma_2 b\right)+B_2 N_1\left(\gamma_2 b\right)\right]}=\frac{\gamma_0\left[A_3 J_0\left(\gamma_0 b\right)+B_3 N_0\left(\gamma_0 b\right)\right]}{\left[A_3 J_1\left(\gamma_0 b\right)+B_3 N_1\left(\gamma_0 b\right)\right]} \tag{1}$$

$$\begin{cases} A_2=\left(\gamma_2/\gamma_0\right) J_1\left(\gamma_0 c\right) N_0\left(\gamma_2 c\right)-J_0\left(\gamma_0 c\right) N_1\left(\gamma_2 c\right) \\ B_2=J_0\left(\gamma_0 c\right) J_1\left(\gamma_2 c\right)-\left(\gamma_2/\gamma_0\right) J_0\left(\gamma_2 c\right) J_1\left(\gamma_0 c\right) \end{cases} \tag{2}$$

$$\begin{cases} A_3=-\frac{\pi}{2}\gamma_0 a N_1\left(\gamma_0 a\right) \\ B_3=\frac{\pi}{2}\gamma_0 a J_1\left(\gamma_0 a\right) \end{cases} \tag{3}$$

$$\begin{aligned} &\gamma_i^2=\omega^2\mu_0\varepsilon_0\varepsilon_i-\pi^2/h^2 \\ &\gamma_1=\gamma_3=\gamma_0 \\ &\gamma_2^2=\gamma_1^2=\gamma_3^2=\gamma_0^2=\omega^2\mu_0\varepsilon_0-\pi^2/h^2 \end{aligned} \tag{4}$$

We got a dimensions $a = 87.5$ mm $b = 43.75$ mm $c = 36.68$ mm $h = 162.9$ mm. Then we used FEM simulation software to simulate the sapphire loaded cavity. The E field in Fig. 2 and Fig. 3 was plotted to recognize the TE_{011} mode. We got the $w = 1.4358$ GHz, unloaded $Q = 54727$.

The FEM software doesn't have the ability to recognize the mode TE_{011}, so we use the E field above to recognize the TE_{011} mode.

After simulation we need to judge if the cavity could achieve H maser self-oscillation. We can use S parameter qualification. If $S > 5900$, the cavity could achieve self-oscillation. S parameter is scatter parameter. It is defined by Eq. (5)

$$S = Q_L\eta' \tag{5}$$

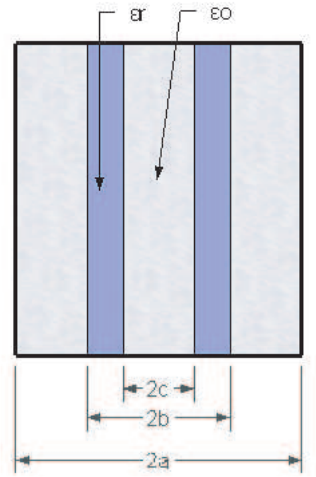

Figure 1: Structure of a sapphire loaded cavity.

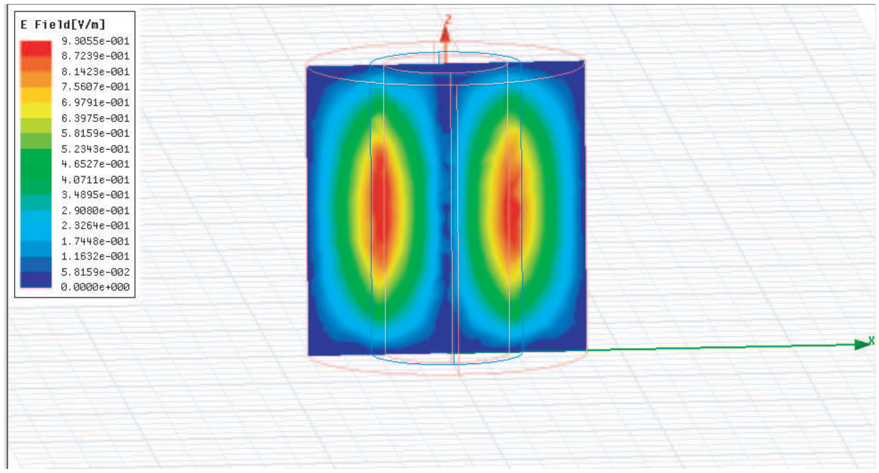

Figure 2: Recognized electric field of the cross section the cavity for TE_{011}.

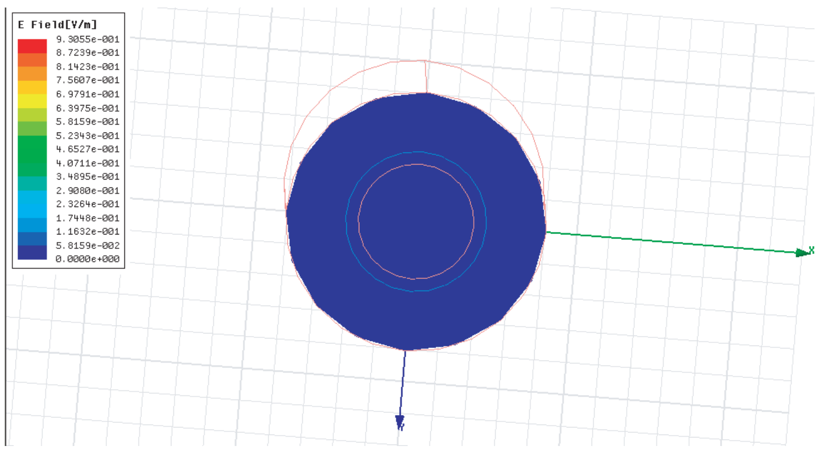

Figure 3: Recognized electric field of ends of of the cavity for TE_{011}.

Q_L is loaded Q. η' is the filling factor of the cavity. The loaded Q is 45000 (Fig. 4) η' was calculated for the cavity by Eq. (5) using FEM software $\eta' = 0.523$. Then We can get the $S = 23535 > 5900$. The cavity can achieve self-oscillation

$$\eta' = \frac{V_b}{V_c}\frac{\langle H_z\rangle_b^2}{\langle H^2\rangle_c} = \frac{1}{V_b}\frac{\left[\int\limits_b H_z dV\right]^2}{\int\limits_c H^2 dV} \tag{6}$$

3. THE EXPERIMENT OF SAPPHIRE LOADED CAVITY

In order to confirm if the sapphire loaded cavity could sustain self-oscillation. We did a experiment on the cavity. We use traditional active H maser (shao-4) as our bed for experiment. That's a convenient way to reduce the cost of the experiment. We designed a equipment to fix the sapphire loaded cavity in the traditional H maser's vacuum system. The cavity frequency and loaded Q can be measured by net analyzer (Fig. 4) and with the flux 1.1 mA $\sim$ 1.2 mA we got a signal of -102.9 dBm (Fig. 5).

And then we test the stability of the maser we got the 1s 9.8×10^{-13}, 10 s 1.33×10^{-13}. For the equipment which fix the cavity still have stress problem, and the temperature control system of the traditional H maser can't meet the need of sapphire load cavity. (Temperature coefficient of the sapphire loaded cavity is much lager than the traditional cavity). We got a very bad long term stability.

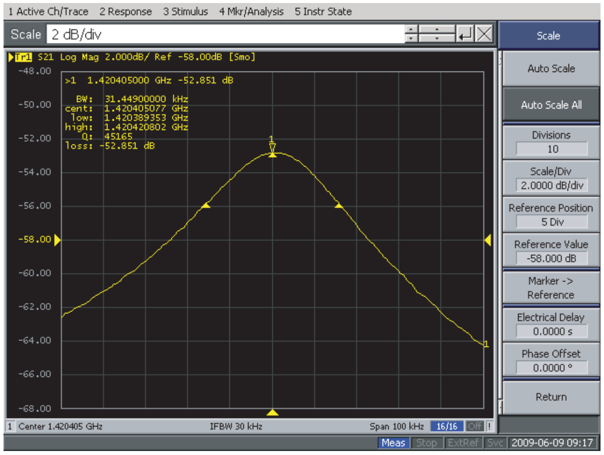

Figure 4: Measured loaded Q and Cavity frequency of the sapphire loaded cavity.

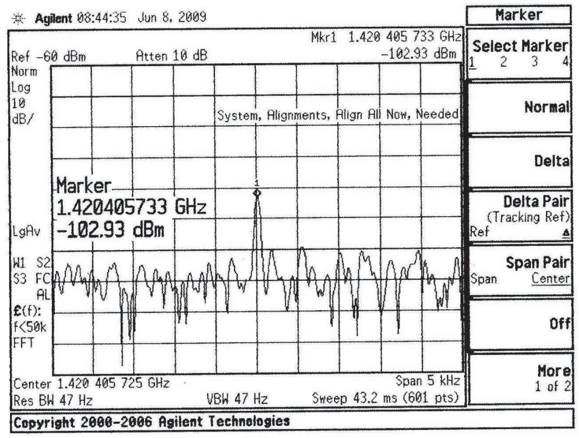

Figure 5: Self-oscillation signal of sapphire loaded H maser Temperature-compensation of the sapphire loaded cavity.

4. TEMPERATURE-COMPENSATION OF THE SAPPHIRE LOADED CAVITY

As we mentioned above, temperature coefficient of the sapphire loaded cavity is about $-55\,\mathrm{kHz}/^\circ\mathrm{C}$. It's much lager than the traditional cavity. There are two ways to reduce the bad effect on stability caused by high temperature coefficient. One is to build a very precisely temperature control system, the other is to compensate the temperature frequency shit of the sapphire loaded cavity. Our analysis is mainly on reducing the temperature coefficient of the cavity.

The sapphire loaded cavity's high temperature coefficient is the result of high temperature shit of the permittivity of sapphire (Al_2O_3). If we use another crystal which have the opposite temperature coefficient of permittivity to compensate the sapphire loaded cavity. We can got a low temperature coefficient cavity. We used the method mentioned in [4] to calculate the temperature coefficient. The equation of the temperature coefficient is as follows.

$$\frac{1}{f}\frac{\partial f}{\partial T}=\frac{1}{f}\left[\frac{\partial f}{\partial \varepsilon_{ts}}\frac{\partial \varepsilon_{ts}}{\partial T}+\frac{\partial f}{\partial \varepsilon_{tc}}\frac{\partial \varepsilon_{tc}}{\partial T}+\frac{\partial f}{\partial d}\frac{\partial d}{\partial T}+\frac{\partial f}{\partial h_1}\frac{\partial h_1}{\partial T}+\frac{\partial f}{\partial h_2}\frac{\partial h_2}{\partial T}\right] \tag{7}$$

$$\frac{1}{f}\frac{\partial f}{\partial T}=A_{r1}\tau_{r1}+A_{r2}\tau_{r2}+A_d\tau_{\alpha1}+A_{h1}\tau_{\alpha2}+A_a\tau_c+A_{h2}\tau_c \tag{8}$$

$$A_{r1}=\frac{\varepsilon_{ts}}{f}\frac{\Delta f}{\Delta\varepsilon_{ts}}\quad A_{r2}=\frac{\varepsilon_{tc}}{f}\frac{\Delta f}{\Delta\varepsilon_{tc}}\quad A_d=\frac{d}{f}\frac{\Delta f}{\Delta d}\quad A_a=\frac{a}{f}\frac{\Delta f}{\Delta a}$$

$$A_h=\frac{h}{f}\frac{\Delta f}{\Delta h}\quad \tau_{r1}=\frac{\Delta\varepsilon_{ts}}{\varepsilon_{ts}\Delta T}\quad \tau_{r2}=\frac{\Delta\varepsilon_{tc}}{\varepsilon_{tc}\Delta T}\quad \tau_{\alpha1}=\frac{\Delta d}{d\Delta T}\quad \tau_{\alpha2}=\frac{\Delta h_1}{h_1\Delta T}$$

$$\tau_c=\frac{\Delta a_1}{a\Delta T}=\frac{\Delta h_2}{h_2\Delta T}$$

τ_{r1}: the permittivity shit with temperature of sapphire (Al_2O_3),

τ_{r2}: the permittivity shit with temperature of compensation crystal,

$\tau_{\alpha1}$ $\tau_{\alpha2}$: the radial and axes, expansion coefficient of the sapphire (AL_2O_3),

τ_c: the expansion coefficient of Ti.

We used $SrTiO_3$ to compensate the sapphire crystal for its high permittivity, which is 300, low dielectric loss, which is $5\times10-4$ and opposite permittivity shit with temperature. The Fig. 5 shows the compensation results of our calculation for sapphire loaded cavity with different dimensions.

From Fig. 6, we notice that the effect of compensation arose with ρ_1. And with $a=87.5$ we could find a zero temperature coefficient point between $\rho_1=0.54$ and 0.56. Also we can find another region where zero temperature coefficient point could be found by fixing ρ_1 to 0.56, taking **a** between 87.5 mm and 85 mm. We took ρ_1 rage form 0.4 to 0.6 because Q and η' of this region is better.

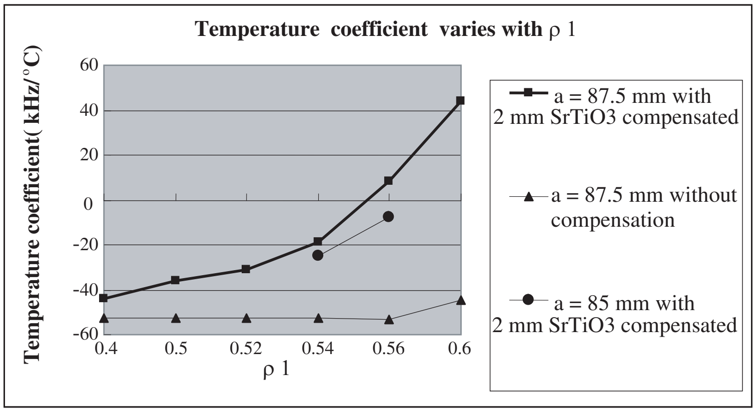

Figure 6: Temperature coefficient varies with ρ_1.

5. CONCLUSION

Small size sapphire loaded cavity for H maser has been analyzed. Its ability to sustain self-oscillation has been confirmed both on theory and experiment. For the temperature coefficient of the sapphire loaded cavity is to high, method of compensation with $SrTiO_3$ was discussed.

REFERENCES

1. Morikawa, T., K. Takahei, M. Uehara, K. Mori, and M. Tsuda, "Design optimization of a sapphire loaded cavity for a spaceborne hydrogen mase," *Proc. of 14th EFTF*, 462–465, 2000.
2. Wang, N.-R., T.-Z. Zhou, and L.-S. Gao, "Recent progress on a sapphire loaded microwave cavity for compact hydrogen masers," *Frequency Control Symposium*, China, 144–147, 2008.
3. Zivanov, S., H. Schweda, D. Goujon, D. Gritti, and G. Perruchoud, "Physics package of the 35 kg active hydrogen maser for the ACES mission of ESA," *Frequency Control Symposium, Joint with the 21st European Frequency and Time Forum*, 637–641, 2007.
4. Yu, C., "Frequency-temperature analysis of sapphire ring dielectric-loaded cylindrical cavity in hydrogen maser atomic frequency standard," *Asia-Pacific Radio Science Conference*, 13–16, 2004.