Force-Frequency Effects of Y-cut Langanite and Y-cut Langatate

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Abstract

Most recently, langasite and its isomorphs (LGX) have been advanced as potential substitutes for quartz, owing to their extremely high quality (Q) factors. At least 3 times higher Q value of LGX than that of quartz has been reported. High Q translates into potentially greater stability. In order to make such materials practical, the environmental sensitivities must be addressed. One of such sensitivities is the force-frequency effect, which relates the sensitiveness of a resonator to shock and vibration via the third-order (non-Hookean) elastic constants.

In this paper, we report measured force-frequency coefficients of a Y-cut LGN resonator and a Y-cut LGT resonator as a function of the azimuthal angle, which is the angle between the crystalline x-axis of a resonator plate and the direction of in-plane diametric force applied to the periphery of the resonator. It was found that the LGN and the LGT behave like AT-cut quartz in the polarity of the frequency changes and the existence of zero-coefficient angle. The maximum magnitudes of the coefficients of the LGN and the LGT are 5 and 7 times smaller than that of SC-cut quartz, respectively (or, 7 and 10 times smaller comparing to AT-cut quartz). The coefficients of planar-stress, which represent the superposition of a continuous distribution of periphery stresses, were also obtained as 0.52×10^{-15} *m·s/N and* 0.38×10^{-15} *m·s/N for the LGN and the LGT, respectively.*

INTRODUCTION

Single crystals of langanite ($La_3Ga_{5.5}Nb_{0.5}O_{14}$ or LGN) and langatate ($La_3Ga_{5.5}Ta_{0.5}O_{14}$ or LGT) are of considerable interest for both bulk acoustic wave and surface acoustic wave devices [1-3]. This is due to a combination of very small acoustic loss (high Q) and temperature-compensated orientations for thickness-shear waves (c mode). These materials are expected to perform better than quartz in certain frequency control applications. The Q values for LGN and LGT are particularly impressive in comparison to quartz as reflected in Q·frequency ($Q{\cdot}f$) products as large as 29 x 10^6, where f is in MHz, for unplated Y-cut plano-convex LGN [4] and LGT [3] resonators driven by thickness-field-excitation. To put these values in perspective, consider that the upper bound $Q{\cdot}f$ for AT-cut natural quartz resonators is 15 x 10^6 [5]. In order for resonator designers to realize precision resonators using these materials, a great deal of non-linear material properties need to be known in addition to the primary knowledge about the material constants (stiffness, piezoelectric, and dielectric) and the temperature-frequency coefficients. Some of non-linear effects are force-frequency, acceleration-frequency, resonance amplitude-frequency, intermodulation, mode coupling-activity dips, dynamic thermal-frequency, and film stress-frequency [6].

It has been determined that the sensitivity of the resonator frequency to shock and vibration could be reduced by selecting certain mounting support orientations of the crystal resonator blank. The phenomenon of frequency changes related to the stress applied to the resonator is referred to as force-frequency effect. The frequency changes are due to primarily the nonlinear (3rd order non-Hookean) elastic constants and secondly the static deformation of the crystal lattice. This paper presents experimentally determined force-frequency coefficients for select Y-cut LGN and Y-cut LGT resonators. The knowledge of the coefficients applies to the design of mounting supports for resonators so that the mounting stress effects may be minimized. The force-frequency effects also contribute to long-term aging.

FORCE FREQUENCY EFFECTS

Figure 1 shows the definition of the azimuthal angle ψ between the direction of applied force and the crystallographic axis of a singly-rotated cut. (It can be generalized for a doubly-rotated cut, also.) Although the force may be either compressive or tensile, compressive force is conventionally adopted since it can be easily realized by a weight pulled down by gravity.

The force-frequency effects produced in a circular crystal plate acted upon by diametric in-plane force at the angle ψ is characterized by means of a force-frequency coefficient K_f, which is defined by [7]

$$K_f = \frac{\Delta f}{f} \cdot \frac{\text{(Diameter)(Thickness)}}{\text{(Force)(Acoustic velocity/2)}} \qquad (1)$$

where $\Delta f/f$ is normalized frequency change due to the applied force. When the compressive force induces a positive

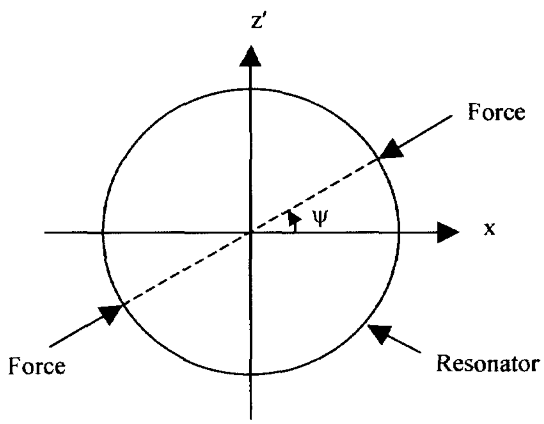

Figure 1. Definition of force application and of angle Ψ.

frequency change, the sign of K_f is defined as positive conventionally and vice versa. Smaller K_f is desirable for precision clock and frequency control applications, but larger K_f for transducer applications.

Another important factor is a coefficient of planar-stress, which is defined by an integral of K_f over the perimeter [6], as follows

$$\langle K_f \rangle = \frac{1}{\pi}\int_0^{\pi} K_f(\psi)d\psi \,. \tag{2}$$

It represents the superposition of a continuous distribution of periphery stresses. Crystal cuts in the vicinity of $<K_f>=0$ are especially important. They are referred to as stress-compensated (SC) cuts. An ideal SC cut resonator is insensitive to planar stress such as electrode film stress at a certain temperature, since K_f is a function of temperature [8-10].

EXPERIMENTAL PROCEDURE

An experimental apparatus was constructed to apply force and rotate the sample for azimuthal angle. The compressive force was realized by loading weights on the top periphery of the sample via a movable rod having a wedge-shaped tip while another rod supported the sample on its bottom periphery. The weight of the rod was included in the total weights. A chuck to hold a resonator sample was mounted on a xyz and rotational translator with positioning micrometers to accurately align the center of the sample between the rods. The resonant frequency was measured with the reflection coefficient S_{11} of a network analyzer. The measurements were performed at laboratory ambient temperature (20°C). One or two Hz differences at most were observed between the frequency shifts from unloading to loading and those from loading to unloading as previously reported [11]. To maintain consistency, the frequency shifts from loading to unloading were read and the average value of several readings was taken for each data point.

A 5 MHz fundamental AT-cut quartz resonator was tested before LGX samples in order to confirm the experimental setup and the procedure. The weights of 200 g including the rod were used. The maximum frequency shift was 83 Hz (or 8.3×10^{-8}/g) near Ψ=0 (due to the electrodes and the mounting clips, the data couldn't be taken at Ψ=0). The corresponding value of K_f is 23.5×10^{-15} m·s/N, which agrees well with previously published one [8]. The overall K_f curve shows a very good agreement, also.

Table 1 lists the parameters of the LGN and the LGT resonators investigated. The 3rd, 5th, and 7th overtones (OT) of the slow-shear mode (c-mode) were investigated since the spectrum of each mode was clean in the vicinity of the resonance. To minimize the tension due to the mounting of the resonator, it was 2-point-mounted with flexible gold-plated molybdenum ribbons, dimensions of which were 2 μm thick and 1.53 mm wide, to serve as holding the crystal and providing electrical connections.

When the LGX resonator was measured, it was found that the 200 g weights were not heavy enough to induce frequency shifts more than 10 Hz, indicating that the LGX has much smaller K_f values than quartz. The weights were increased to 1 kg. Nevertheless, the sample was strong enough not to break from repeated loading and unloading of the weights. Under a microscope, very small chips developed around the periphery could be seen, but they were confined within very short distance from the periphery. The chips didn't affect the experiments since they were in acoustically inactive area as evidenced by no changes of the resonant frequencies.

Table 1. Resonator parameters.

	Y-cut LGN	Y-cut LGT
Crystal disk	Plano-convex, 14 mm Ø	
diopter	3	2
Electrodes	6.35 mm Ø gold with chrome adhesion layer	
Slow-shear velocity [m/s]	2859.36	2600.32
3rd OT [MHz]	6.047	6.149
5th OT [MHz]	10.082	10.254
7th OT [MHz]	14.102	14.347

RESULTS AND DISCUSSIONS

The measurements were repeated with the azimuthal angle intervals of 5°. For example, at 5th OT, the maximum frequency shift near Ψ=0 was 44 Hz and 33 Hz (or, 4.4×10^{-9}/g and 3.3×10^{-9}/g) for the LGN and the LGT, respectively. The normalized frequency shifts for 3rd and 7th OT were close to the ones for 5th OT. The measured frequency shifts were converted to the K_f values by using Eq. (1). The thickness variation of the sample due to contouring was ignored. The acoustic velocity of the slow-shear mode was 2659.36 m/s and 2600.32 m/s for Y-cut LGN and Y-cut LGT, respectively [12-14].

The K_f values of the Y-cuts are symmetric about Ψ = 0° and 90° and are well fitted with a polynomial of cosine square terms [15],

$$K_f(\psi) = \sum_{i=0}^{N} A_i \cos^{2i}(\psi). \quad (3)$$

The K_f values of all the OT's of the LGN and the LGT are best fitted with 7 terms and 5 terms, respectively, and the corresponding coefficients are listed in Table 2. Integrating the K_f curve-fit expressions by Eq. (2) yield the $\langle K_f \rangle$ values.

Figure 2 (a),(b) contain the measured K_f values represented by symbols and the least-square fitted curves of the Y-cut LGN and the Y-cut LGT, respectively, as a function of Ψ. Note that zero crossings of K_f exist. The data are absent on some angles due to the electrodes and the mounting ribbons of the resonator. Since the prepared resonators have the electrodes approximately perpendicular to the reference flat (nominally perpendicular to x-axis), the data should be absent near 90°. However, the data show some deviations from 90°; especially ~30° deviation for the LGN. The K_f curve ought to be symmetric about 0° and 90° because of the symmetry of Y-cut crystals; thus, both the measured data and the fitted curves were numerically shifted along the angle to satisfy the symmetry condition. It was speculated that the reference flat of the sample was off from the real reference flat. Further investigation to confirm this speculation was not performed since this was not critical for the study. Except that the extrema K_f of the LGN (3.1×10^{-15} m·s/N and -2.2×10^{-15} m·s/N) are larger by 41 % and 47 % than those of the LGT (2.2×10^{-15} m·s/N and -1.5×10^{-15} m·s/N), two curves show very similar shapes with almost identical zero crossing angles (51° and 129° for the LGN vs. 53° and 127° for the LGT). The differences of 6% in magnitude and 2° in angles can be well accommodated within the scatter of the data. In fact, increasing the K_f data of the LGT by 44% makes them superimposed on those of the LGN without showing any differences between two materials.

Table 2. K_f curve-fit coefficients.

Coeff. A_i	Y-cut LGN	Y-cut LGT
A_0	-2.208	-1.481
A_1	6.145	3.51
A_2	-3.833	3.821
A_3	8.679	-8.398
A_4	-1.638	4.755
A_5	-12.342	-
A_6	8.266	-

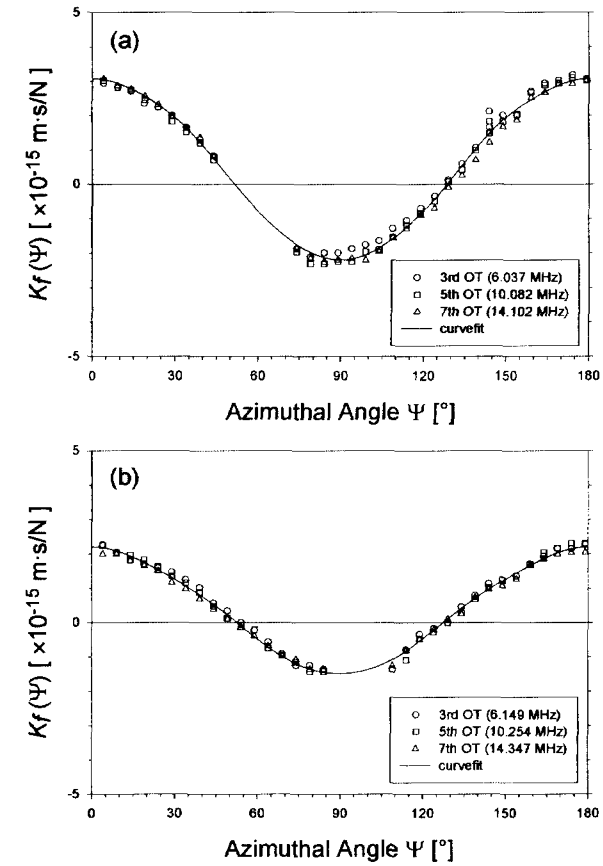

Figure 2. Measured data and curve-fit of K_f(Ψ) versus Ψ: (a) Y-cut LGN, (b) Y-cut LGT.

In order to compare LGX with quartz, the K_f curves of Fig. 2(a),(b) are plotted again in Fig. 3 against those of AT-cut and SC-cut quartz, which are generated using the expressions in Ballato's paper [8]. Note that LGX has substantially smaller K_f than quartz over the entire range of Ψ.

Table 3 lists some notable data points, *i.e.* the azimuthal angles for $K_f = 0$ and $K_f =$ extrema, and extrema K_f and $<K_f>$ values. The positive (negative) extrema of K_f of the LGN and the LGT are 7 and 10 (5 and 8) times smaller than those of AT-cut quartz, respectively. The small K_f values of the LGN and the LGT reflect the smaller $<K_f>$ values by 18 and 25 times than that of AT-cut quartz, respectively. Exact numbers may deviate slightly from the numbers shown due to measurement error. In addition, the force-frequency coefficients and their zero crossings depend on temperature [8-10]. For example, the zero crossings for AT-cut quartz shift by a few degrees between 25°C and 80°C [9]. The K_f values of the Y-cut LGT here is comparable to the one previously reported [16], but it should be noted that their values were obtained using velocity instead of frequency-constant (or a half of velocity) in Eq. (1).

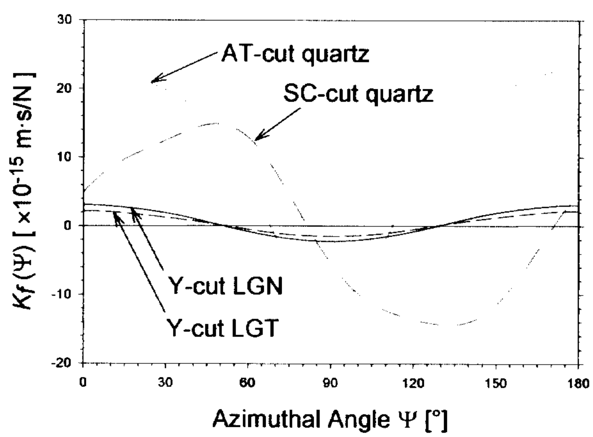

Figure 3. Comparison of K_f between LGX and quartz.

Table 3. Comparison of K_f and $< K_f >$ between LGX and quartz. Dimension of K_f and $< K_f >$ is 10^{-15} m·s/N.

Material	Ψ [°] for K_f=0	Ψ [°] for K_f= extrema	Extrema K_f	$< K_f >$
Y-cut LGN	51 129	0 90	3.1 −2.2	0.52
Y-cut LGT	53 127	0 90	2.2 −1.5	0.38
AT-cut quartz	68 112	0 90	23 −11.3	9.4 (exp.) 10.0(theo.)
SC-cut quartz	81 171	48 133	15 −13.4	0

Vibrational force contributes frequency excursions and K_f correlates diametric (static) force to frequency excursions. Question arises naturally how the small K_f value guarantees low acceleration sensitivity. One may argue that K_f reveals only the simple effects related to the diametric force but the vibrational force is more complicated, including combinations of all directions, bending, twisting, and twitching. The nature of such complication can be easily explained by the fact that AT-cut quartz sometimes shows lower acceleration sensitivity than SC-cut quartz even though the maximum K_f value of AT-cut is larger than that of SC-cut. Force-frequency effects for general directions may be readily quantified by investigating K_f for many different cuts of the material. Previous investigations on quartz for several rotated cuts reveal that the maximum magnitudes of K_f fall within the same order of the magnitudes [6,11]. It is highly probable that LGX also behaves similarly to quartz with respect to K_f. Considering substantially smaller values of K_f comparing to quartz, we believe that LGX has a potential to produce a lower acceleration sensitivity resonator than quartz. Ultimately, acceleration sensitivity of LGX should be tested with an optimum device structure in the crystal cut and the mount.

CONCLUSIONS

It is found that the extrema K_f of LGN and LGT are substantially smaller than those of quartz. Also, found that LGN and LGT behave like quartz, *i.e.* zeros exist for the force-frequency effect and the sign of K_f changes from positive to negative as Ψ angle changes from 0° to 90°. The Y-cut LGN and the Y-cut LGT show very similar shapes with the same zero crossing angles at ~52° and ~128° except that the overall magnitudes of K_f of the LGN are larger by ~44% than those of the LGT. Among myriads of cuts including doubly-rotated cuts, SC-cuts may exist for LGX, too. With SC-cuts found, smaller K_f implies that LGX would have lower film stress-frequency effects and lower thermal transient effects than quartz. Combined with the high Q of the material, the material is promising for yielding lower acceleration sensitivity and lower noise resonators than quartz.

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