Miniature Sapphire Acoustic Resonator (MSAR)

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***Abstract*— We present recent progress towards a Miniature Sapphire Acoustic Resonator (MSAR). Our goal is to develop an ultra-stable oscillator with a high Q room temperature sapphire resonator and low noise Quartz electronics with a stability better than $1x10^{-14}$ @ 1s.**

Specific experimental plans are to demonstrate a high Q (>$1x10^8$) sapphire acoustic resonator at room temperature in bulk acoustic modes near 5 or 10MHz. Initial acoustic resonator studies are being carried out with both Sapphire (Al_2O_3) and Calcium Fluoride (CaF_2).

I. Introduction

Current quartz oscillator technology is limited by quartz mechanical Q. Using sapphire acoustic modes we contemplate a 10-fold improvement to possibly improve on the stability limit of current quartz oscillators to $1x10^{-14}$ @ 1 second. The electromagnetic modes of sapphire that we have previously developed at JPL require cryogenic temperatures to achieve the high Q levels needed for high stability[1]. 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 should allow electrostatic excitation of the acoustic modes with a combination of DC and AC voltages applied across a small sapphire disk (~1mm thick). The first evaluation will test prediction of an estimated input impedance of ~10K Ohm at $Q=10^8$, and explore the Q values that can be realized in a smaller resonator not previously tested for acoustic modes.

For resonator experiments, we selected sapphire and calcium fluoride. Synthetic sapphire has long been a favorable material due to its properties of high purity and uniformity. Many different applications such as high Q microwave whispering gallery modes[1] and low frequency high Q mechanical transducers[3] use sapphire as their resonator material. Calcium fluoride will also be examined as it also has high Q modes at room temperature (though not as high as sapphire) but may be easier to work with experimentally. Room temperature mechanical Q's have been demonstrated in Al_2O_3 as high as $1.5x10^8$ at 53.4 kHz[2] and for CaF_2 $4x10^7$ at 42 kHz[4].

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Sapphire's acoustic modes are similar to mechanical resonator modes in many ways and the mode frequency is tied to the speed of the sound in the resonator. Dissipations of both modes are also expressed in the same equations. (See discussion below). The difference lies in the location of maximum displacement. In typical mechanical resonators the nodes are at the end surfaces while in our acoustic mode the node is at the center, allowing support of the resonator at the node. For a bar type resonator[3] the eigen-modes are selected to allow nodes at the boundary surface while MSAR acoustic mode excitation produce nodes in the middle of the cross section giving maximum displacement at the two end surfaces.

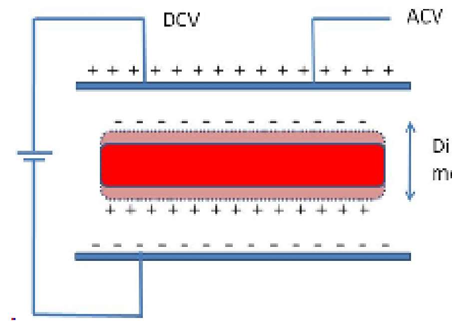

Figure 1 shows a schematic of the non-contact excitation of acoustic modes. When a DC voltage bias is applied, the sapphire experiences a "tension" to allow acoustic modes to be excited by an AC voltage tuned to the resonant frequency. With reasonable AC amplitudes applied, the sapphire displacement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

As discussed in "System with small dissipation"[5], there are two types of associated losses for resonators made with dielectric materials: thermoelectric dissipation and dissipation due to phonon-phonon interaction. Both effects are strongly related to crystal structure and imperfections. Limitation to achieving high Q also depends strongly on lattice defects and internal structures. Presently sapphire resonators of very high purity and uniformity can be fabricated. To develop a high Q resonator, the losses due to coupling to the supporting material also become important.

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II. DESIGN AND EXPERIMENTAL SETUP

Our resonator design begins with two back to back ¼ wave resonators. A single ¼ wave resonator provides maximum displacement at the sapphire boundary and therefore maximum signal or gap variation (impedance variation). The sapphire resonator resides between two non-contacting endplates. To generate sufficient excitation, the gap spacing will be varied between 10 to 300 microns. A commercial vacuum sealed positioner allows steps in 2 micron increments and a total range of 25 mm. Parameters such as dielectric number, speed of sound in the resonator, and Young's modulus were folded into the calculation of impedance, resonator size, and frequency. For an initial experiment with a 5 MHz resonator, we would expect an impedance of ~10k Ohm and a center surface motion of 0.1 micron.

Experimentally we have prepared six small resonators of various dimensions, a small sample mounting fixture, and gap control mechanism to vary the distance between the resonator and electrodes. Pictures of two resonators are shown in Figure 2.

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

The present resonator samples being tested are four sapphire disks made by Crystal Systems and two calcium fluoride disks made by Schott Lithotec AG. 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 0.1micron.

The resonators are being tested in a modest vacuum system. The vacuum requirement is derived from a calculation by Uchiyama et al[5], showing the gas dissipation can be estimated by

$$\frac{1}{Q_{gas}} \approx \frac{PA}{M\,\omega_0}\sqrt{\frac{\mu}{\kappa_B T}}$$

Where P=pressure, A= surface area, M= Mass of resonator, μ=mass of the molecule, T= temperature, κ_B= Boltzmann's constant. For a background pressure of 10^{-3} torr, the gas damping effect using the dimensions of a typical resonator would limit the Q to 1.3×10^{10} at 300K. Therefore due to the small size of our resonator we are not limited by the gas damping effect.

This 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 will be tested at 5 MHz. The initial gap spacing is 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 determined with a high frequency impedance analyzer. Data collected from HP4294A Impedance Analyzer will provide impedance verse frequency plots. A Q value can be fitted and calculated at the resonant frequency. Q dependent parameters such as gap spacing, vacuum, DCV levels, and ACV levels will be tested for optimum operation when integrated into an oscillator. The experiment with the first sapphire resonator is in progress

III. SUMMARY

We present recent progress towards a new Miniature Sapphire Acoustic Resonator (MSAR) with a goal of achieving a Q value of higher than 1×10^8. The current test configuration is set up to measure the impedance at resonant frequencies near 5 MHz. Other resonator frequencies will also be investigated. To achieve high Q values, many experimental factors such as gas damping effects, charge buildup on the sapphire surface, heat dissipation, sapphire anchoring, and the sapphire mounting configuration require careful attention.

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