Behavior of Quartz Crystal Resonators at Liquid Helium Temperature

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Abstract—**Bulk acoustic wave (BAW) quartz crystal resonators working at liquid helium temperature are an exciting topic of interest. Indeed, high-quality devices can exhibit quality factors of a few hundreds of millions, from tens of megahertz to hundreds of megahertz, and can reach a few billions for the best ones. As a consequence they are good candidates to various applications ranging from frequency references to fundamental physics. A brief review is first proposed regarding Q-factor properties of BAW SC-cut resonators within the temperature range 3K - 12K. The A, B and C mode behaviors are also examined in terms of frequency versus temperature, as well as the frequency dependence with the excitation power. Finally measurements on Nyquist noise are presented.**

I. INTRODUCTION

The behavior of bulk acoustic wave (BAW) quartz crystal resonators at liquid helium temperature has been a real topic of interest in the 1960's-1970's, in the theoretical domain as well as experimentally [1], [2], [3], [4], [5], [6]. Some studies have continued a few years later [7], [8], [9], and have been developed again from 2008 [11], [12]. Up to 2008, the operating temperature was reached by means of helium cryostats. From 2008, pulse-tube cryo-refrigerators have been used instead of cryostats, enabling longer experiments without needing helium supply. From these first experiments with cryo-refrigerators, measurements often revealed better results than those previously published in terms of quality factors, probably due to an improvement of the quartz crystal quality. More recently, it has been demonstrated that quality factors greater than 1 billion can be reached by the best units of bulk acoustic wave quartz crystal resonators working below 6 K [13]. Such low-loss resonators are good candidates for various applications including potentially very stable frequency sources but also experiments in fundamental physics involving acoustic cavities in quantum hybrid systems for example [14], [15], [16], [17], [18]. The devices tested in the frame of this paper are mainly doubly-rotated SC-cut quartz resonators. By means of their slowly varying thickness, these spherically contoured resonators look like plano-convex disks where the acoustic energy is trapped, according to Tiersten and Stevens theory [19]. They are initially optimized to work at room temperature on the 3^{rd} overtone of the C-mode, one of both quasi-pure thickness shear modes, at 5 or 10 MHz. After a short review of theoretical basis, some collected data are shown to illustrate the behavior of such resonators in the vicinity of 4 K, in terms of quality-factor, temperature, and power dependence versus frequency.

II. BACKGROUND

When operating at low temperature typically lower than 20 K, lower mechanical losses than at room temperature can be expected just because of the thermal phonon reduction. Nevertheless, this can be achieved provided that the engineered losses of the acoustic resonator are minimized. These engineered losses obviously include energy losses inside the holders because of a certain lack of trapping, scattering due to the surface roughness depending on lapping and polishing quality, but also absorption due to impurity and/or defect density according to the material quality. In short, the resulting loss $1/Q$ can be expressed as a sum of individual losses $1/Q_i$. Ideally, when all the engineering losses are minimized, the remaining losses are intrinsic losses due to phonon-phonon interaction and thermoelastic effect. Actually, the latter do not exist for shear modes (B and C modes) and even in the case of the extensional mode - the A mode- it can be shown that losses are no longer significant for frequencies typically greater than a few megahertz.

Regarding the interaction of the acoustic phonon with thermal phonons, mechanisms at cryogenic temperatures are different from those at 300 K. Indeed, the thermal phonon lifetime τ_{ph} increases as the temperature goes down below 10 Kelvins, and achieves the condition $2\pi f \tau_{ph} > 1$. Thus, the absorption coefficient $\alpha(f)$ of the propagating wave is changed, and in turn, the Q-factor which is proportional to $\frac{f}{\alpha(f) \times V}$ where f is the frequency, and V the corresponding acoustic wave velocity. At room temperature, $\alpha(f)$ is proportional to f^2 whereas at liquid-helium temperature, it becomes proportional to $T^4 \times f$ according to the Landau-Rumer theory [20]. It turns that the product $Q \times f$ is a constant at room temperature - a feature of the so-called Akheiser regime [21] - whereas Q does not depend on f anymore at liquid helium temperature. In addition, it behaves as $1/T^n$ with $1 < n < 9$ depending on whether the mode is a longitudinal or transverse one [4], [20], [22]. Fig. 1 shows a set of results at low temperature for resonators exhibiting a $Q \times f$ product slightly greater than $1\,10^{13}$ at room temperature. For temperature lower than about 6 K, it can be notice that the slope decreases towards $1/T^{1/3}$, which could be attributed to a two-level-dependency (TLS) effect [23] due to the presence of impurities [9] (see also [10]). Another feature that may be highlighted from Fig. 1 is that Q-values of the A mode are always greater than those of the B-mode which are themselves greater than those of the C-mode. It has been demonstrated that this is the result of the energy trapping whose efficiency can be sorted exactly like the observed losses [24] [11]. At least, it should be mentioned that a special attention should be paid to the high-Q measurements. The experimental set-up and the corresponding measurement procedure have already been described (see for example references [11] [25]). It can simply be reminded that three coaxial cables similar to that feeding the device under test (DUT) are ended at their cold ends by a 50-ohms load, a short-circuit, and an open-circuit respectively. Thus, the calibration procedure of the network analyzer can easily be used for measuring efficiently the impedance modulus and phase of the DUT, and then, the requested Q-value.

III. OTHER EXPERIMENTAL DATA

A. *Quality factors versus frequency*

When plotting the quality factor of a given mode against the frequency of its overtones, a constant Q-value would be expected according to Landau-Rumer theory, as mentioned above. Actually, as illustrated in Fig. 2, from low frequency values, Q-values usually increase as the frequency increases before being a constant up to the vicinity of 100 MHz from which Q-values decrease with frequency. At lower frequencies, this trend, hiding the expected constant value of the quality factor, can easily be explained: the higher the overtone order, the better the energy trapping. On the other end of the explored frequency range, the Q-value decrease at higher frequencies can be explained by scattering due to the surface roughness and/or the amorphous layer resulting from lapping and mechanical polishing [13].

B. *Frequency versus temperature*

Typical frequency-temperature behaviors are shown in Fig. 3. As expected at low temperature, one can observe that the frequency to temperature sensitivity decreases with the temperature like most material properties. Nevertheless, when taking into account the measurement uncertainty, there is no turning point seemingly. The latter would be needed for using a cryogenic acoustic resonator as the heart of a frequency standard.

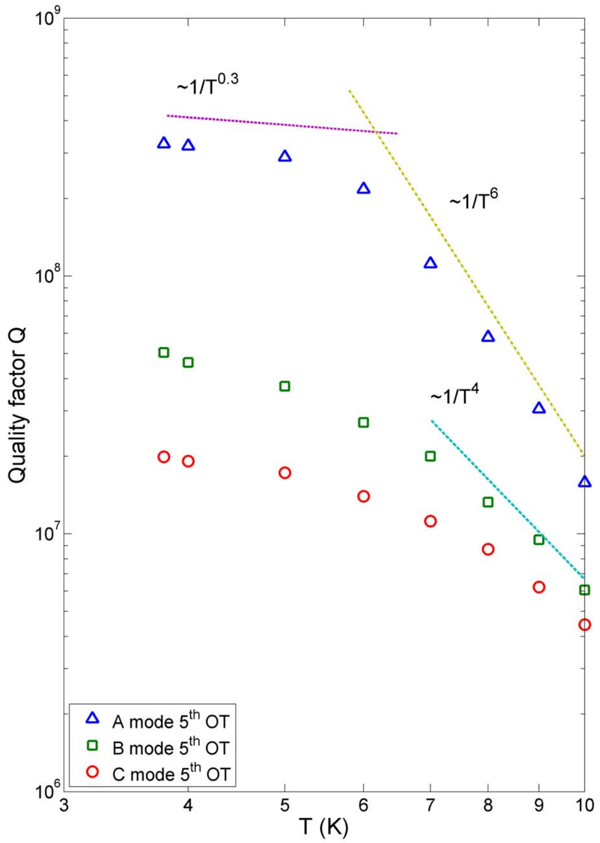

Fig. 1. Quality factor versus temperature for a 13 mm-diameter BVA-type resonator optimized to work at 5 MHz on the 3^{rd} overtone of the C-mode at room temperature. The frequencies of the 5^{th} OT are about 8.400 MHz, 9.197 MHz and 15.597 MHz for the C, B and A mode respectively.

IV. NONLINEARITIES

Wrong values of Q-factors may result of an excess of feeding power. As an example, plots of the impedance modulus and phase shown in Fig. 4 demonstrate that slopes strongly depend on the excitation power.

Beyond this mishandling, the issue of the dissipated power inside the resonator becomes relevant because of the high quality-factors Q. Indeed, the energy stored inside the resonator can be expressed as: $E_{stored} = Q \times p \times 1/\omega_0$, where p is the power dissipated inside the resonator (i.e. in the motional resistance), and ω_0 the resonance angular-frequency. So, the excitation power should be very weak to avoid nonlinearities as well as an excessive dissipation, and justifies values typically in the order of one nano-watt (see Fig. 4). It can also be noticed that a ”high” excitation power can lead to a visible frequency shift during the measurement, resulting from an increase of the resonator temperature.

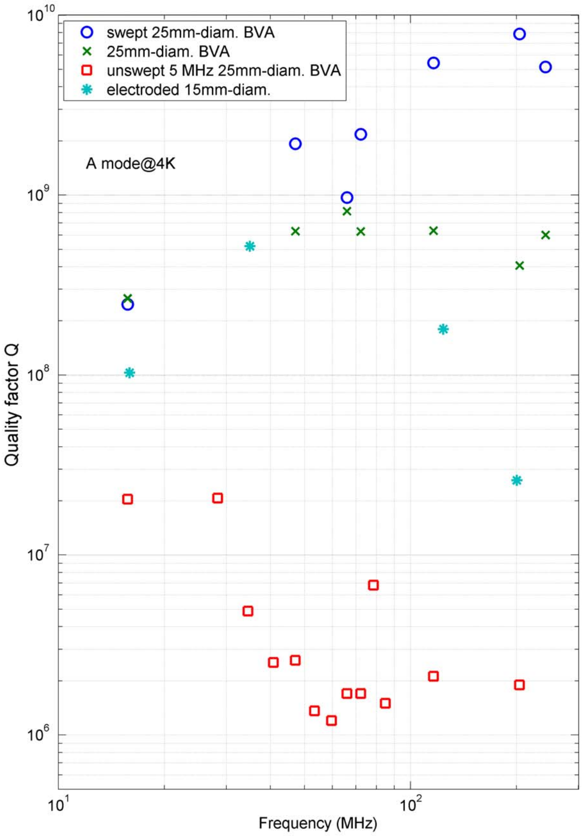

Fig. 2. Q-values versus frequencies of A-mode overtones at 4 K for various type of resonators originally optimized to work at 5MHz on their 3^{rd} overtone at room temperature. The best resonator is seemingly an exceptional unit. Conversely, an unswept material can provide a very bad resonator in terms of Q-values at low temperature, even if at room temperature this resonator exhibits Q-values very similar to that of a premium-quality resonator.

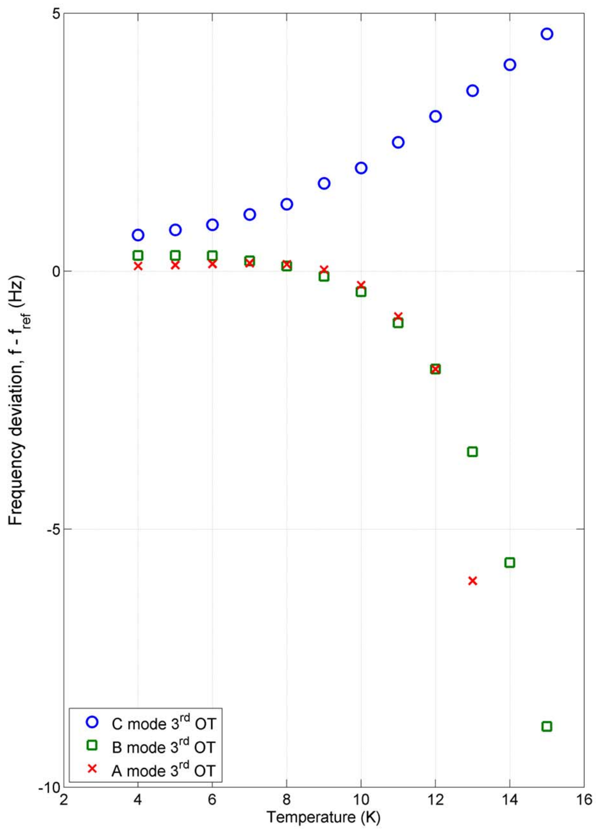

Fig. 3. Frequency deviation versus Temperature. The reference frequencies f_{ref} are 4993048.0 MHz, 5505583.0 MHz, and 9410720.0 MHz for the 3^{rd} overtones of the C-mode, B-mode and A-mode respectively. Temperature uncertainty is about ±0.1 K whereas frequency uncertainty is ±0.05 Hz.

V. NYQUIST NOISE

Recently, thermal Nyquist noise fluctuations of a high-Q BAW resonator have been observed at cryogenic temperatures [26]. The device was coupled with a DC superconducting quantum interference device (SQUID) amplifier. One of the goals of this step was to confirm whether or not BAW devices are dominated by intrinsic Nyquist noise due to quantum or thermal fluctuations when the carrier is not present. Actually, this observation is an important step towards the preparation of a BAW resonator in the quantum ground state which would be one the ultimate aim. Moreover, this work is obviously one step towards a frequency source based on very high Q-factor mechanical resonator. It combines the benefit of high-Q resonators to low-noise superconducting technology. Fig. 5 illustrates one of the measurement result. Data can be fitted by a lorenzian plot as a function of the motional resistance, from which the Nyquist noise originates. The integral of this Lorenzian fit is proportional to the power p dissipated inside the resonator (see section ”Nonlinearities” above), when assuming a constant SQUID transfer function within the analyzed frequency range. Details are given in ref [26].

VI. CONCLUSION

This digest on features of cryogenic BAW resonators highlights properties of matter related to these specific operating conditions. For example, quality factors can increase from one million at room temperature to hundreds of millions at cyogenic temperature. Some applications can obviously take advantage of these outstanding features such as ultra-stable frequency sources, but also experiments of fundamental physics [15], [18]. Regarding frequency source the next step will be to look for a temperature compensated cut. Measurements of the elastic coefficients of quartz at liquid helium temperature are currently in progress.

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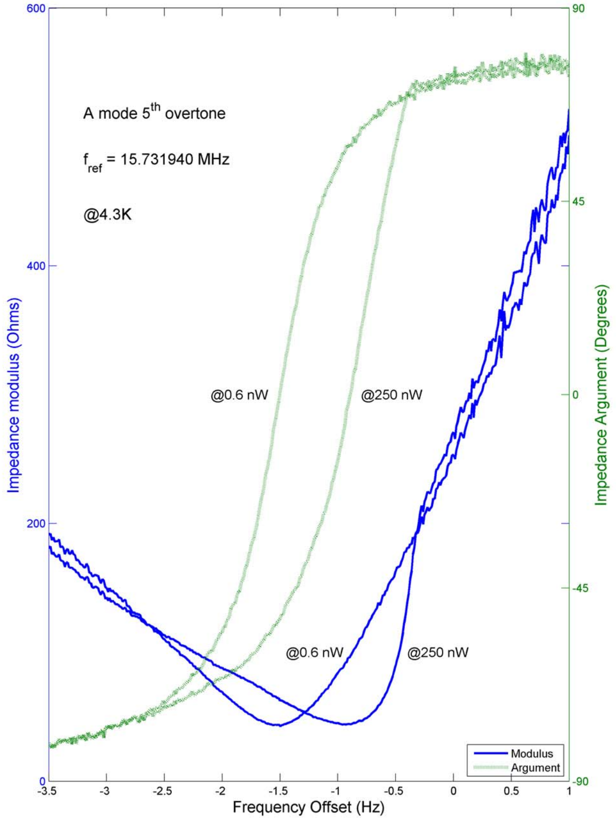

Fig. 4. Impedance argument and phase versus frequency offset (with respect to 15.731940 MHz) for two different feeding powers, when the resonator is at 4.3 K.

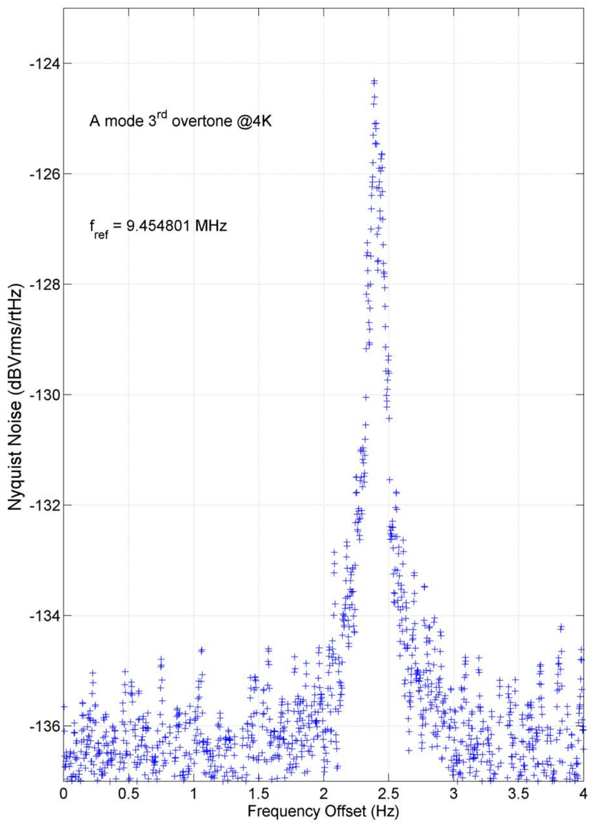

Fig. 5. Nyquist noise around the 3^{rd} overtone of the A-mode at 9.454801 MHz.

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