Thermal characterization of crystal ovens used in phase noise measurement system

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Abstract— **In this paper, the thermal stability characterization of crystal ovens used in a phase noise measurement system of ultra-low noise crystal resonators is proposed. This bench is dedicated to test 5 MHz and 10 MHz crystal devices packaged in HC40 enclosures. New double ovens have been designed to improve the ultimate noise floor of our carrier suppression bench. A brief description of the temperature environment and processing are given. In addition, experiments to measure the thermal stability of the oven control are given. These new crystal ovens present an Allan standard deviation of about $2{\cdot}10^{-15}$ at 1 s in terms of relative frequency fluctuations.**

I. INTRODUCTION

The first carrier suppression techniques to measure phase modulation (PM) and amplitude modulation (AM) noise were demonstrated by K. H. Sann [1] in 1968. A similar technique was proposed by C. H. Horn [2] in 1969. At the end of nineties, crystal resonator testers were designed to assist in the PM noise characterization of quartz crystal resonators in the 1 to 200 MHz region. These units use carrier suppression based on the bridge technique [3-5]. This system allows one to measure the inherent phase stability of quartz crystal resonators in a passive circuit without the noise usually associated with an active oscillator. The noise floor of these systems obtained by means of resistors is approximately -155 dBc/Hz for a carrier power of about 70 µW. Measurements of quartz crystals have shown the difficulty to get a good thermal stabilization.

For an oscillator at room temperature, a short term stability of about 10^{-10} is about the best result that can be obtained. For ultra stable oscillator (USO) applications, thermal ovenization is necessary to get a better stability. In this context, SC-cut quartz crystal resonators are the best resonators in term of phase noise. Their frequency temperature behavior is usually given by a classical third order polynomial approximation [6]. An example of a SC-cut quartz crystal resonator vibrating in C-mode is shown in Fig. 1. The temperature turnover point of the C-mode is usually close to 80 °C. To get the inherent noise of resonators, temperature control by means of oven is necessary to suppress the contribution of thermal effects.

In this paper, we present a new kind of temperature quartz crystal controlled ovens and their characterization. The temperature fluctuations of the oven are measured by means of the B-mode of a SC-cut quartz crystal resonator working in an oscillator. The resonator is previously characterized in terms of frequency-temperature behavior. Thermal fluctuations of the oven are reached in the time domain through the measurement of the B-mode oscillator frequency. Then, it can be translated into C-mode frequency fluctuations using the thermal sensitivity of the resonator C-mode.

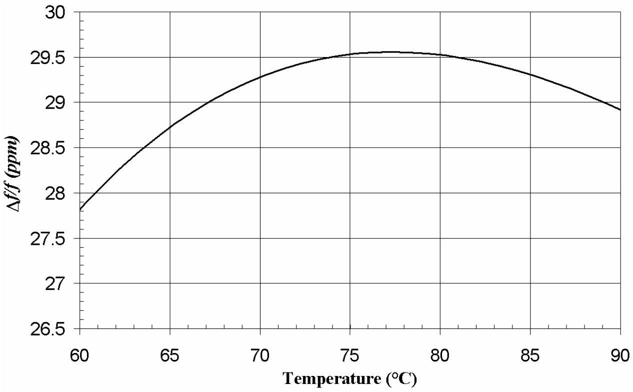

Figure 1. Thermal behaviors of 3rd overtone 10 MHz C-mode SC-cut.

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II. PHASE NOISE MEASUREMENT SYSTEM

A. Principle

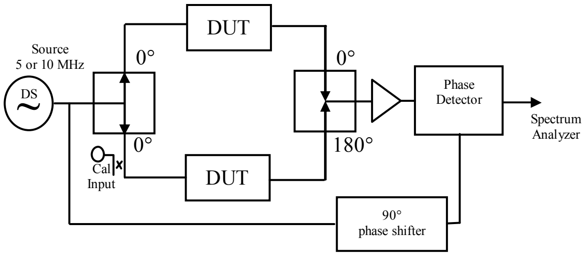

Figure 2. Carrier suppression principle.

Fig. 2 shows the principle of the carrier suppression technique [4-5]. The carrier signal of the driving source (DS) is split into two equal parts to drive both devices under test (DUT).

The DUTs can be resistors (to measure the noise floor of the system) or crystal resonator pairs. The resonant frequency of each arm of the bridge is tuned to the DS frequency with a series capacitor. The carrier signal is canceled when the two signals are combined 180° out of phase. Since phase noise is defined relative to the carrier power, reducing the carrier has the effect of amplifying the phase noise of the DUT. The output signal is amplified and then detected by the phase noise detector.

Calibration of the measurement system is obtained by injecting a known side band on one of the arms of the bridge. The noise of the DUT, as seen on the fast Fourier transform analyzer, is corrected using the calibration factor determined with the side band.

B. Results with single oven

Usually, single temperature ovens were used in phase noise measurement systems (Fig. 3). In this kind of simple homemade oven, the operating temperature is set by means of a soldered resistor.

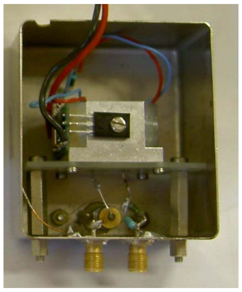

Figure 3. Single oven.

Results of phase noise measurement of 5 MHz quartz crystals are shown in Fig. 4. A thermal drift can be observed for Fourier frequency lower than 0.5 Hz.

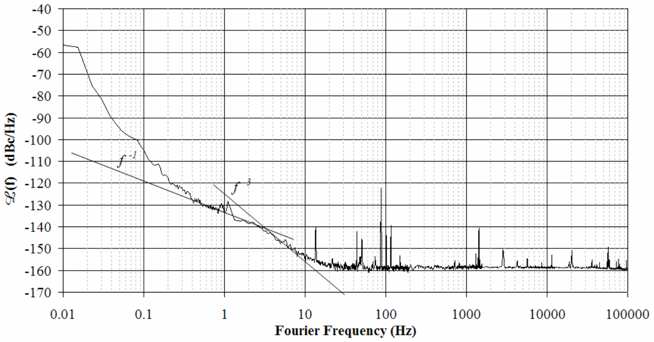

Figure 4. $\mathscr{L}(f)$ of both 5 MHz quartz crystals.

C. Improvement of ovens

The main improvement of ovens is shown in Fig. 5. It consists in a double enclosure and two thermally controlled ovens, used in order to control the quartz crystal temperature. Fig. 5a shows the crystal box of the new ovens. Fig. 5b shows the cable ovens and the second enclosure including the tuning capacitor. Fig. 5c shows the crystal oven. Moreover, the temperature of the crystal oven is controlled by means of a tuning resistor chip. A resistor step of about 30 Ω allows a temperature adjustment of 0.05 °C.

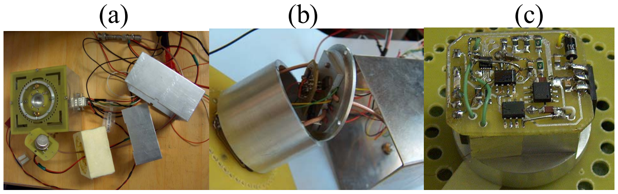

Figure 5. Double quartz crystal ovens.
(a) oven top view, (b) external box and cables oven, (c) crystal oven.

By this way, a remote temperature control can be easily achieved without opening the overall device. The cable oven temperature is set at a fixed value between the room temperature and the crystal temperature.

III. RESULTS AND COMMENTS

A. SC-cut quartz crystal resonator

The SC-cut is a doubly rotated cut. As a consequence, it exhibits a resonant thermometric mode (B-mode) in addition to the metrological mode (C-mode) at 10 MHz in our case. Thus, the B-mode frequency is closed to f_B = 10.9 MHz. Its frequency-temperature behavior has been measured (Fig. 6) over the usual crystal temperature range.

Measurement results give a linear relationship with a slope equal to $a_B \approx -230$ Hz·K^{-1}. Because of its high temperature sensitivity, we assume that all non-thermal extra-disturbances can be neglected.

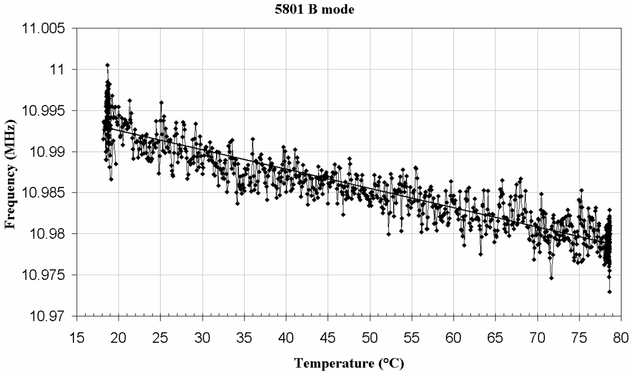

Figure 6. Thermal behavior of SC-cut, 3rd overtone 10.9 MHz B-mode.

B. Measurement oscillator

The B-mode oscillator that we used is a classical one-transistor USO. Its electronics is identical with that for the C-mode, except for the frequency tuning. Note that the B-mode quality factor of a SC-cut is higher than the C-mode one. As a consequence, the B-mode frequency is the natural starting frequency of a SC-cut crystal oscillator. The short term stability of electronics circuit is given by the C-mode of the oscillator (Fig. 7). It exhibits an Allan standard deviation of about $1{\cdot}10^{-12}$ for a measurement time τ of 1 second. That is sufficient for our B-mode measurements.

C. Allan deviation measurements of the ovens

Allan standard deviation measurements of the oscillator frequency working in B-mode are given in Fig. 7 for both ovens.

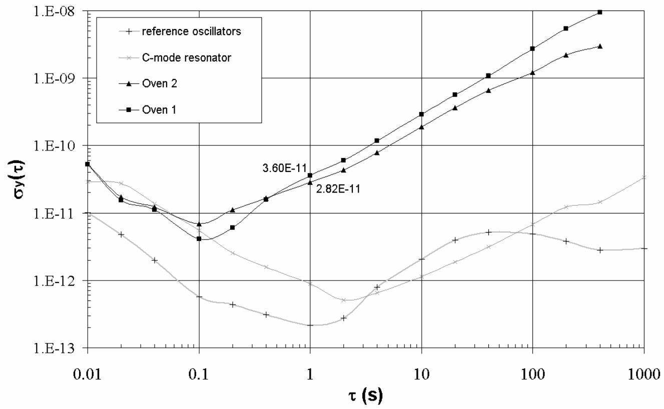

Figure 7. Allan standard deviation measurements.

At the end of measurements, the relative frequency stabilities $\Delta f/f$ of the oscillator in B-mode, which measures the average thermal stability of the ovens, are $3.6{\cdot}10^{-11}$ at 1 s for Oven 1 and $2.82{\cdot}10^{-11}$ for Oven 2 at 1 s. Thus, we can calculate the thermal stability of the thermostat.

$$\Delta T = \frac{\Delta f}{f_B} \times \frac{f_B}{a_B}$$

With $f_B = 10.9$ MHz, $|a_B| = 230\ \mathrm{Hz{\cdot}K^{-1}}$

ΔT can be computed at 1 second :

$$\Delta T_{Oven1} = 3.6 \cdot 10^{-11} \times \left(\frac{10.9 \cdot 10^6}{230} \right) \approx 1.7 \cdot 10^{-6}\ K$$

$$\Delta T_{Oven2} = 2.82 \cdot 10^{-11} \times \left(\frac{10.9 \cdot 10^6}{230} \right) \approx 1.35 \cdot 10^{-6}\ K$$

The ideal operating point for quartz crystal in C-mode is the temperature T_{to} of its turnover point (Fig. 8).

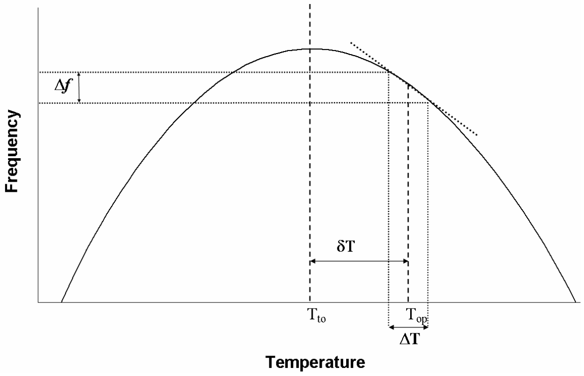

Figure 8. Temperature effects on resonator frequency.

In fact, this ideal point can never be reached rigorously, thus a difference exists between the temperature of the ideal turnover point and the actual operating temperature T_{op}:

$$\delta T = \left| T_{to} - T_{op} \right|$$

As a consequence, the relative frequency variation in C-mode is given by :

$$\frac{\Delta f}{f} = a_c \times \Delta T_{oven}$$

The slope a_C can be obtained in a real case by means of frequency-temperature behavior of the C-mode (Fig. 9). In our case, for this crystal, the turnover temperature is around 72 °C. We can note that is a badly case because for a SC-cut resonator when T_{to} decreases, a_C increases.

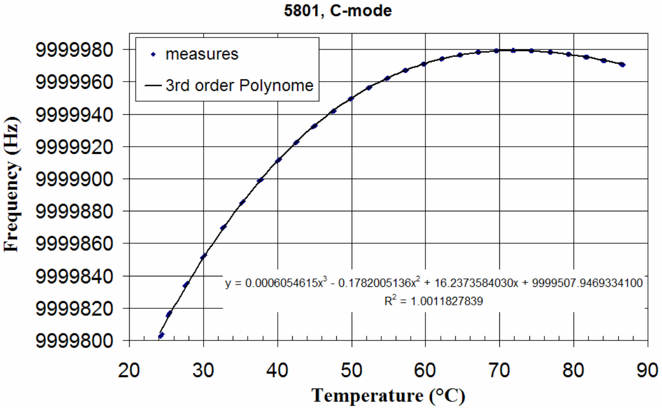

Figure 9. Frequency temperature behavior of a real SC-cut quartz crystal at 10 MHz.

Frequency-temperature relationship is given by the classical equation at $T_0 = 25$ °C :

$$f(T) = f_0(1 + \alpha(T - T_0) + \beta(T - T_0)^2 + \gamma(T - T_0)^3)$$

From the third order polynomial approximation, we can find α, β, γ and f_0. $\alpha = 8{,}46 \cdot 10^{-7}$, $\beta = -1{,}33 \cdot 10^{-8}$, $\gamma = 6{,}05 \cdot 10^{-11}$ and $f_0 = 9999811{,}97$ Hz.

Then, the relative slope a_C at T_{op} is:

$$a_c = \frac{f'(T_{op})}{f_0} = (2\beta + 6\gamma(T_{to} - T_0))(T_{op} - T_{to}) + 3\gamma(T_{op} - T_{to})^2$$

$$a_c = [2\beta + 6\gamma(T_{to} - T_0)] \cdot \delta T + 3\gamma \cdot \delta T^2$$

a_c depends on δT (Fig. 10). For δT = 0.1 °C, a_c is about $1 \cdot 10^{-9}$ Hz/ °C.

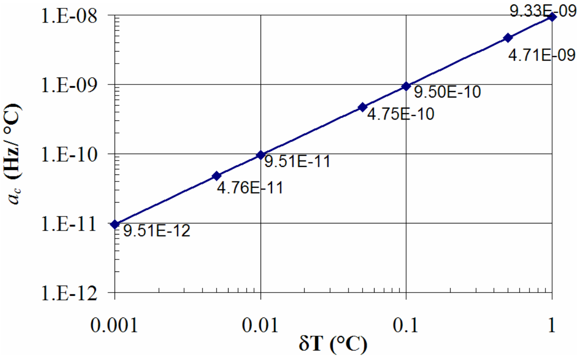

Figure 10. a_C according to δT.

Taking into account the precision of the ovens, one can ensure a turn over point below 0.1 °C. Thus, the relative frequency fluctuation of $\Delta f/f$ of the bench due to the thermal effects on the resonator are:

$$\left.\frac{\Delta f}{f}\right|_{Oven1} = 1 \cdot 10^{-9} \times 1.7 \cdot 10^{-6} = 1.7 \cdot 10^{-15}$$

$$\left.\frac{\Delta f}{f}\right|_{Oven2} = 1 \cdot 10^{-9} \times 1.35 \cdot 10^{-6} = 1.35 \cdot 10^{-15}$$

New bench that uses double ovens is presented in Fig. 11.

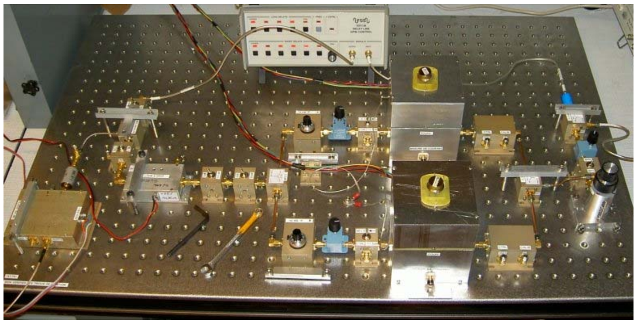

Figure 11. Phase noise measurement system.

Both ovens are inserted in the bench. Fig. 12 shows $\mathscr{L}$(f) of both 5 MHz quartz crystal obtained with new ovens. Improvement of results is really satisfying below 1 Hz as compared with Fig. 3.

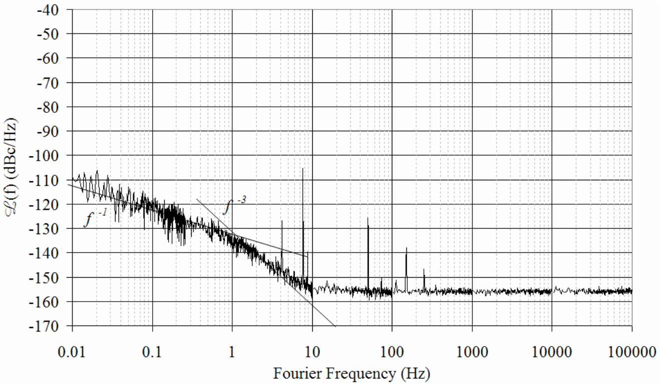

Figure 12. $\mathscr{L}$(f) of both 5 MHz quartz crystal obtained with new ovens.

IV. CONCLUSION

New double ovens have been designed to improve the ultimate noise floor of our carrier suppression bench. The temperature can be controlled within 70 to 90 °C, by means of tuning resistor chip. The remote setting of the operating temperature exhibits an accuracy of about 0.05 °C.

These new crystal ovens present an Allan standard deviation of about $2 \cdot 10^{-15}$ at 1 s in terms of relative frequency fluctuations. Their design is appropriate to measure the phase noise of very low noise crystals. We hope that they will help us to find noise origins of quartz crystal resonators in future works.

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