Investigations on perturbations of microwave dielectric resonator thermometer

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Abstract

Investigations of antenna probe length, antenna-dielectric distance, cavity filling and humidity on microwave resonator thermometer with respect to Q, spurious mode depression, coupling strength, accuracy, shock resistance or sensitivity were carried out in order to improve the whispering-gallery mode thermometer (WGMT) performance. Significant improvement of Q and depression of spurious mode coupling were obtained when the antenna length was reduced. It also turns out that the Q and spurious mode coupling strength vary with the distance between dielectric and antenna pin, as well under appropriate antenna length. Filling the cavity with nitrogen increases coupling strength but decrease frequency-temperature sensitivity compared to a vacuum-pumped cavity. Besides, the microwave resonator sensitivity to air humidity was also investigated in the paper.

Keywords: antenna length, antenna-dielectric distance, cavity filling, humidity, dielectric resonator thermometer, perturbation

1. Introduction

The whispering-gallery mode (WGM) is a stable, high quality factor (Q) resonance mode which travels along the periphery of a dielectric by total internal reflection. The WGM principle is one of the most sensitive and accurate sensing methods from the microwave to optical frequency range and widely used for characterizing the dielectric property of low-loss crystals [1-12]. Microwave resonator thermometer is a new kind of thermometer which offers greater vibration immunity, improved stability, smaller uncertainty in temperature measurement and potential lower cost than platinum resistance thermometry. In the resonator, two coaxial cables are used, one is for coupling to the dielectric (often a single-crystal sapphire) to provide signals which propagates at a resonance frequency around the equatorial path, while the other is to detect the signal from the dielectric. In the optical frequency range, for practical application of WGM resonators, efficient and controllable coupling of light to and from the resonator is crucial and a large amount of literatures for studying the coupling of the WGM are available [13-15], however, little attention has been focused on the microwave resonator coupling.

The state-of-the-art studies are mainly focused on the thermometer feasibility and dielectric shape investigations of the microwave resonator. Strouse *et. al.* [16] 25-28 carried on sapphire-based WGM resonator thermometer experiments with the antennae probes flush with the cavity and the sapphire, assembled on the same cap with antennae probes so that the resonances modes were optimized and the spurious mode coupling were depressed. Unfortunately, no investigations on antennae length and antennae-dielectric distance perturbations were provided in the paper. Yu *et al*. [17] investigated the resonator perturbation based on sapphire rod, it turns out that materials of supporting screws, amounts of the Teflon washer under the same thickness and the holes around the cavity are all insignificant while the resonator is significantly sensitive to the materials of supporting washer. No further work on antenna length and antennae-dielectric distance was made, unfortunately. Moreover, so far, neither cavity filling nor humidity perturbations on Q, coupling strength, accuracy and sensitivity were investigated based on the microwave resonator.

This paper will focus on the microwave resonator perturbation study based on a cylindrical sapphire based resonator. Experiments were carried out to investigate perturbations of antenna probe length, antenna-dielectric distance, cavity filling and humidity with respect to Q, spurious mode depression, coupling strength, accuracy, shock resistance and sensitivity.

2. Microwave resonator thermometer

The microwave dielectric resonator thermometer was made of a sapphire cylinder whose nominal diameter and length are both 12 mm suspended inside a cylindrical gold-plated copper cavity with aspect ratio 1:1, i.e. with inner diameter and height both equal to 24 mm. The sapphire cylinder, purity of material 99.996%, is an anisotropic single crystal synthetic sapphire (α-Al_2O_3) with its c-axis aligned with the geometric z-axis within ± 6’. The permittivity at room temperature is around ε_x=ε_y=9.391, ε_z=11.5869.

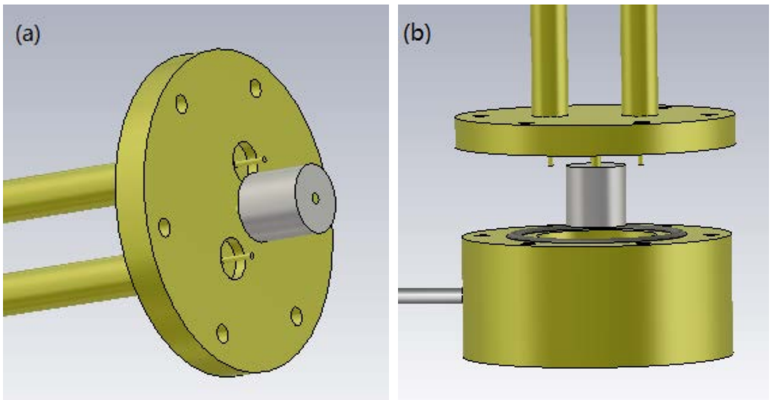


Figure 1. a) Top cap of the cavity with the cylindrical sapphire and two antennae probes; b) full opened cavity with O-rings seal, bottom cap with drilled hole, the vacuum line and top cap shown in (a)

Figure 1a shows a 3D drawing of the top cap of the cavity where the mounted sapphire, the microwave cables, and antennae are set. The antenna length started from 6.6 mm, for the first exploration, trimmed to 5.0 mm, 4.0 mm, 3.0 mm and 2.0 mm, respectively. A 2-mm bore was drilled through the z-axis of sapphire where a brass screw and suitable spacers holds the sapphire in place inside a copper cavity at chosen positions. Figure 1b represents full opened cavity including top cap and the gold-plated bottom cap with drilled hole, cavity body with O-ring seals and the vacuum line. The sapphire can be assembled either on the top or bottom cap in order to cover a wide interval between the sapphire and the antenna.

3. Experiments

3.1 Antennae probes lengths test.

Experiments were carried out at two resonance frequencies around 8.96 GHz (mode 1) and 14.77 GHz (mode 2) at room temperature with the sapphire assembled on the top cap, in a position near to the antennae probes. Significant improvements were obtained on both resonant modes when the probes were gradually trimmed. As shown in Figure 2, the color-coded lines represent the modes shapes of mode 1 and 2 when probes lengths is trimmed to 6.6 mm, 5.0 mm, 4.0 mm, 3.0 mm and 2.0 mm, respectively with a radial distance between the center of straight antenna and the periphery of dielectric is 3 mm. The center frequencies are purposely shifted to compare how the resonance frequency varies with the length of antennae probe. The blue line indicates a mode that is broad in frequency span and low in amplitude (small Q) with several overlapping peaks which could be attributed to the coupling to the surrounding cavity. As seen in the figure that mode 2 is more affected by spurious modes than mode 1. As probes length became shorter, the resonance shape greatly improves, Q rises sharply and spurious mode coupling to the neighbors reduces simultaneously. In order to obtain high Q resonator, shorter antennae probes are preferred: under this circumstance, the INRIM WGM thermometer exploited a 0-mm length antennae probes (flush with the cavity inner surface as shown in ref. 18-20) which offered a Q of more than 10^5 while when the intruding length is as long as 6.6 mm the Q is only hundreds due to the great coupling with neighbors. The length of the antenna can improve the Q by several magnitude through cutting the intruding length. Since long antennae will move with the resonator shocks which will change the radial distance between dielectric and antennae and results to resonance frequency change and therefore affect the accuracy. As a result, in view of its use in industrial applications as a transfer standard thermometer, a minimum intrusion into the cavity is preferred in order to achieve a better sensor repeatability, reproducibility and a greater tolerance to mechanical shocks. This perfectly matches with the published paper in ref. 18, and ref. 19-20 where authors got higher Q, good accuracy and great shock resistance. In particular, papers 19 and 20 were based on the spherical sapphire and the relative antennae-dielectric distance is longer even with the same length of antenna compared to the cylindrical sapphire and this results some modes disappear. Therefore, this should be one of the reasons that paper 19 and 20 only investigated on one of the resonance modes.

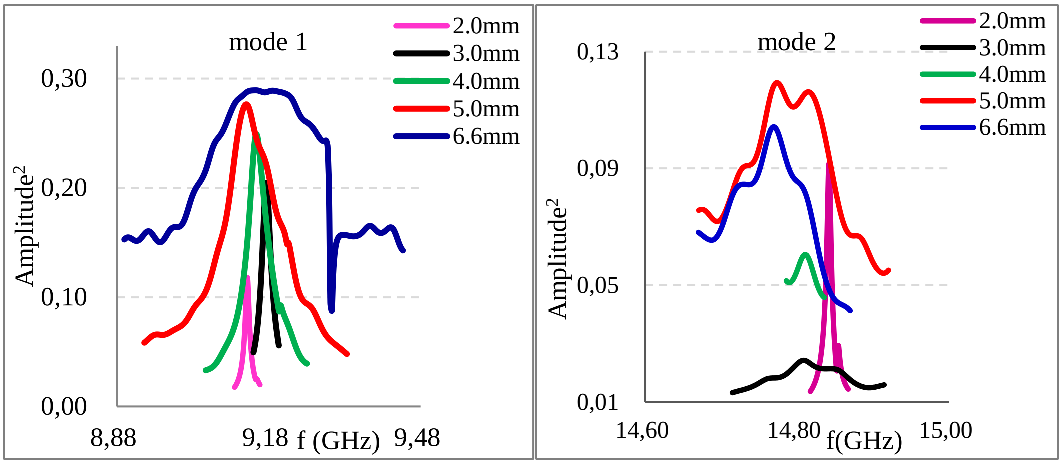


Figure 2 Resonance modes under different lengths of antennae probes for mode 1 and mode 2.

3.2 Antennae-dielectric distance test.

In order to check the antennae-dielectric distance perturbations on the resonance mode, the sapphire was also assembled on the opposite (bottom) cap, that is far from the antennae as shown in Figure 3 and the top cap where the antennae are located as drawn in Figure 1.

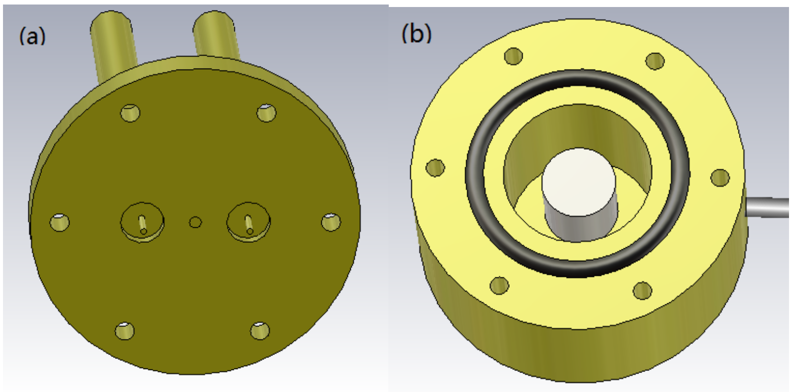


Figure 3. a) Top cap of the cavity without sapphire assembled and two antennae probes; b) full opened cavity with O-rings seal, bottom cap with cylindrical sapphire assembled, the vacuum line

Figure 4 and Figure 5 (a-d) show the resonance modes for antennae length of 6.6 mm (a), 5.0 mm (b), 4.0 mm (c) and 3.0 mm (d), respectively. The red line shows the result of assembling the dielectric on the bottom cap (far from the antennae) while the blue one the dielectric is assembled on the top cap (near to the antennae). The two center frequencies are purposely shifted to help the comparison. It is obvious from Figure 4 that the sapphire-antennae distance is the further the better from the point of view of lower spurious coupling and higher Q when the probes are very long (*e.g.* 6.6-mm and 5-mm long) and the Q can improve by several magnitude as cutting the intruding length in Fig. 2. Nevertheless, when the antennae probes got shorter the improvements become insignificant and when they were 2.0-mm long, the mode disappeared due to the weak coupling strength of the dielectric fixed on the bottom cap. Furthermore, the amplitude got smaller and smaller when probes became shorter. Nonetheless, when the dielectric was close to the antennae, the amplitude was largely insensitive to the antenna probes length. However, mode 2 in figure 5 did not show significant dependencies as aforementioned for mode 1 when the antenna length changed from 6.6 mm to 3 mm when assembled on different caps and this is very similar to the situation in Figure 2, which may due to the strong coupling of mode 2 with spurious mode.

In summary, when the resonator assembly has long antennae probes, high Q and low spurious mode coupling was achieved by raising the antennae-dielectric distances moderately. Nevertheless, shorter lengths of antennae are preferred in the interest of higher repeatability, reproducibility and shock resistance. Flush probes with dielectric assembled near to it reached an acceptable compromise. This also helps to understand why some of resonance modes in paper 19 and 20 disappeared in the experiments, which certainly should exist according to the simulation. The spherical sapphire was assembled on the upper cap that is close to the zero-length antenna and some resonance modes disappeared which is accordance with our experiments in this paper when the antenna length is 2 mm and the cylindrical sapphire is assembled on the lower cap. Due to the shape influence of the sapphire, the antennae-dielectric distance is increased and the coupling strength maybe one magnitude of weaker which results to the resonance modes missing.

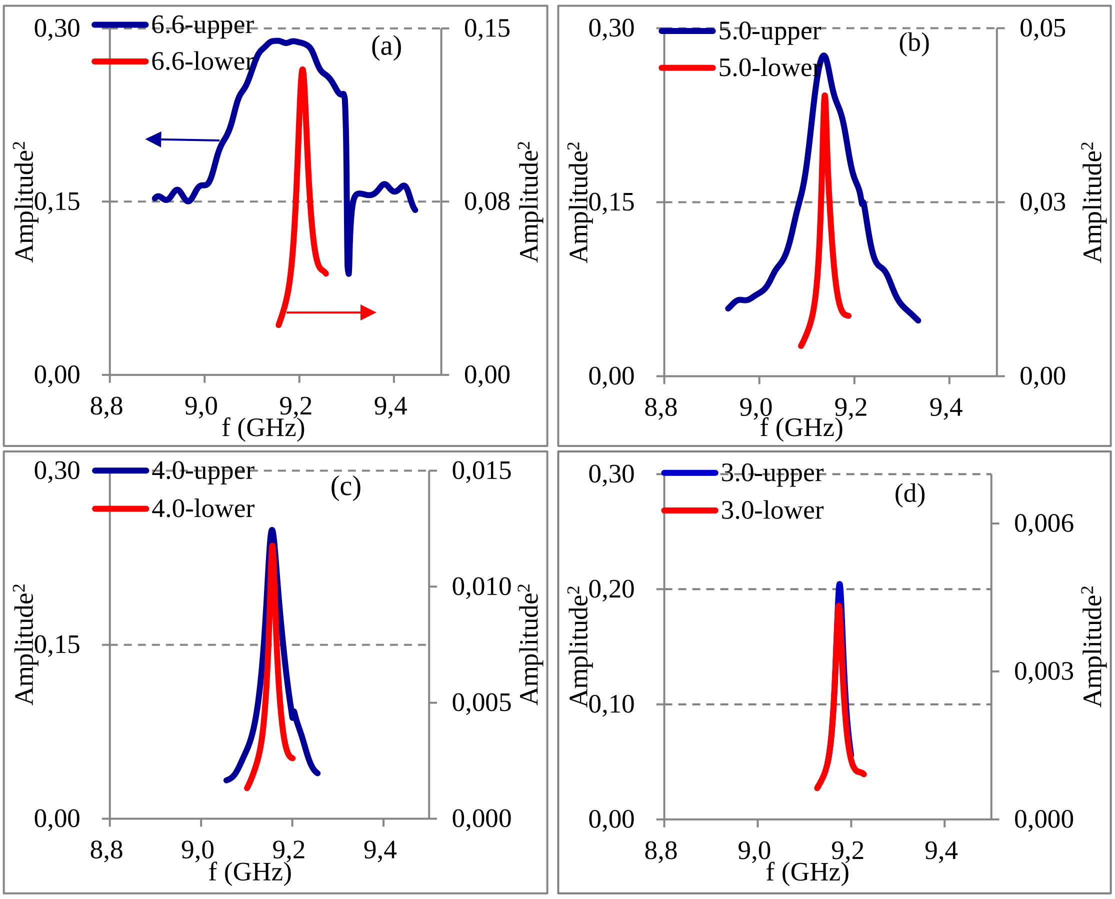
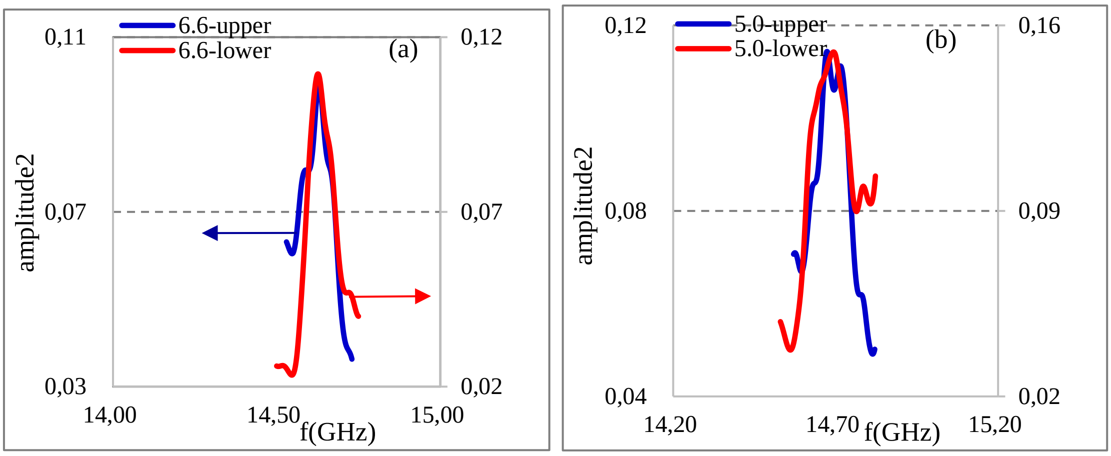


Figure 4. Comparisons between different assembling positons with each pair of same antennae length for mode 1.



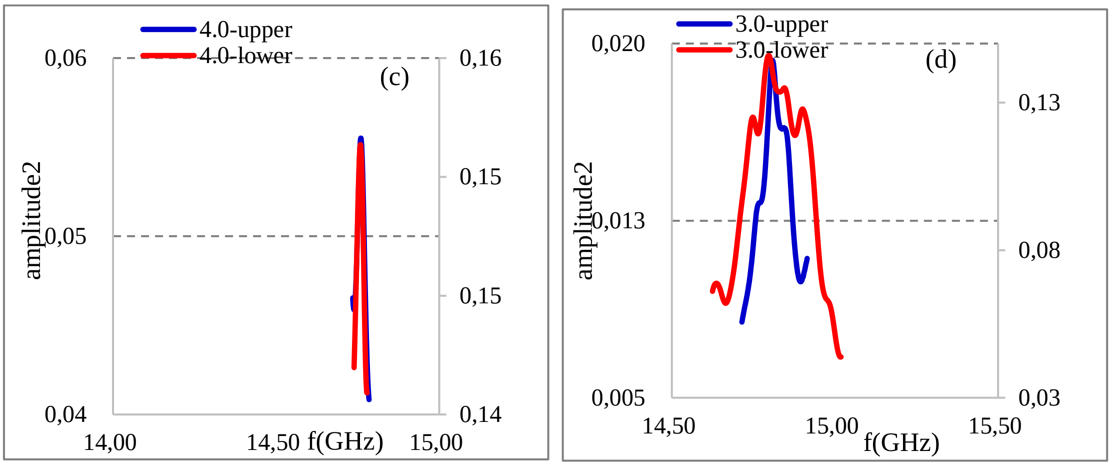


Figure 5. Comparisons between different assembling positons with each pair of same antennae length for mode 2.

3.3 Cavity gas filling test.

The resonator was tested under room temperature with a cavity vacuum-pumped, filled with nitrogen and air respectively. As indicated in Figure 6, most resonance modes show similar magnitude, i.e. coupling strength, and no obvious improvement for Q after the cavity was pumped to vacuum from air filling while filling with nitrogen did raise coupling strength by 2-4 times larger for lots of resonance modes which is good for cutting the antennae shorter without compromising some wanted modes disappearance for shock resistance. The cavity was filled with nitrogen inside with pressure around 1000 mbar.

Moreover, the resonator thermometer was also tested at 20 °C, 25 ℃, 37 ℃ and 50 ℃ with a cavity vacuum-pumped and filled with nitrogen, respectively for mode 1 and mode 2. The antenna had a length of 2mm and the sapphire was assembled on the upper cap of the resonator. We estimated that filling with nitrogen increased the thermal conductivity to make the resonator a better thermometer compared to the vacuum pumped resonator. However, Figure 7 shows that with compared to the pumped cavity filling with nitrogen decreased the frequency-temperature sensitivity for two test modes which may due to the gas nitrogen permittivity temperature dependence together with dielectric resonator dimensions variation and mode 2 is less sensitive to the cavity filling than mode 1.

Hence, filling with nitrogen or other gas collaborates with shorter antennae probes can work on increasing coupling strength and thermometer shock resistance but with the cost of decreasing thermometer sensitivity. This compromise was not the choice in ref. 19 and 20 in order to get higher temperature sensitivity and higher Q for accuracy. The next step is suggested for authors to investigate is a better compromising point between antennae length, and cavity gas filling for suitable accuracy, shock resistance and coupling strength.

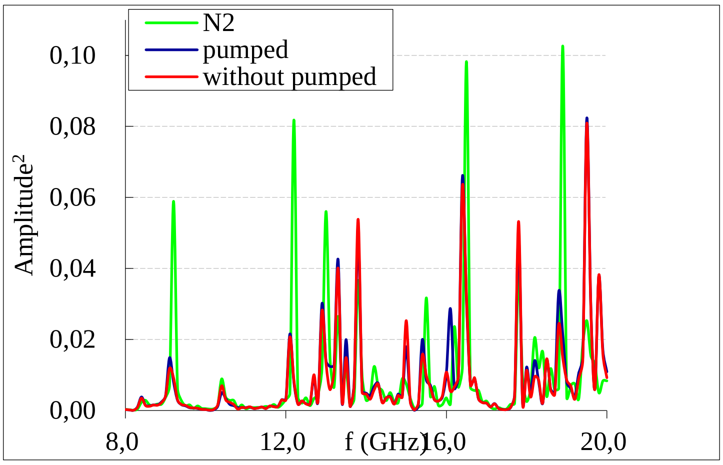


Figure 6. Comparisons between different cavity gas filling with the same length of antennae probes.20

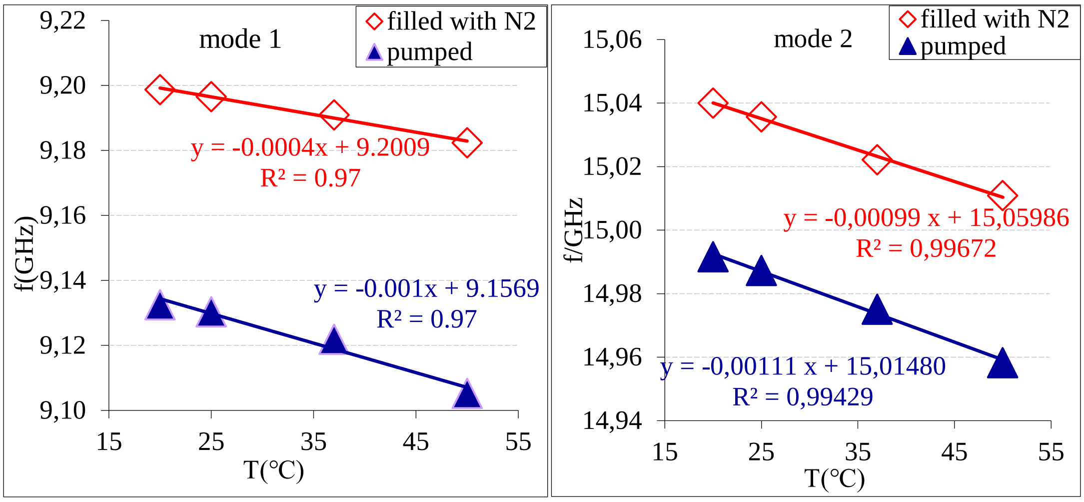


Figure 7. Frequency-temperature sensitivity for mode 1 and 2 with cavity pumped and filled with nitrogen respectively

3.4 Reproducibility test.

This experiment was done with antenna length of 2.0 mm and sapphire was put on the upper cap of the cavity which was pumped all the time. Microwave resonator had small leakage due to sealing problem during temperature experiments from 20 ℃ to 50 ℃. Trial started at 20 ℃, 25 ℃ and then a small leakage happened at 28 ℃, afterwards, the cavity was opened and cleaned to finish the experiments at 37 ℃ and 50 ℃ respectively. It turns out that the resonator is a reproducible thermometer has high sensitivity to humidity for both modes as seen in Figure 8 and the frequency sensitivity to humidity (df/f) is around 2.24×10^{-3} at this point.

It is well known that the permittivity of water is larger than 70 under room temperature which is 6~10 times larger than the permittivity of sapphire. The reason that a microwave resonator can work as a thermometer is mainly due to the permittivity change of the sapphire, which will also be greatly increased by water vapor on sapphire surface where the electric energy mainly concentrates. Therefore, humidity is an important factor to control for microwave resonator thermometer or we may say that the microwave resonator can work as a good hygrometer.

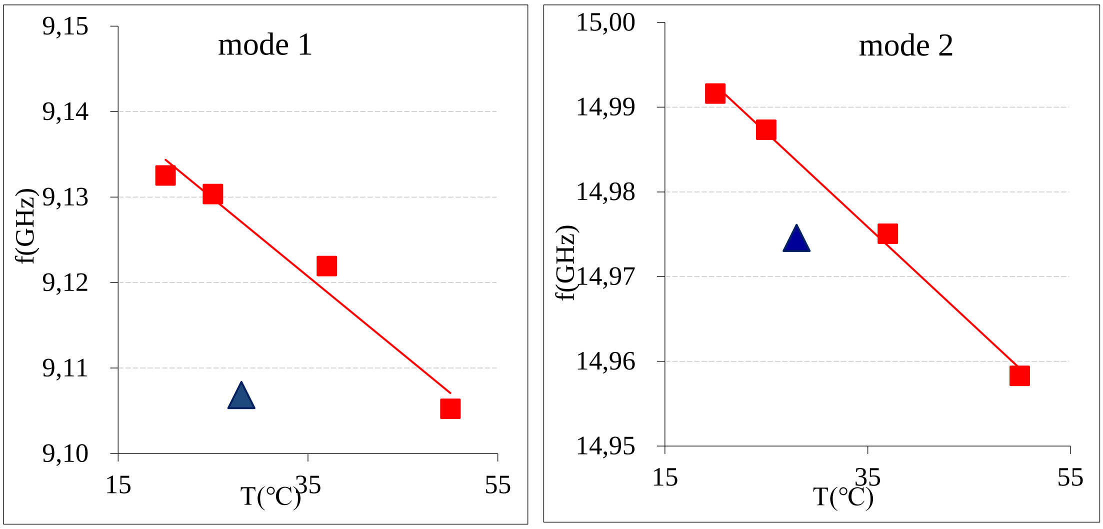


Figure 8. Reproducibility test for mode 1 and 2

4. Conclusions

The experimental investigations on perturbations of the microwave resonator thermometer show antennae probes lengths, antennae-dielectric distance, cavity gas filling and humidity all have significant effects on the resonance frequency.

Cutting antennae probe helps to the spurious mode depression and increase Q factor of the resonator by several magnitude as well as contributes to improve sensor repeatability, reproducibility and shock resistance. When the antennae are long, increasing antennae-dielectric distance is conductive to spurious mode depression and Q factor enhancement and coupling strength is little sensitive to the antennae length when the dielectric is very close to the antenna. Nevertheless, when the antennae-dielectric is large the amplitude can be an order of magnitude lower with antennae go shorter. Summarizing the aforementioned two factors, reducing antennae lengths and keeping them close to the dielectric are subject to low spurious mode coupling, high Q, moderate coupling strength, great repeatability, reproducibility and shock resistance.

Filling with nitrogen can raise coupling strength significantly for lots of resonance modes but at the cost of reducing thermometer sensitivity compared to pumping the cavity to vacuum. Moreover, the microwave resonator thermometer is very sensitive to humidity which should be controlled in order to ensure the thermometer accuracy.

Above all, shorter antennae probes, close antennae-dielectric distance, vacuum cavity filling and hermetical seal can guarantee the microwave resonator work as a good thermometer.

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