Low drive level sensitivity (DLS) of quartz crystal resonators

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Abstract: This work is a contribution to a better understanding of the DLS mechanism. The paper describes an experimental set-up allowing resonator's motional parameter measurements with variable drive level as low as – 100 dBm in a controlled temperature enclosure. As the drive level becomes very low, measurement becomes more and more noisy and difficult to exploit. Specific experimental procedures and data processing required to improve the signal-to-noise ratio are described. Resistance vs. drive level curve of several crystals exhibiting DLS reveal different behaviours that have been investigated. Phase noise measurement of resonators exhibiting DLS by using a high performance interferometric instrument developed in our lab are currently being performed at the idea of answering the question of the correlation between the two phenomena. Eventually, by using a submicron resolution scanning electron microscope, a number of surface defects have been observed on the surface of the resonators exhibiting DLS. The responsibility of these defects for the DLS is discussed.

1. INTRODUCTION

Drive Level Dependency (DLD) or Drive Level Sensitivity (DLS) of quartz resonators, i.e. the increase of the resonator's series resistance at low drive level is known for about fifty years [2, 3, 4, 12, 16, 20]. Very early, that phenomenon has been attributed to surface defects coming from microscopic scraps of various origin often associated with a sticky surface coating or surface scratches. A lot of work and experiments have been done and many models have been described to explain the DLS mechanism and to correlate the resistance increase with the surface defects [8, 9, 10, 11, 13, 14]. Attempts also have been made at relating the DLS with the noise of the resonator with contradictory conclusions [1, 6]. On the other hand, the need for resonators of higher and higher performance in the domain of telecommunication and/or space localization encourages to further investigate on this phenomenon. The reader can refer to [5] for a more complete bibliography on the DLS.

II. DESCRIPTION OF THE DLS

A large number of experiments carried on for decades have led to the following observations:

– Increase of the series resistance is always associated with a positive or negative frequency shift,
– The DLS "signature" strongly depends on temperature,
– The DLS behaviour can be modified or suppressed permanently or temporarily by overdriving the resonator, by polishing, etching or cleaning the crystal. Cleaning is often considered the most efficient [7, 13],
– The most disconcerting aspect of this phenomenon is its lack of reproducibility. Crystals seemingly identical may be drive sensitive or not, and DLS of crystals apparently cured may reappear after a long time of inactivity.

A lot of work and efforts have been put into understanding the origin of the phenomenon, and very early the attention has been focused on the surface imperfections as a possible cause of DLS. Among the most often reported defects one can cite:

– Particles of metal, quartz, or abrasive,
– Thin coat of resin or oil,
– Surface scratches,
– Flaking of quartz surface or metal electrode,
– Poorly adhesive electrodes or blisters,
– Surface stress.

Various experiments have proved the relationship of cause and effect between the surface pollution and DLS. For example, talc blown in the vicinity of an unsealed quartz resonator may induce DLS [4]. Another interesting and dramatic demonstration of the correlation between surface contamination and DLS has been reported a few years ago [6]: a 100 MHz 5th overtone AT-cut crystal resonator exhibiting no noticeable DLS has been opened and the surface has been sprinkled with alumina particles, after the resonator has been resealed, it presented an important DLS, and once the resonator has been reopened, cleaned and resealed, it approximately recovered its original state (Fig. 1). It should be noted first that a single particle not bound to the surface, cannot induce the observed phenomenon.

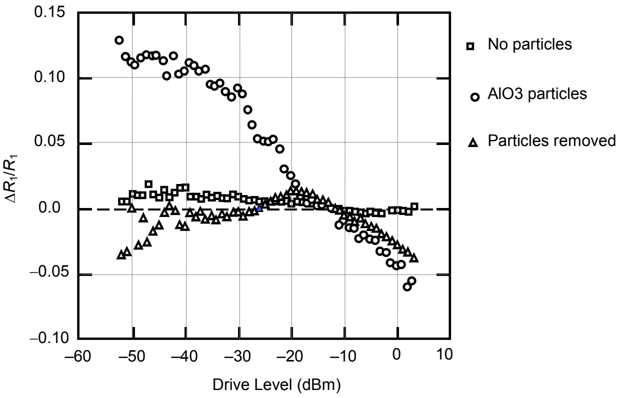

Figure 1: *Effect of a surface contamination* [6].

Similarly, a particle tightly bound to the surface acts as a loading mass and thus induces a negative frequency shift, which is often refuted by experiments. So, the observed phenomenon can be explained only if the particle is bound to the surface by an elastic force that can be due to a thin sticky coating of oil or resin, or any other attractive force such as Van der Waals, electrostatic, or capillarity forces for example. In this case, as the surface moves back and forth under the shear motion, the bounded particle acts as a small oscillating system that absorbs a part of the vibrating energy. Although this simple coupling system does explain that the resonant frequency can either decrease or increase, it doesn't account for the drive level sensitivity of the damping term that should be explained only if some non-linear mechanism is involved. Dworsky [8] has proposed a model assuming that the particles trapped in some surface imperfections experience inelastic collisions with scratch walls, thus inducing the required non-linear damping term.

III. EXPERIMENTAL SET-UP

Some preliminary experiments have been performed by using an Agilent 4395A Network-Spectrum-Impedance Analyser and the 43961A Impedance Kit [23]. The accuracy of the measurements has been improved by using a precision oven keeping the crystal at its turnover point as shown in Fig. 2. In addition, to comply with the standard motional parameter measurement technique, the experimental set-up has been modified as shown in Fig. 3 that implements the popular pi-network IEC–444 [15, 22]. A problem with our arrangement is that the network analyser is no longer able to extract the motional parameters, as it would do in normal conditions, and the measurements becomes more and more doubtful as the drive level decreases. So, the measurement relies only on amplitude and phase of the transfer function and on our own algorithms.

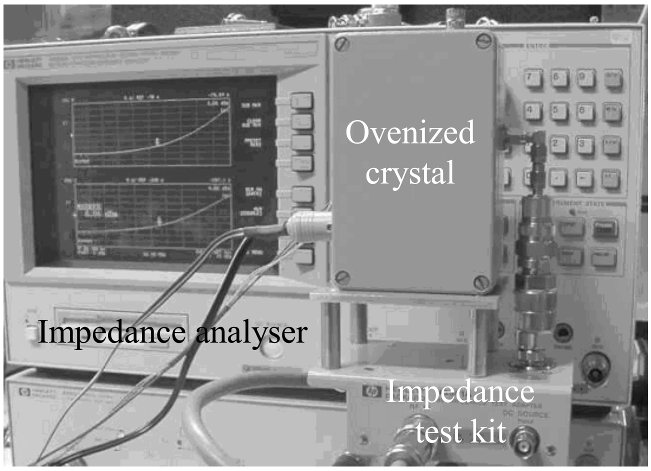

Figure 2: *Experimental set-up*.

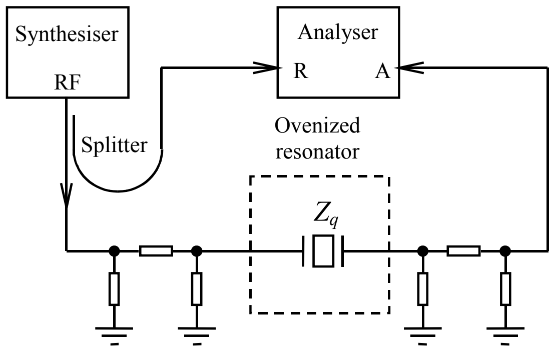

Figure 3: *Set-up using pi-network IEC–444*.

IV. DATA PROCESSING

Let first recall that in the Nyquist plane, the admittance of a resonator represented by its classical Butterworth - Van Dyke equivalent circuit shown in Fig. 4 follows approximately a circle whose diameter is the inverse of the series resistance R_q and the centre coordinates are $(\frac{1}{2R_q}, \omega_q C_p)$ where ω_q is the series resonant frequency and C_p the parallel capacitance (Fig. 5).

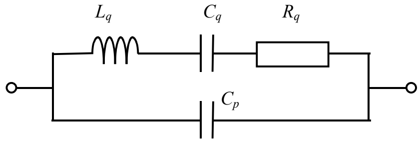

Figure 4: *Butterworth – Van Dyke equivalent circuit.*

The algorithm used to extract the motional parameters as well as their uncertainty from the experimental data is inspired by the method proposed by R. J. Williamson [19]. Given N measures of the real and imaginary parts (x_i, y_i) of the admittance, at frequencies f_i equally spaced over a span Δf around the resonance, our problem is to calculate the centre coordinate (x_0, y_0) and the radius r_0 of the fitting circle (Fig. 6).

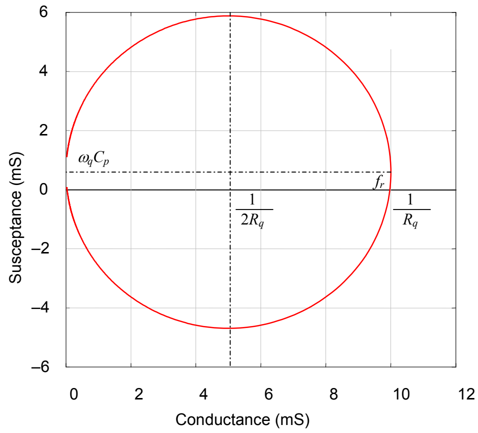

Figure 5: *Resonator admittance circle.*

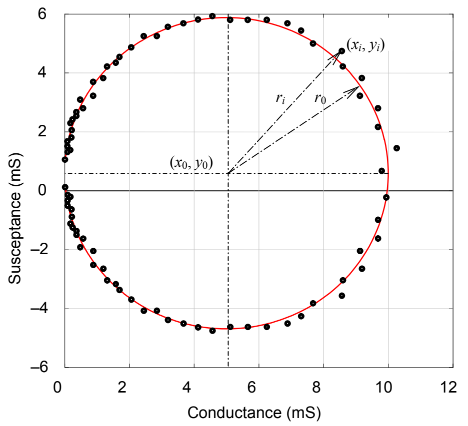

Figure 6: *Least squares fitting.*

Among several possible criteria to measure the closeness between the experimental data and the rebuilt circle, the best result has been obtained by using a norm defined as the difference between the square of the experimental radius r_i and the expected radius r_0:

$$\varepsilon(x_i, y_i, x_0, y_0, r_0) = r_i^2 - r_0^2 = (x_i - x_0)^2 + (y_i - y_0)^2 - r_0^2$$

A cost function is then defined as the quadratic sum of the norms associated with each one of the N experimental data:

$$E(x_0, y_0, r_0) = \sum_{i=1}^{N} [\varepsilon(x_i, y_i, x_0, y_0, r_0)]^2$$

The unknown centre coordinates (x_0, y_0) and the radius r_0 of the expected circle are eventually calculated by a least square method that amounts to solve the following set of three partial derivative equations:

$$\begin{cases} \dfrac{\partial E(x_0, y_0, r_0)}{\partial x_0} = 0 \\ \dfrac{\partial E(x_0, y_0, r_0)}{\partial y_0} = 0 \\ \dfrac{\partial E(x_0, y_0, r_0)}{\partial r_0} = 0 \end{cases}$$

$$r_0 > 0$$

Usually, 401 data points equally spaced over a span of ± 250 Hz on either side of the resonant frequency have been used in the experiments presented in the next section. Fig. 7 shows the experimental data obtained with a –70 dBm drive level and the fitting circles calculated by the analyser internal algorithm and by the least squares method described above. An estimation of the uncertainty δ in the radius determination can be obtained by calculating the average difference between the experimental radii r_i^2 and the calculated radius r_0^2:

$$\delta = \frac{1}{N} \sum_{i=1}^{N} \frac{r_i^2 - r_0^2}{r_0^2} = \frac{E(x_0, y_0, r_0)}{N r_0^2}$$

In all experiments performed: $\delta < 1$ %.

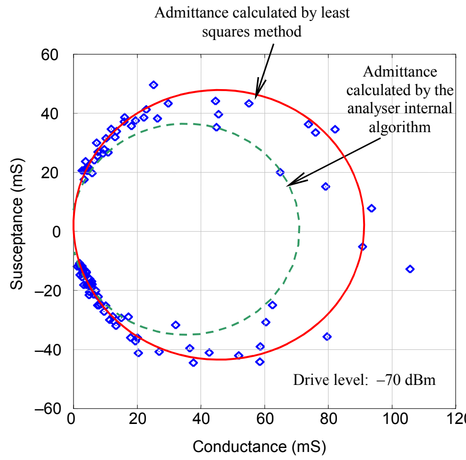

Figure 7: *Internal algorithm and least squares fitting.*

V. DLS MEASUREMENTS

We have measured a set of 11 resonators of frequency about 13 MHz AT-cut fundamental among which some pieces exhibited a strong DLS. The average series resistance of the group has been found to be about 10–20 Ω. This set has been mainly used to validate the correctness of data processing. Due to the resistance bridges of the pi-network, the drive level range was approximately –60 dBm to 0 dBm.

Fig. 8 shows a general picture of the series resistance vs. drive level of the group where it is obvious that parts #1, 3, 12, and 14 have a strong DLS, parts #5, 6, and 8 have a less marked defect, while parts #2, 4, 7, and 20 have no perceptible DLS.

To assess the reliability of the measurement procedure and data processing, five frequency sweeps are performed for each value of the drive level, Fig. 9 shows a pretty good reproducibility of the different sweeps.

As outlined in Sec. II and quoted in the literature [9, 10, 11], the resonator series resistance is not the only parameter affected by the DLS. From the admittance measurements, it is possible to obtain the resonant frequency f_r as the intersection of the admittance circle with the real axis (Fig. 5) and to plot this parameter vs. drive level as shown in Figs. 10 to 12. It can be observed in theses figures that the resistance change is always associated with an important frequency shift. Correlation between these two parameters can be evidenced by plotting the resistance change against the resonant frequency change.

For resonators having no DLS this representation would reduce to a single point since the two parameters do not depend on the drive level, for resonators having a marked DLS, the representation in the plane (*resistance* vs. *frequency*) forms more or less interlaced cycles that reveal a high degree of correlation as shown in Figs 10 to 12.

After the first set of measurements, the resonators under test have been left fifteen days at rest and measured again. The curves obtained (in dotted line in Figs. 10 to 12) show that some parts seem cured, while other ones still have a DLS with a different location.

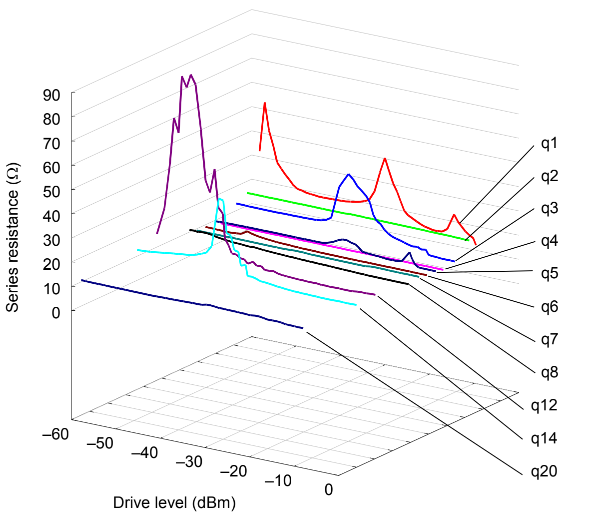

Figure 8: *Series resistance of a set of 11 resonators.*

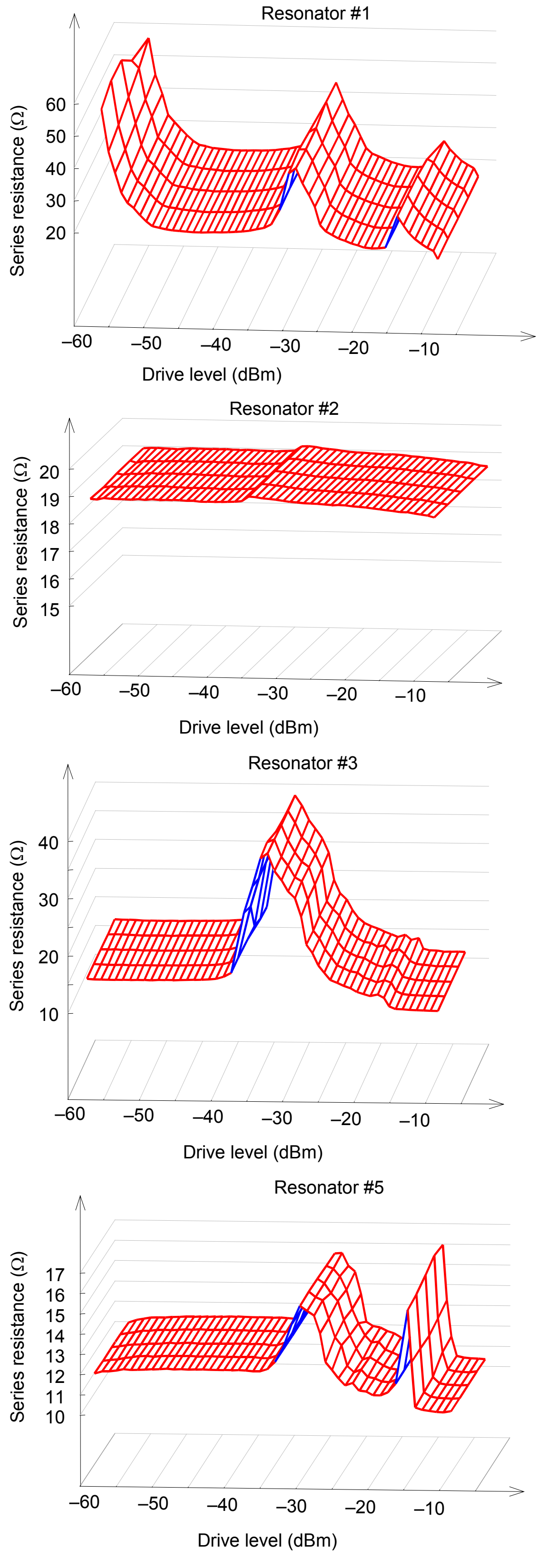

Figure 9: *Series resistance of some resonators.*

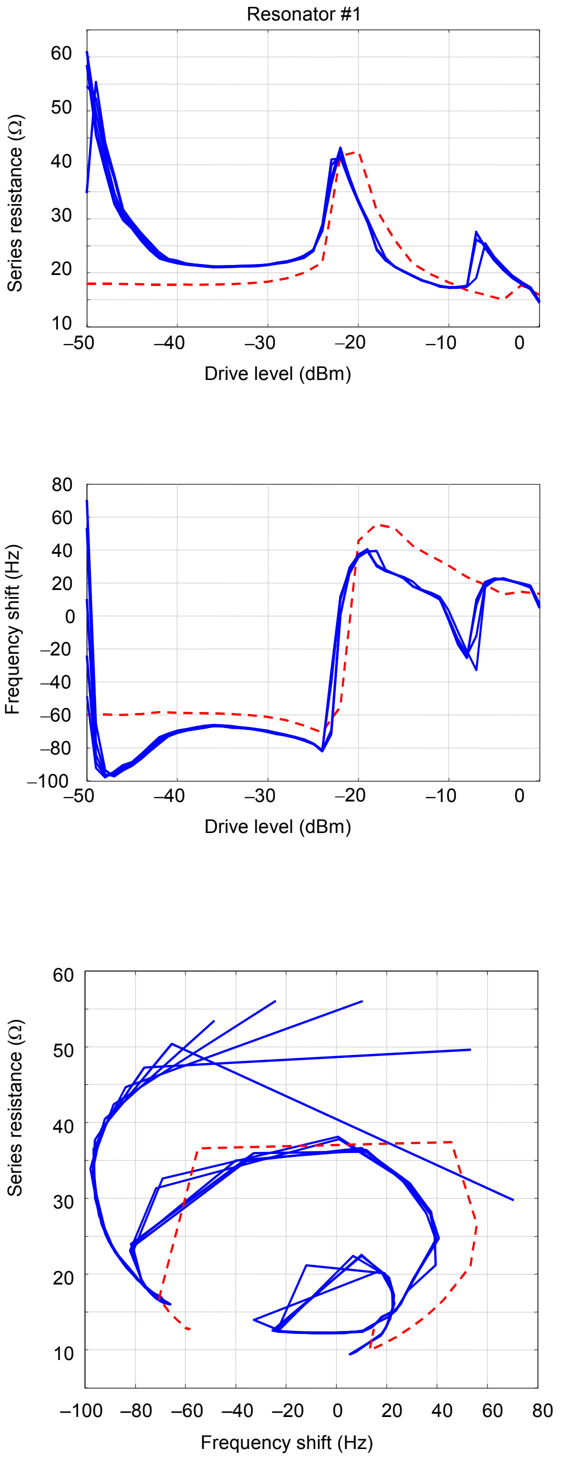

Figure 10: *Series resistance and resonant frequency of some resonators.*

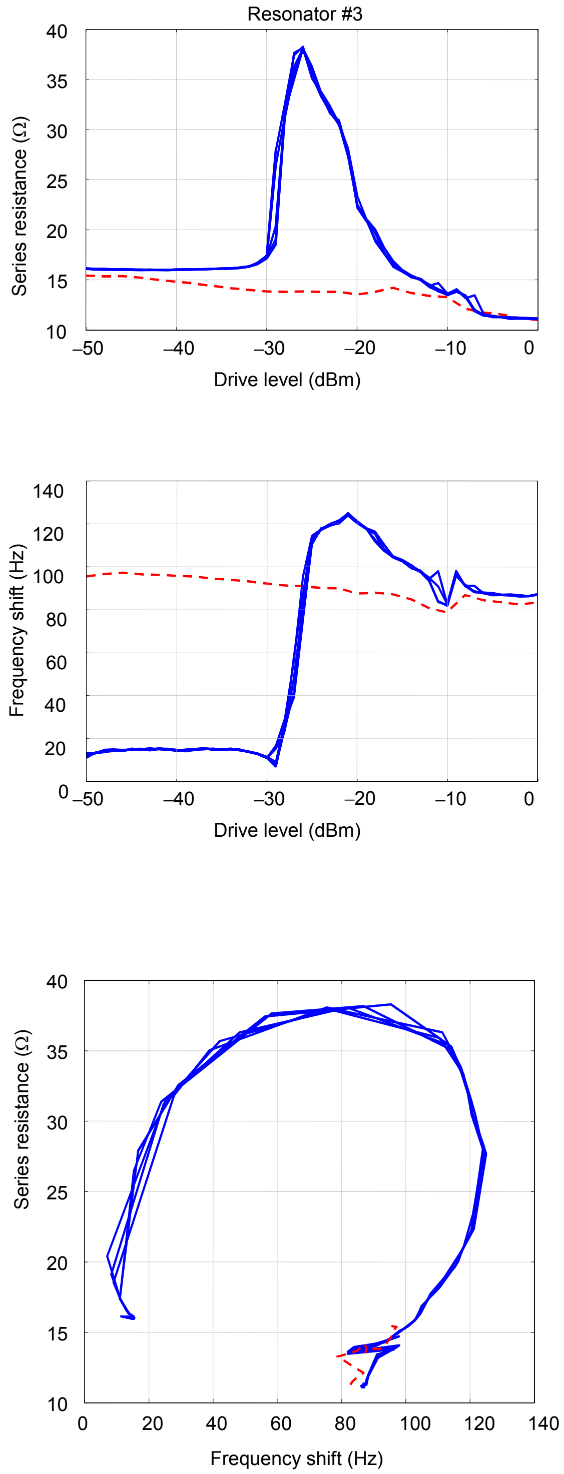

Figure 11: *Series resistance and resonant frequency of some resonators.*

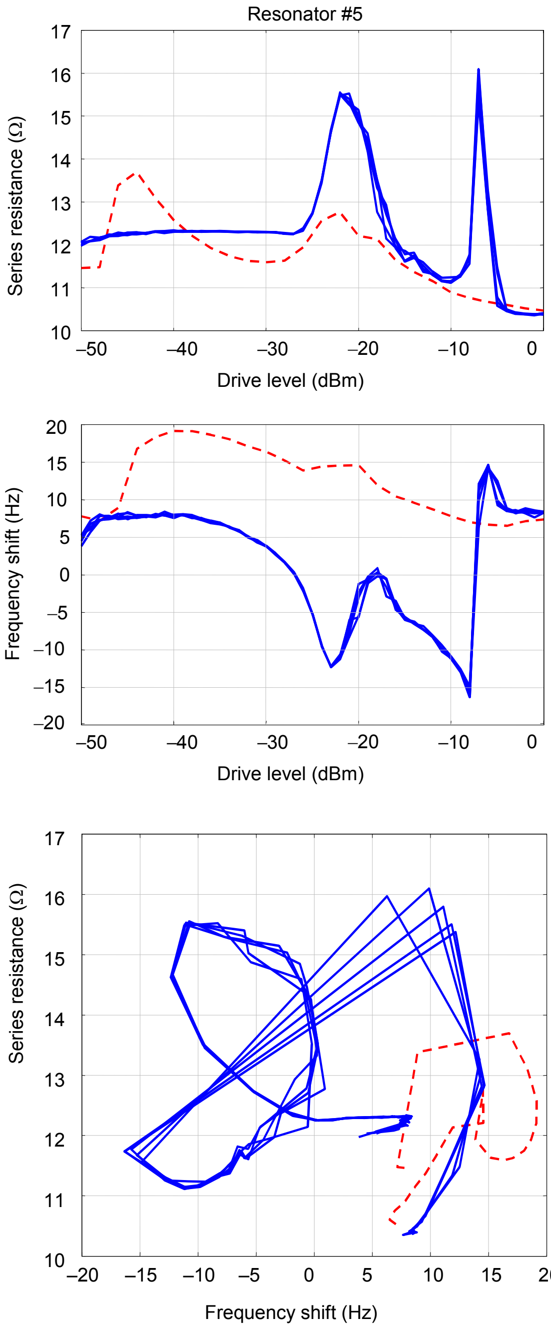

Figure 12: *Series resistance and resonant frequency of some resonators.*

VI. SURFACE SCANNING

Two of the 11 parts have been opened to examine their surface by using a scanning electron microscope. Fig. 13 is a picture of one of the taken down resonators. Numerous defects are observable in Figs. 14 and 15, in particular a blister in the electrode of the resonator #1 and two fragments, probably of quartz, on the surface of the resonator #2. In this latter case, the sharpness of the outlines indicates that the fragments have been trapped by the electrode plating during the fabrication process, in which case they cannot move anymore and cannot play a role in the DLS. Nevertheless, it is highly probable that other smaller particles, trapped in the numerous surface defects with a more or less degree of freedom, vibrate in their trap and thus take part in the DLS mechanism in absorbing a part of the acoustic energy.

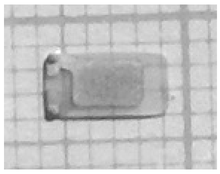

Figure 13: *Resonator* #1.

Figs. 14 and 15 show that the surface of resonators #1 and #2 are particularly irregular compared with the surface of a test resonator coming from another source (Fig. 16).

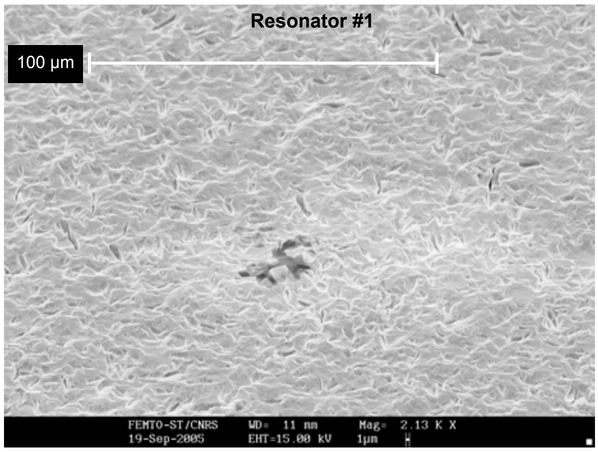

Figure 14: *Surface of resonator* #1.

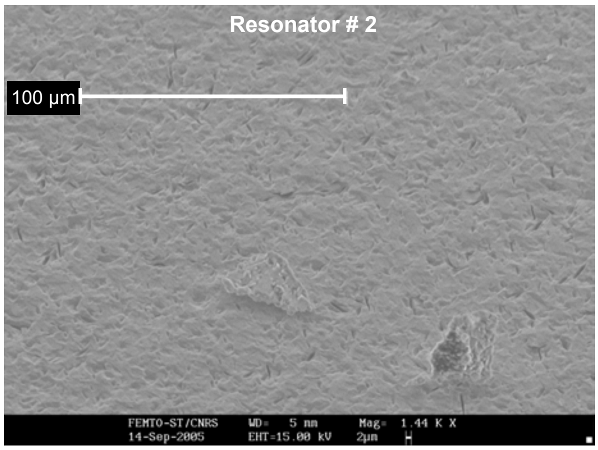

Figure 15: *Surface of resonator* #2.

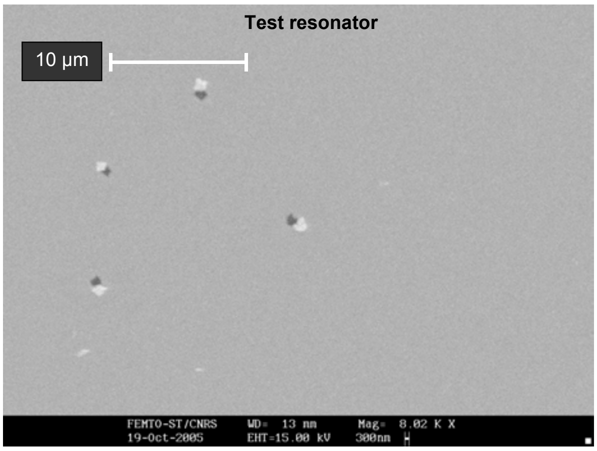

Figure 16: *Surface of a test resonator*.

VII. NOISE AND DLS

The main reason why these experiments are currently carried out is to check for a possible correlation between drive level sensitivity and noise of the resonators that should have the same origin. One of the possible mechanisms relating these two phenomena has been suggested in the past [21].

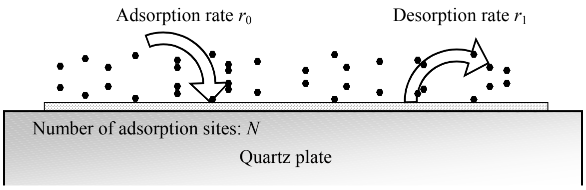

Figure 17*: Noise induced by a contaminant species* [21].

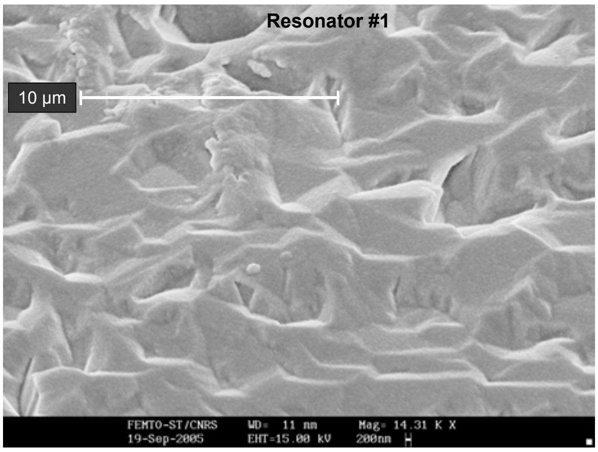

Figure 18: *Enlargement of Fig.* 14.

It assumed that some contaminant species are randomly trapped to and released from N possible surface sites at different rates, each trapped particle causing an average relative frequency shift $\Delta f/f$ (Fig. 17). This assumption can be considered plausible in looking at Fig. 18, which is an enlargement of Fig. 14, where a large number of surface defects, clearly visible in the picture are so many possible traps for contaminants.

Nevertheless, experimental verifications of the expected correlation between drive level sensitivity and resonator noise investigated so far have led to contradictory conclusions [1, 6] so that the question remains open.

A new series of experiments is going to be started to clarify this question based on the following assumptions:

- Small particles located on the surface of a resonator exhibiting DLS often induces large frequency change.
- Submicron particles located on or near the surface of most resonators could bring about DLS not measurable at normal drive level but evidenced only at very low drive level and could also be partly responsible for the frequency noise of the resonator.
- Correlation between noise and DLS, if any, should be demonstrated by performing noise and DLS measurements in the same experimental conditions and, if possible, at the same time.

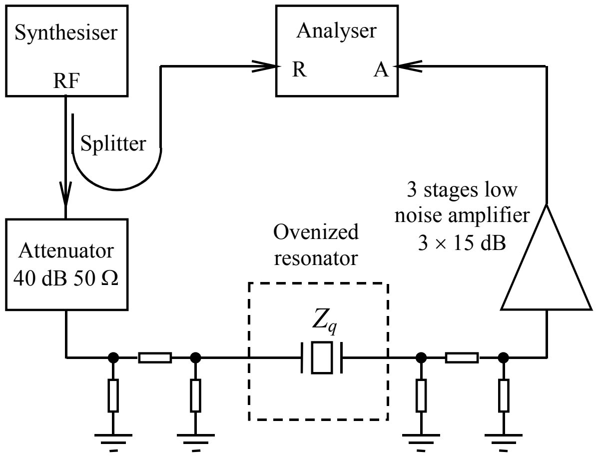

Figure 19: *Dedicated set-up for low level measurement*.

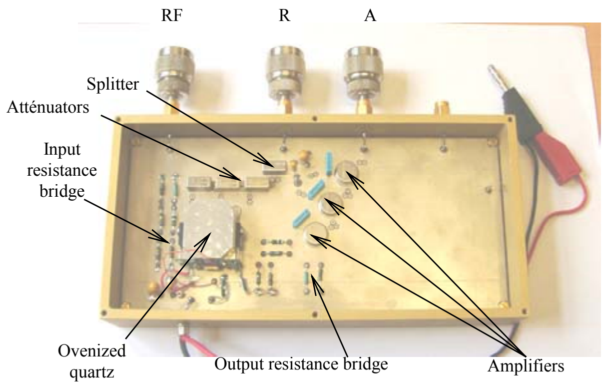

Figure 20: *Picture of the set-up*.

The high performance interferometric instrument currently developed in our lab to measure the intrinsic noise of resonators [17, 18] is being modified to allow simultaneous noise and DLS measurements. The

equipment used so far described in Sec. III, allows measurements from –50 dBm to +15 dBm. So as to lower the crystal drive level below the limits of the analyser, a dedicated arrangement has been designed as shown in Figs. 19 and 20.
A 40 dB wide band attenuator is inserted in between the synthesiser RF output and the pi-network input while the output signal, amplified by a three-stage low noise amplifier feeds the analyser measurement input. The analyser reference signal comes directly from the synthesiser.
The set-up allows measurement with crystal drive level as low as –100 dBm. It should be noted here that a careful attention has to be paid to the calibration procedure. In addition, as outlined in Sec. III, the measurement relies only on amplitude and phase of the transfer function and on our own algorithms.

VIII. CONCLUSION

SEM pictures of the surface of some resonator exhibiting DLS reveal a large number of particles and other defects. It is not proved that these defects are responsible for the DLS but there is a strong suspicion. The series resonant frequency change in the DLS effect is always accompanied by an often important relative frequency change (several ppm). This experimental observation leads to the hypothesis that in any resonator, smaller particles loosely trapped near the surface by electrostatic forces or in structural cavities located under the electrodes could be, at least partly, responsible for the frequency noise of the resonator. Because of their small size, these nanoparticles could be activated and revealed by a much lower drive level as those used up to now. The imminent finalizing of a high performance interferometric instrument able to measure simultaneously very low level DLS and intrinsic noise of resonators should clarify the possible correlation between the two phenomena.

Acknowledgements

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