High Q Miniature Sapphire Acoustic Resonator

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***Abstract*— We have demonstrated high Q measurements in a room temperature Miniature Sapphire Acoustic Resonator (MSAR). Initial measurements of bulk acoustic modes in room temperature sapphire at 39 MHz have demonstrated a Q of 8.8×10^6. The long term goal of this work is to integrate such a high Q resonator with small, low noise quartz oscillator electronics, providing a fractional frequency stability better than 1×10^{-14} @ 1s.**

I. Introduction

Quartz USO's are needed for a number of high performance frequency and timing applications, and are often the component limiting short term performance in many atomic frequency standard implementations. Quartz oscillator technology and electronic instrumentation is very mature.

Last year we discussed the possibility of replacing the quartz resonator with a room temperature sapphire acoustic resonator [1]. Quartz oscillator technology is limited by quartz mechanical Q. Using sapphire acoustic modes a 10-fold improvement in Q could possibly improve the stability limit of current USO's to 1×10^{-14} @ 1 second.

The sapphire's acoustic modes, which have not been used before in a high-stability oscillator, indicate that required Q values (as high as 10^8) can be achieved at room temperature in the kHz range [2]. Even though Sapphire is not piezo-electric, such a high Q allows electrostatic excitation of the acoustic modes with a combination of DC and AC voltages applied across a small sapphire disk (~1mm thick).

For resonator materials to study, we selected sapphire and calcium fluoride. Synthetic sapphire has long been a favorite material due to its properties of high purity and uniformity. Many different applications such as high Q microwave whispering gallery modes [3] and low frequency high Q mechanical transducers [4] use sapphire as their resonator material. Calcium fluoride is also being examined as it also has high Q modes at room temperature (though not as high as sapphire) and was felt to be easier to work with experimentally.

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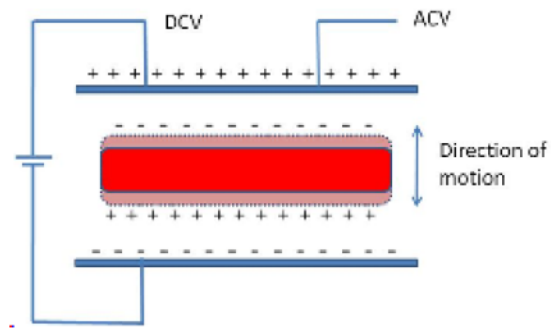


Figure 1 shows a schematic of the non-contact excitation of acoustic modes. When a DC voltage bias is applied, the sapphire experiences a "tension" to allow acoustic modes to be excited by an AC voltage tuned to the resonant frequency. With reasonable AC amplitudes applied, the sapphire displacement of ~0.1 µm is expected.

II. Experimental Approach and Measurement

The initial Q measurement and excitation demonstration can be viewed similar to a transducer converting electrical energy to mechanical energy and back. Such an electrostatic tweeter type excitation of a mechanical resonator was designed to resonate at 5 MHz. The simple experiment consisted of a sapphire (or Calcium Fluoride) resonator sandwiched between parallel electrodes. Figure 1 shows a schematic configuration, where a DC+AC voltage is applied to generate a driving force on the sapphire resonator. The needed gap spacing was estimated to be around 25 µm. With the frequency of the AC voltage tuned to the sapphire resonator frequency, a resonant condition occurs and the sapphire Q can be measured with an impedance analyzer. Frequency scans were performed over a range from 1 MHz to 110 MHz. Experimental activities included:

A. Test configuration Buildup: Two kinds of materials (sapphire and calcium fluoride) in various sample sizes were procured. The smallest sample was about 0.5 cm in diameter and 0.1 cm thick. Two of the samples are shown in Figure 2.

Figure 3 shows a sample resonator mounted in a vacuum chamber. Before insertion, a dummy Teflon block was used to calibrate the distance between electrodes and the resonator surface. To generate and optimize sufficient excitation, the gap spacing can be varied between 10 to 300 microns. A commercial vacuum-sealed positioner is adjustable with 2 micron increment steps and a total range of 25 mm. The first sample holder was designed to hold the sample in mid-cross-section at four points in order to allow minimum interference to oscillation (Fig. 3). Due to the small sample size it was hard to reproduce alignment with this assembly method. A second design consisted of holding the sample around the entire perimeter. This simpler approach allowed only ~78% of the surface to be exposed to the excitation. Nevertheless, with this second approach, high Q measurements were successfully performed.

B. Resonator Samples: Experimentally we prepared six small resonators of various dimensions, two sample mounting fixtures, and a gap control mechanism to vary the distance between the resonator and the electrodes. Four sapphire resonator disks and two calcium fluoride disks were fabricated. The smallest sample is about 0.5 cm in diameter and 0.1 cm in thickness. Both sapphire and calcium fluoride surfaces were optically polished to a smoothness of 0.1 micron.

Figure 2: Sapphire (right) and calcium fluoride (left) disks compared to a U.S. dime.

C. Data collection: Experimental values were collected with an HP4294A Impedance Analyzer which provides impedance/phase verse frequency plots. A Q value can be fitted and calculated at the resonant frequency. Q dependent parameters such as gap spacing, vacuum condition, DCV levels, and ACV levels are varied and recorded for optimum operation when integrated into an oscillator.

D. Acoustic Mode verification: In order to verify the "true" acoustic modes, we performed three checks: 1) Turn DC bias voltage on and off. We found the modes would slowly disappear due to the rate of charge dissipation on the electrodes. 2) Turn off turbo pump and allow background pressure to drift upward. This resulted in a pressure dependent condition. 3) Remove sources of external vibration. When doing so the SNR improved and results were much more reproducible from scan to scan.

E. Resonator testing of calcium fluoride: Calcium fluoride has shown Q values as high as $4x10^7$ at 42 KHz [5]. We also designed and tested a Calcium fluoride resonator at 5 MHz. Initial tests of acoustic modes showed a low Q value of about 3000. Two possible causes were a poor mounting design (mentioned in section II A) and possible contamination on the resonator surface. Future plans are to remount this sample with the second design and retest.

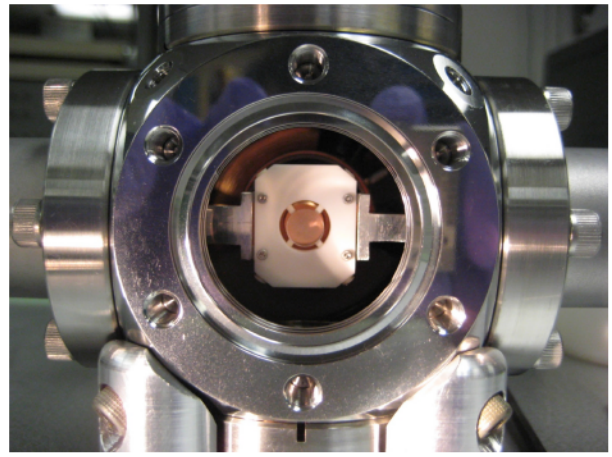


Figure 3 shows the resonator mounted in the vacuum chamber. The initial resonator mounting is clamped from the mid-cross-section with four equally spaced fingers.

III. RESULTS

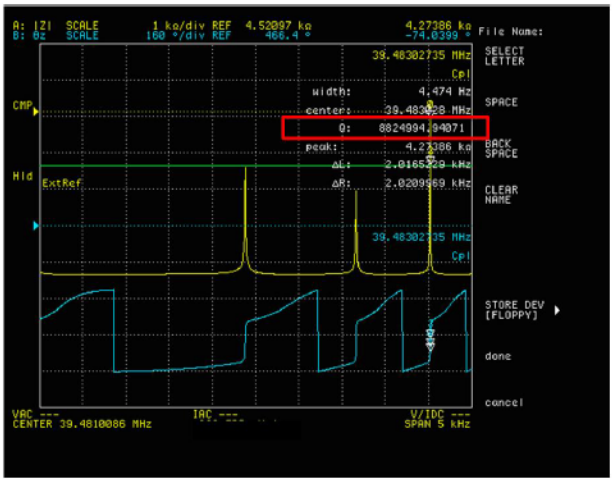
With the impedance analyzer various acoustic modes were measured. Figure 4 shows the results of a typical scan of high Q modes, and lists the peak frequency and corresponding Q. A zoom-in plot of one high Q mode with each measured data point is shown in lower plot of Figure 4. From this data, three high Q modes were identified around 39 MHz and their values of Frequency, Q, and impedance are shown in Table 1.

Discussion:

1. Resonator Temperature effects: Due to the expansion coefficient of sapphire (~ $8.6x10^{-6}$ per deg C) mode frequency scans had to be performed quickly and long averaging cannot be easily performed. Each time the mode is excited, the sapphire temperature increases by a few degrees C and the mode frequency is not stationary. For this reason, scanning of modes was limited to a 5 kHz span. If the sapphire resonator can be temperature controlled to a few 0.1 degrees C there are indications that the measured Q value could be higher.

2. Frequency mismatch: The sapphire resonator frequency was designed to be near 5 MHz. The vendor that cut and polished the sapphire resonators had trouble producing the smaller resonator and several samples were damaged during fabrication. The successful resonator showed measured modes to be near 40 MHz. Impedance scanning from 1 to 110 MHz showed no other high Q modes to be present. This mismatch from the design frequency is under investigation. In addition we tested another sapphire resonator at 3 times the thickness and expect the frequency to be x3 lower at 13 MHz if we excited the same mode. Test result shows a Q of $1.2x10^6$ at about 4.5961 MHz. We also see impedance in the mega-ohm

range which also indicated the logical direction of acoustic modes of a thicker resonator. Possible reason for this lower frequency was that part of the support material was part of the effective resonance circuit. That would also explain the lower frequency and lower Q value. Further investigation is needed.



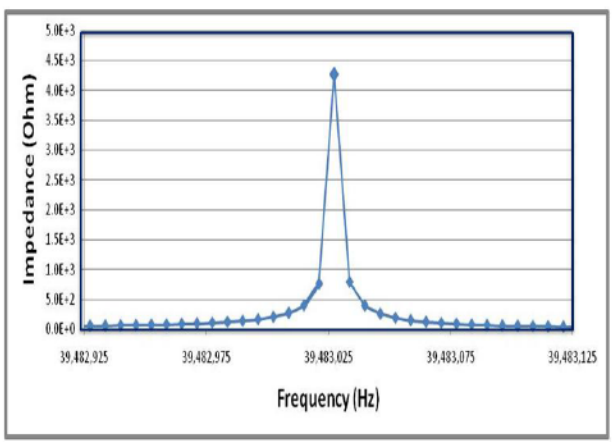


Figure 4 shows a screen capture of the Q measurement. Information is displayed on screen including the Q value, impedance value, and peak frequency. The lower graph shows the plot of each data point to ensure creditability of the scan and uniformity around of the both sides of the peak.

Frequency (MHz)	Q	Impedance (kΩ)
39.4809	3.70E+06	2.97
39.4822	4.20E+06	2.30
39.4830	8.80E+06	4.27

Table 1: three modes measured in a typical scan (detail in Fig. 4). The highest Q mode shows an impedance of 4.27 kΩ, within the design range of incorporating it into an oscillator.

IV. Summary

We have validated a development pathway towards achieving a ten-fold stability improvement over current quartz based Ultra Stable Oscillators (USO) using a high Q Miniature Sapphire Acoustic Resonator (MSAR) biased with a low DC voltage and housed in a modest vacuum. To date we have measured a Q of 8.8 x 10^6 at 39 MHz in a room temperature sapphire resonator with a very rudimentary mounting scheme. This is already 9x higher than achievable in a quartz oscillator with further improvements expected. For practical application at the $1x10^{-14}$ @ 1s level, a Q higher than $1x10^8$ will be needed and a thermal compensation scheme developed.

V. Acknowledgements

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