Bulk Acoustic Wave Resonator Thermal Noise Measurements

M. Goryachev, E.N. Ivanov, S.R. Parker, J. Winterflood, M.E. Tobar
ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, University of Western Australia, Crawley, Australia
E-mail: maixm.goryachev@uwa.edu.au

S. Galliou
Time and Frequency Department
FEMTO-ST Institute
Besancon, France

***Abstract*—This work presents some progress in thermal noise measurements of quartz Bulk Acoustic Wave resonators. A simple system based on low-noise broadband operational amplifiers demonstrates the ability to detect thermal noise of state-of-the-art BVA quartz resonator both at room and cryogenic temperatures.**

Keywords— quartz resonators; thermal noise; cryogenic operation; low noise operational amplifier

I. INTRODUCTION

Precision frequency generation using quartz Bulk Acoustic Wave (BAW) resonators has been extensively studied over the last half a century. Most of the aspects of fabrication and behavior has been carefully analyzed and taken into account. Thus the question has arisen if this technology is capable of further improvement. Since performance of many state-of-the-art quartz oscillators is limited by their own phase noise, improvement can be achieved either by providing higher Q.f-products or lower self-noise. One of the attempts to answer this question is to investigate quartz BAW devices at cryogenic temperatures. Demonstration of record high Q-factors and Q.f-products [1-3] have been recently achieved. In addition, some new sources of nonlinearities [4] and impurities [5] have been discovered at low temperatures. However, it is also necessary to understand the resonators own phase noise with the aim of reducing its level. Despite extensive measurements of quartz resonator phase noise in the recent years, its mechanism is still unknown. The intrinsic limit of the resonators self-noise normally observed in many dissipative system is thermal noise, and despite a long history of quartz BAW resonators development, the thermal noise limit has never been measured. Moreover, another motivation for thermal noise measurements comes from the area of quantum measurement, where characterization of noise and fluctuations in mechanical systems is an important milestone towards observation of quantum ground states in such systems.

II. PRELIMINARY MEASUREMENTS

The reason why thermal noise of high-frequency BAW quartz resonator devices has never been directly observed experimentally is due to its challenging nature, whereby one requires an amplifier with low current noise, high input impedance and low stray input capacitance in order to prevent low-pass filtering of the thermal fluctuations. It is difficult to satisfy these technical requirements in the relevant frequency range (5–10 MHz). By comparison, thermal noise in low-frequency (10-100 kHz) tuning-fork mechanical quartz resonators can be observed by using readily available high input impedance amplifiers.

In this work, the measurement problem is solved by implementing a high input impedance amplification stage, based on a low noise and ultra-high speed Operational Amplifier ADA 4817 (LFCSP package). The gain-bandwidth product of this amplifier is 500 MHz. The amplifier current and voltage noise are 2.5 fA/rtHz and 7 nV/rtHz respectively. The stray capacitance at the input port of the amplifier is approximately 8.5 pF. This stray capacitance, along with the large resistance of the BAW resonator (~30 kOhm), sets the upper boundary of the accessible resonant frequencies to approximately 10 MHz.

The Device Under Test (DUT) in this work is an SC-cut BVA quartz resonator. Motional parameters of this particular device have been investigated earlier [1-2]. In particular, extremely high values of the quality factor for different overtones (OT) of the longitudinal mode have been achieved at milli-kelvin temperatures. Nevertheless, in this work we investigate only the 3rd OT of the C-mode, partially due to its convenient frequency (about 5 MHz), and partially due to the high electro-mechanical coupling factor at room temperatures.

This work was supported by Australian Research Council grants CE110001013 and FL0992016.

978-1-4799-4915-1/14/$31.00 ©2014 IEEE

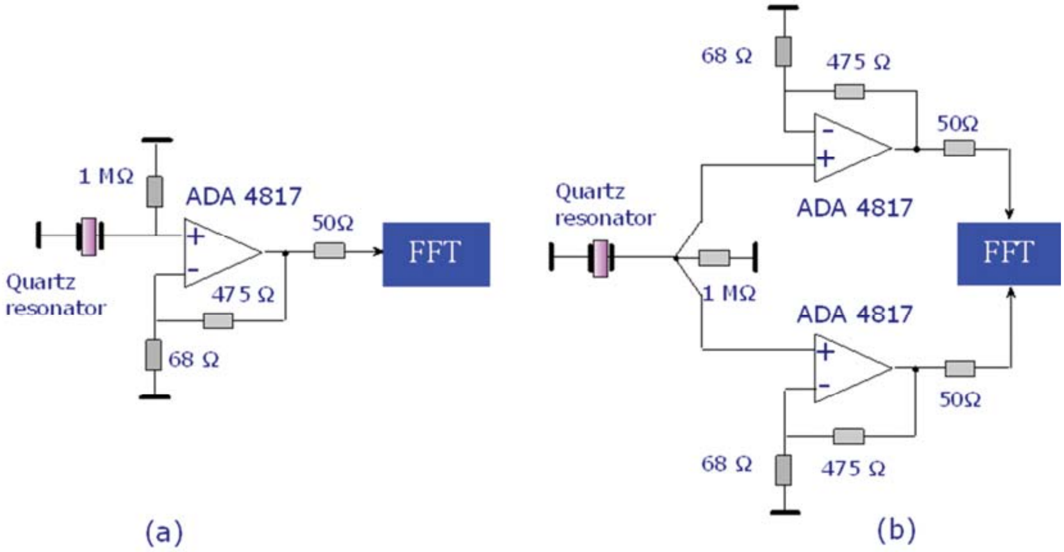

Fig. 1. Noise measurements systems used for observations of thermal fluctuations in the 5 MHz BVA quartz resonator.

In order to find out whether the system is able to detect the thermal noise arising from a quartz BAW, one can compare measurements made with 50 Ohm and 30 kOhm loads, where the latter load matches closely the impedance of the quartz BVA resonator at the frequency of its anti-resonance. Thus, the ratio between noise amplitudes of these measurements is able to predict a signal-to-noise ratio. The one channel noise measurement system is shown in Fig. 1 (a). The corresponding measurement results for the two values of loading are shown in Fig. 2; according to these voltage noise spectra the expected height of the thermal noise peak at 5 MHz above the background noise is close to 3 dB.

The signal-to-noise measurements in this system can be improved by implementation of the double channel measurement scheme shown in Fig 1 (b). In this case, the measurement apparatus calculates the spectral densities of the individual processes, as well as their cross-spectrum. This scheme has a well-known advantage over the single channel approach: the uncorrelated noise of amplification stages can be removed from the final spectrum. For this purpose two identical amplifiers were built. The spectral resolution of the dual-channel noise measurement system was measured to be approximately 5 dB better relative to the single-channel system. This relatively modest improvement was due to the increased low-pass filtering of the input signal: parallel connection of the front ends of two operational amplifiers doubled the input stray capacitance. The results of preliminary measurements at room temperature are shown in Fig. 3

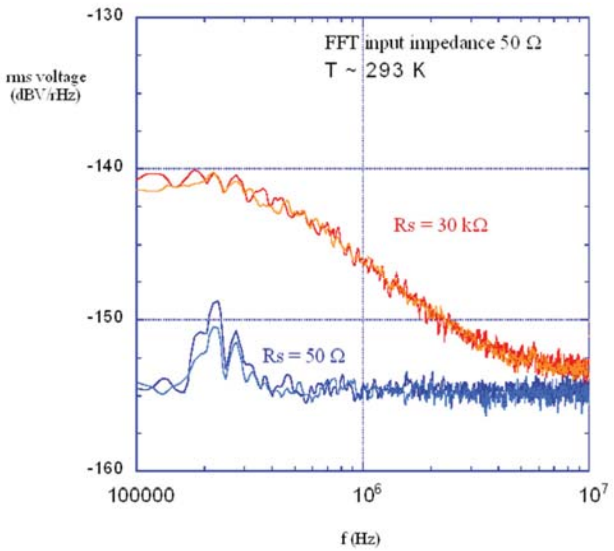

Fig. 2. Voltage noise spectra at the output of a single-channel noise measurement system with different loads at the input of the operational amplifier.

III. QUARTZ THERMAL NOISE MEASUREMENTS

Since the double channel measurement system is able to reliably detect thermal fluctuations of a resistor corresponding to the quartz device anti-resonance at 5 MHz, it was implemented for both cryogenic and room temperature measurements. A series of measurements were made at room, liquid nitrogen and liquid helium temperatures. For the cryogenic cases, the first amplification stage is also cooled to about 77 K. Two identical amplification stages were used to realize a cross-correlation type of measurement, which allowed us to detect noise coming from a BAW resonator at its working frequency near 5 MHz. The measured noise peaks precisely coincide with the measured anti-resonance of the mode, where the device exhibits a very high impedance. The result is shown in Fig. 3 where both one and two channel results for room temperature preliminary measurements are shown.

Next the entire measurement system was cooled down. The Device Under Test was put at the lowest temperature stage reaching 4 K, the amplifiers were placed at the intermediate 50 K stage of the cryocooler. The gains of the LNAs were found to be almost independent of physical temperature down to 80 K. We observed almost no noise floor improvement from cooling the amplifiers down. Futhermore, both amplifiers did

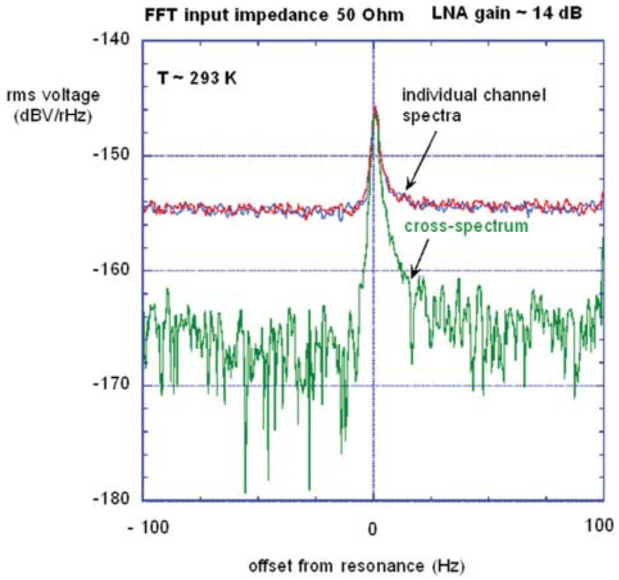

Fig. 3. Voltage noise spectra at the output of a single-channel and dual-channel noise measurement systems at 293 K.

not operate below 50 K; this is most likely related to the carrier "freeze-out" effect in silicon.

The measurement results of noise from the quartz BVA resonator in liquid nitrogen (55-77 K) and liquid helium (4.5 K) temperature ranges are shown in Figs. 4 and 5 correspondingly. As the BAW device is cooled the frequency of the anti-resonance decreases. While the physical temperature of the BAW resonator has been reduced, the impedance at the anti-resonance increases. The net result is that the level of thermal noise generated by the BAW resonator at cryogenic temperatures does not decrease as much as one might initially expect. As such, we are still clearly able to resolve the signal with both measurement systems.

IV. FUTURE PERSPECTIVES

For cryogenic applications of quartz BAW resonators the ultimate sensitivity in noise measurements could be achieved using superconducting technology. Indeed application of SQUIDs (superconducting quantum interference device) in many areas of physics proved their high sensitivity and low noise performance. This approach allows nearly quantum-limited characterization of these extremely low loss devices.

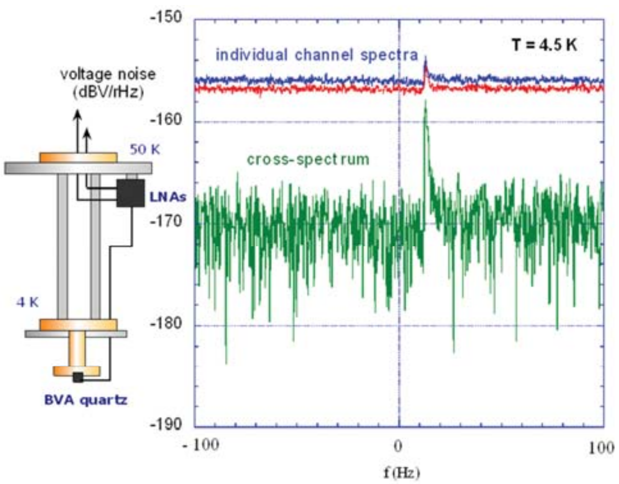

Fig. 5. Cut-view of the cryostat and voltage noise spectra at 4 K: LNA current ~ 20 mA, LNA heating power ~ 1.4 W. FFT resolution bandwidth 300 mHz

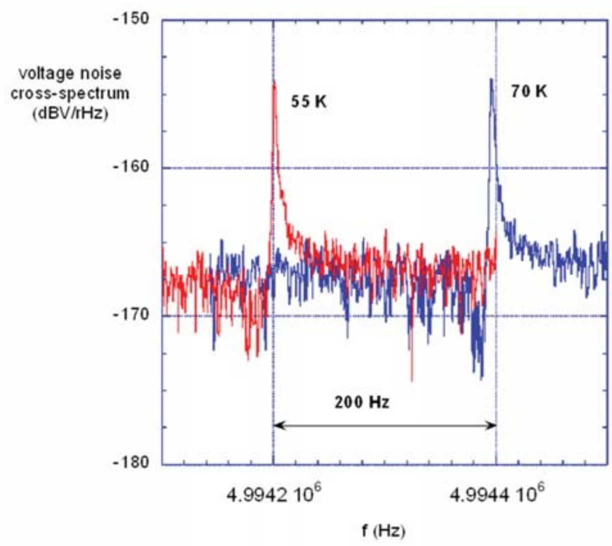

Fig. 4. Cross-spectra of voltage fluctuations at 77K.

Early work at 4 K with a commercial DC SQUID amplifier and a single-channel measurement system indicates a 12 dB improvement in sensitivity relative to the single-channel measurements involving the JFET low-noise amplifiers utilized in Figs. 3-5.

REFERENCES

[1] M. Goryachev, D.L. Creedon, E.N. Ivanov, S. Galliou, R. Bourquin, M.E. Tobar, "Extremely low-loss acoustic phonons in a quartz bulk acoustic wave resonator at millikelvin temperature", Appl. Phys. Lett. vol. 100, 243504, 2012.

[2] S. Galliou, M. Goryachev, R. Bourquin, Ph. Abbe, J-P. Aubry, M.E. Tobar, "Extremely Low Loss Phonon-Trapping Cryogenic Acoustic Cavities for Future Physical Experiments", Nature: Scientific Reports, v. 3, 2132, 2013.

[3] M. Goryachev et al, "Observation of Rayleigh phonon scattering through excitation of extremely high overtones in low-loss cryogenic acoustic cavities for hybrid quantum systems", Phys. Rev. Let., vol. 111, 085502, 2013.

[4] M. Goryachev, W.G. Farr, E.N. Ivanov, M.E. Tobar, "Anomalously strong nonlinearity of unswept quartz acoustic cavities at liquid helium temperatures", J. Appl. Phys. vol. 114, 094506, 2013.

[5] M. Goryachev, W.G. Farr, M.E. Tobar, "Giant g-factors of natural impurities in synthetic quartz", Appl. Phys. Lett. vol. 103, 262404, 2013.