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Short-Term Stability of Miniature Double Oven Crystal Oscillators Using Conventional and DHR Technology

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Abstract. The present work is devoted to experimental research on the influence of thermal fluctuations in the oven-controlled system on phase noise and short-term stability (STS) of the high stability double-oven crystal oscillators (DOCXO). The paper describes the method of the study and discusses obtained results. The research showed that measured level of STS of the DOCXO $(3.0\text{-}3.5)\cdot10^{-12}$ - is not limited by the thermal noise of the ovens. However, improvement of the STS below $(1\text{-}2)\cdot 10^{-12}$ will require minimization of the temperature fluctuations in the double-oven system.

1. Introduction.

Recent developments of the double oven controlled crystal oscillators (DOCXO) are aimed at creation of the lower cost, power consumption, and smaller size alternative to rubidium frequency standards, which require ultimate performance in stability over temperature and long–term. At the present time temperature stability of the DOCXO of $1\cdot10^{-10}$ and $(1\text{-}2)\cdot10^{-8}$ per year aging can be considered as standard requirements [1].

Obviously, achievement of the highest temperature stability requires a very careful double-oven system design to provide minimal influence of the ambient temperature on the crystal and sustaining oscillator circuit. Any oven system, however, produces its own temperature fluctuations due to the presence of residual noise sources amplified and transformed into the fluctuations of the heating power through the temperature control system. Obviously, the higher the gain of the system, the higher the static accuracy of crystal temperature can be achieved, but at the same time, the higher the amplitude of the oven temperature fluctuations. The temperature fluctuations applied to the crystal resonator or just crystal plate causes modulation of its frequency via the thermo-dynamic effect and the frequency versus temperature dependence. That results in degradation of close to-the-carrier phase-noise and STS of the oscillator [2].

On the other hand, minimization of the aging rate demands optimization of the sustaining circuitry providing minimal value of current through the crystal as well as minimal influence of the components aging. It is a trade-off between low aging and high STS requirements, the latter usually requiring the highest loaded Q-factor and larger value of the crystal current.

Since both factors affect STS of the oscillator simultaneously, it's important to define contribution of each one to optimize STS with minimal impact on the temperature and long-term stability.

The goal of the present work was to study of temperature fluctuations in two essentially different designs of DOCXO. First one is built with "conventional" approach, using OCXO module enclosed in the second-stage box oven. Second design contains the OCXO module using DHR technology and packaged inside the TO-8 vacuum holder, which in turn is heated with outside second-stage oven [3].

Essentially different designs of the oven systems result in different mechanisms of impact of temperature fluctuation on STS. Starting from description of the designs and typical performance of the DOCXO the paper then presents an experimental method to evaluate contribution of the temperature fluctuations in the phase noise and Allan variance. On the basis of the study the limitations put by the oven system on the STS improvement of the both DOCXO designs have been determined.

2. Designs and typical performance of the DOCXO.

The "conventional" and "TO-8" designs of a DOCXO are schematically drawn in figures 1, 2. Both designs contain 5 MHz, 3d overtone SC-cut crystals. In the case of "conventional"

DOCXO the crystal is packaged in the low profile TO-8 holder.

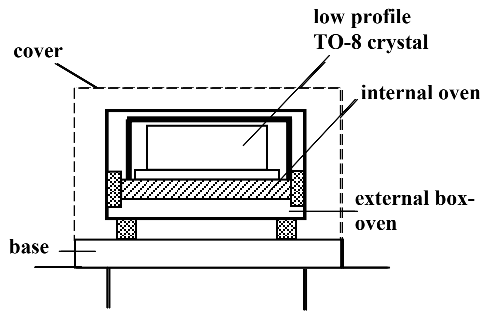

Fig.1. Schematic drawing of the "conventional" DOCXO.

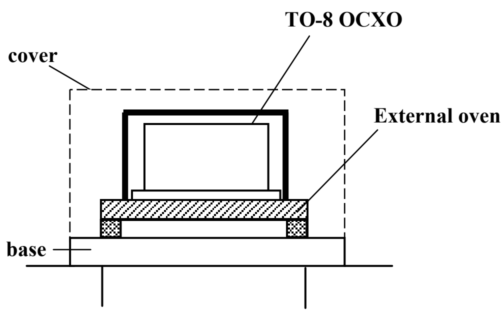

Fig. 2. Schematic drawing of the "TO-8" DOCXO.

The resonator, along with the sustaining and thermo-controller circuitry is arranged inside the first stage oven, which in turn is placed in the second stage "box-oven". In case of the "TO-8" design the crystal with deposited heater, thermistors, and hybrid OCXO circuit assembly is packaged in TO-8 vacuum holder which in turn is mounted inside the second stage oven. Both "conventional" and "TO-8" assemblies are packaged in the "europack" holder with heights ¾" and ½" respectively. Both oscillators use the same sustaining circuitry providing about 750 μA current through the crystal resonator.

Typical characteristics of the DOCXO including temperature stability of oscillators and Allan variance are shown in table 1. Typical phase noise performance of the oscillators is shown in fig.3, 4.

As it follows from the table, both designs provide equally high temperature stability, resulting from about 0.01°C accuracy of maintaining the crystal temperature.

Table 1.

Performance	"Conventional"	"TO-8"
Temperature stability (-30 +70) °C, ppb	0.1	0.1
Power consumption, W	1.5	0.8
Size, mm	27x32x18	27x32x12
Allan variance, 10^{-12}, at τ = 0.1 s τ = 1.0 s τ = 3.2 s	 4.1 3.0 3.3	 3.5 3.1 3.4

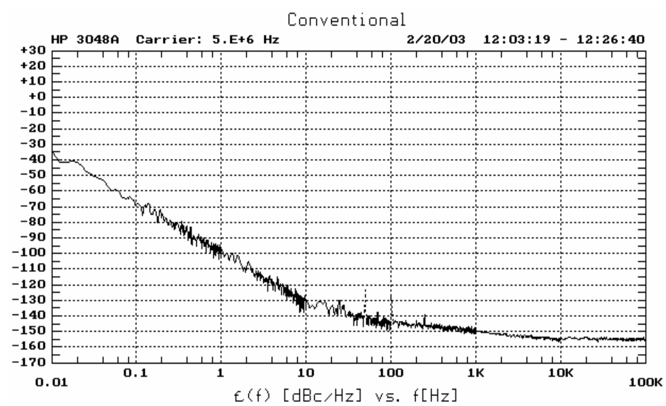

Fig. 3. Typical phase-noise behavior of two "conventional" DOCXOs.

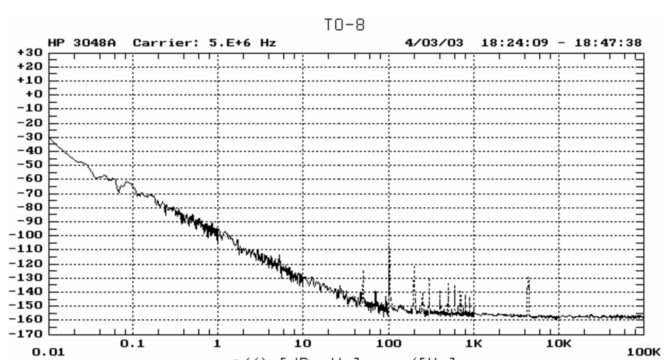

Fig. 4. Typical phase-noise behavior of two "TO-8" DOCXOs.

The "TO-8" design has smaller size and lower power consumption comparing with "conventional" DOCXO, as expected trade-off for some degradation in STS and phase noise performance, due to the method of directly heating the crystal.

No apparent difference in the parameters, however, was obtained, that may imply that temperature fluctuations have no dominant effect. Method, described below allows for numerical evaluation of that influence.

3. Experimental method of estimation of temperature fluctuation contribution in STS and phase noise.

It's well-known, that phase-noise spectral density in a crystal oscillator can be represented as a sum of several components, derived from different origins – sustaining circuitry, buffer amplifier, oven system, as well as of some environmental fluctuations which have direct impact on the oscillator frequency. Referring all the factors produced by the oscillator circuitry to one term $S^{osc}_{\phi}(f)$ and neglecting the direct environmental factors the phase noise spectral density of a DOCXO can be expressed as following:

$$S^{\Sigma}_{\phi}(f) = S^{osc}_{\phi}(f) + S^{ov1}_{\phi}(f) + S^{ov2}_{\phi}(f), \quad (1)$$

where $S^{\Sigma}_{\phi}(f)$ – phase noise spectral density of a DOCXO; $S^{osc}_{\phi}(f)$ – part of $S^{\Sigma}_{\phi}(f)$ caused by oscillator circuitry; $S^{ov1}_{\phi}(f)$ and $S^{ov2}_{\phi}(f)$ parts of $S^{\Sigma}_{\phi}(f)$ caused by fluctuations in the internal (1st stage) and external (2nd stage) ovens respectively.

We accept that impact of the ovens fluctuations on the DOCXO phase noise results from fluctuations (random or periodical) of the heating current. Then $S^{ov1}_{\phi}(f)$ and $S^{ov2}_{\phi}(f)$ can be written as:

$$S^{ov1}_{\phi}(f) = S^{ov1}_{i}(f) * K_{1i}(f) \quad (2)$$
$$S^{ov2}_{\phi}(f) = S^{ov2}_{i}(f) * K_{2i}(f) \quad (3)$$

Here, $S^{ov1}_{i}(f)$, $S^{ov2}_{i}(f)$ – spectral density of noise of the heating current fluctuations in the 1st stage and 2nd stage ovens; $K_1(f)$, $K_2(f)$ - coefficients of transformation of the heating current fluctuations of 1st stage and 2nd stage ovens into phase-noise of the oscillator.

$S^{ov1}_{i}(f)$ and $S^{ov2}_{i}(f)$ can be easily measured with standard spectrum analysis method. To define coefficients $K_1(f)$, $K_2(f)$ we produced significant fluctuations of the oven heating current by injecting sine-wave voltage into the thermo-sensitive bridge. Measuring then spectral density of the fluctuating heating current and resulting phase noise of the oscillator the coefficients $K_1(f)$, $K_2(f)$ can be calculated as follows:

$$K_1(f) = S^{\Sigma 1}_{\phi o}(f) / S^{ov1}_{io}(f), \quad (4)$$
$$K_2(f) = S^{\Sigma 2}_{\phi o}(f) / S^{ov2}_{io}(f), \quad (5)$$

where $S^{\Sigma 1}_{\phi o}(f)$, $S^{ov1}_{io}(f)$, $S^{\Sigma 2}_{\phi o}(f)$ and $S^{ov2}_{io}(f)$ spectral density of the phase-noise and the heating current under induced fluctuations of the ovens.

Relations (4), (5) can be also expressed in more convenient logarithmic form:

$$\Lambda_1(f) = \wedge^{\Sigma 1}_{\phi o}(f) - \wedge^{ov1}_{io}(f) \quad (6)$$
$$\Lambda_2(f) = \wedge^{\Sigma 2}_{\phi o}(f) - \wedge^{ov2}_{io}(f) \quad (7)$$

Influence of the ovens temperature fluctuations on the DOCXO phase noise can be expressed then as:

$$\wedge^{ov1}_{\phi}(f) = \wedge^{ov1}_{i}(f) + \Lambda_1(f) \quad (8)$$
$$\wedge^{ov2}_{\phi}(f) = \wedge^{ov2}_{i}(f) + \Lambda_2(f) \quad (9)$$

Above equations represent a model for measurements and evaluation of the temperature fluctuation factors.

Experiment test set realizing measurements of the oven heating current fluctuations is shown in fig. 5.

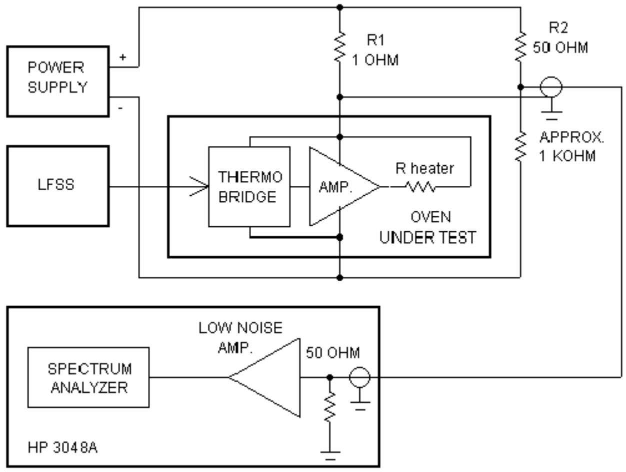

Fig. 5. Experiment test set for oven's current noise measurements.

Measurement of the spectral density of the residual heating current noise $\wedge^{ov1}_{i}(f)$, $\wedge^{ov2}_{i}(f)$ of the oven is realized in the off-state of the low-frequency sine-wave source (LFSS), while the heating current noise under the induced perturbation ($\wedge^{ov1}_{io}(f)$, $\wedge^{ov2}_{io}(f)$) was measured in the on-state of the LFSS producing voltage in the thermo-bridge sufficient for noticeable distortion of the phase-noise figures.

4. Discussion of the experimental results.

Using above method, coefficients $\Lambda_1(f)$, $\Lambda_2(f)$ were defined for both DOCXO designs (fig.6, 7).

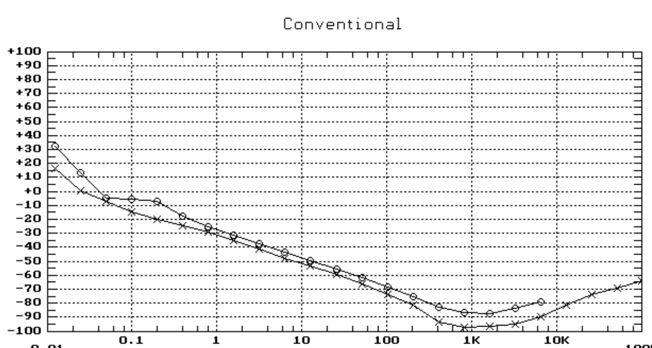

Fig. 6. o – $\Lambda_1(f)$, x – $\Lambda_2(f)$.

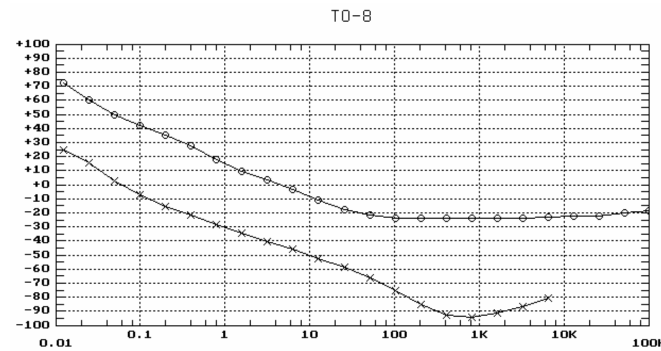

Fig. 7. o – $\Lambda_1(f)$, x – $\Lambda_2(f)$.

Comparing the behavior of the coefficients one can conclude the following:

1. Coefficient of the internal oven $\Lambda_1(f)$ exceeds the coefficient of the external oven $\Lambda_2(f)$ for both DOCXO designs. However, for the "conventional" design that difference is much smaller than for the "TO-8" one due to the stronger coupling of the external oven with the crystal.

2. Influence of the temperature fluctuations of the external ovens decreases at 20 dB/decade rate in the 1 Hz to 1,000 Hz range for both designs. However, influence of the internal oven decreases with the same rate only for the "conventional" DOCXO, while for the "TO-8" design this influence remains at - 20 dB/decade rate only in the 1 Hz to 10 Hz range reaching the floor at about 100 Hz offset. Such behavior can not be explained in terms of physical properties of the design, and most likely results from electrically induced fluctuations from the heating loop into the oscillating one.

3. Coefficient $\Lambda_1(f)$ for the "TO-8" design essentially exceeds that for the "conventional" design that obviously results from stronger coupling of the oven with the crystal in the "TO-8" design.

In addition to the above conclusions it's important to notice that the coefficients $\Lambda_1(f)$, $\Lambda_2(f)$ do not depend on the thermo-controller circuitry gain but are determined by construction of the oven system and thermo-dynamic properties of the crystal.

To calculate contribution of the temperature fluctuations into phase-noise of the real DOCXO units the heating current noise of both oven stages was measured with the test set in fig. 5. Results are shown in fig. 8, 9 in terms of fluctuation of voltage in resistors R1-R2 and can be translated into fluctuation of the heating current by adding 6 dB. One should notice, that only the range from 0.1 Hz to 10,000 Hz (where the test set noise is at least 10 dB lower than the measured one) is valid for analysis.

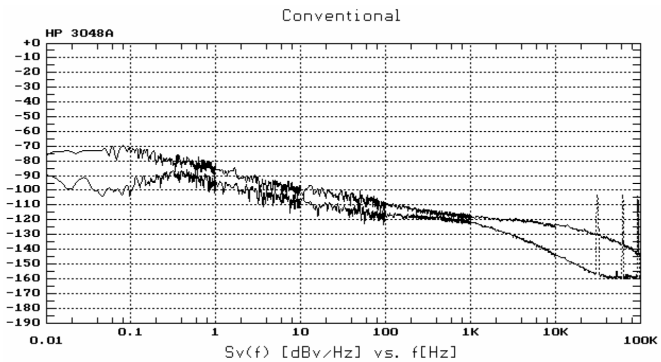

Fig. 8. Spectral density of the voltage in R1-R2; the heating current noise is 6dB higher.

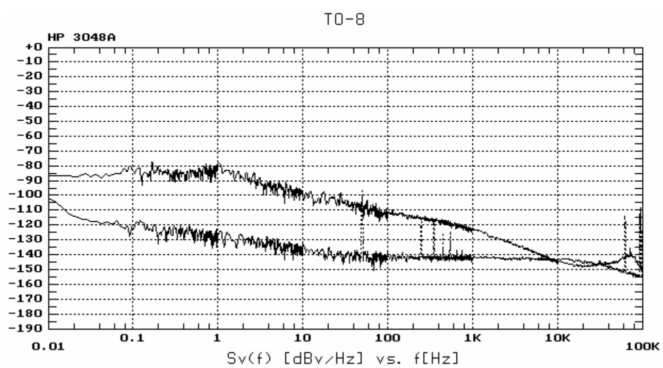

Fig.9. Spectral density of the voltage in R1-R2; the heating current noise is 6 dB higher.

As one can see, the highest current noise takes place in the external oven of the "conventional" design. The current noise in the internal oven of "conventional" design and internal oven of the "TO-8" design are almost equal, while the lowest noise is produced by internal oven of the "TO-8" OCXO.

Using measured current noise data along with the calculated values $\Lambda_1(f)$, $\Lambda_2(f)$ contribution of the thermal noise into the DOCXO phase fluctuations can be easily defined. Calculated values of $\wedge^{ov1}_{\phi}(f)$, $\wedge^{ov2}_{\phi}(f)$ for both oscillator designs are displayed in fig. 10, 11. Table 2 shows the calculated values in terms of Allan variance.

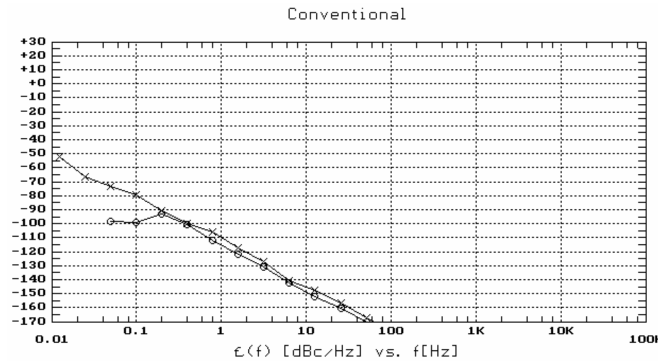

Fig. 10. o - $\wedge^{ov1}_{\phi}(f)$, x - $\wedge^{ov2}_{\phi}(f)$.

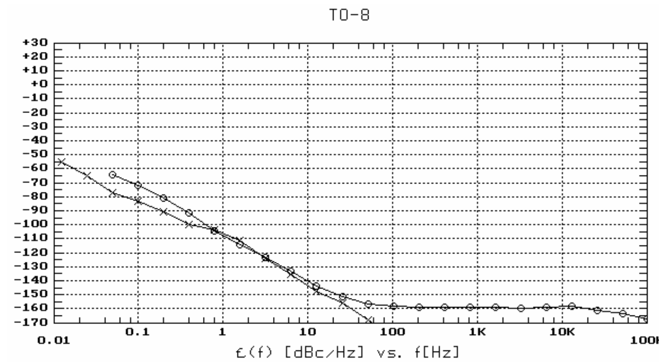

Fig. 11. o - $\wedge^{ov1}_{\phi}(f)$, x - $\wedge^{ov2}_{\phi}(f)$.

Table 2.

τ	"Conventional" DOCXO			"TO-8" DOCXO		
	Inter-nal	Ex-ternal	Total	Inter-nal	Ex-ternal	Total
s.	$\bullet 10^{-12}$					
3.2	0.28	0.94	0.94	2.35	0.70	2.40
1	0.63	0.89	1.08	2.34	0.88	2.50
0.1	0.50	0.81	0.95	2.24	1.30	2.60

Comparing the obtained results with measured phase noise and Allan variance in fig.3, 4 and in the table 1, one can come to the following conclusions.

1. Influence of the temperature fluctuations on STS of the "TO-8" DOCXO exceeds that of the "conventional" design by about a factor of 2 and the primary source of it for the former is the internal oven, while for the latter is the external oven.

2. For both "conventional" and "TO-8" designs the temperature fluctuations are not the main source of short-term instability, however,

for the “TO-8” design that fluctuation can somewhat affect value of the STS.

3. Obviously further reduction of the phase-noise or Allan variance of the considered DOCXO will demand optimization of their oscillator circuitry as the primary source of short-term instability. However, such reduction is limited by the temperature fluctuations at the level of about $1.0 \cdot 10^{-12}$ for the “conventional” and $2.5 \cdot 10^{-12}$ for the “TO-8” designs.

6. References.

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2. **A. Kutalev, ”Influence of Temperature Fluctuations in Crystal Oven on Short-Term Stability and Phase Noise of Quartz Crystal Oscillators “, EFTF 2002 St. Petersburg**
3. **I. Abramzon, R. Boroditsky “Miniature Double OCXO with Low Power Consumption”, EFTF 2001, Neuchatel**