Extraordinary OCXO solutions based on the IHR technology

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***Abstract*—The present paper reviews recent achievements in the Internally Heated Resonator (IHR) technology which has resulted in creation of advanced OCXO devices possessing extraordinary combination of performances.**

I. INTRODUCTION.

The IHR technology utilizes miniature oven control structure integrated with the crystal plate inside the TO-8 vacuum holder. Heating of only the crystal plate and excellent thermo-insulation from environment ensure very low power consumption and fast warming up of the OCXO as compared with the oscillators based on conventional external oven control concept. At the same time, extremely small sizes of the internal oven cause difficulty of uniform heating the crystal plate that makes for arising the thermal gradients contributing essential instability of the IHR frequency. Another constructive feature of the IHR oscillator (IHRO), arrangement of the sustaining circuitry outside the heated oven volume, makes its temperature sensitivity a serious source of frequency instability of the OCXO considerably exceeding this factor at the conventional oven designs. Thus, to provide radical reduction of frequency instability of the IHRO both shortcomings of its constructive concept should be overcome. The paper describes implementation of advanced techniques in the IHRO construction and circuitry which have enabled significant increase of their temperature frequency stability - to the level of the best conventional OCXO designs.

The long-term stability (aging) of a crystal resonator to a great extent depends on vacuum degree in its vacuum volume. For the IHR design sealed in miniature TO-8 holder and containing at the operation temperature various electronic and constructive materials preserving of perfect vacuum conditions during the OCXO lifetime is a serious problem. The paper presents long-time aging behavior of modern IHROs confirming low aging rate which earlier was a property only of high stability conventional OCXOs using ordinary crystal construction.

The short-term frequency stability (STS) of most OCXO designs at more than 1 s average time is noticeably influenced by thermal fluctuations of the oven control system. This influence becomes more evident in the IHRO designs for very low thermal inertia of the integrated oven and its strong thermal coupling with the crystal plate. The paper shows results of optimization of the internal oven and circuitry that has enabled for the IHR oscillator as low as $1x10^{-12}$/1s Allan variance combined with its utmost temperature stability.

Very low power consumption is most extraordinary property the IHROs providing them most important advantage over conventional OCXO concept. The paper displays ultimate figures of the power consumption of the developed IHRO designs measured for different ambient temperature ranges.

Short warm-up of the IHRO designs provides them another significant superiority over traditional OCXOs. The paper depicts warming-up processes of the indirect and direct heated IHR versions resuming the latter provide extremely fast warming-up combined with high temperature stability and STS.

Moreover there are considered in the work the ultra-durable and low g-sensitivity versions of the IHR designs providing operation of the OCXOs under severe mechanical shocks and vibration at high temperature stability, low power consumption and minimal degradation of the phase-noise level.

In conclusion the paper summarizes the basic performances of the new generation IHROs resuming the extraordinary combination of the characteristics makes the devices state-of-the-art solution for a frequency control and timing of various modern equipment.

II. CONSTRUCTION FEATURES OF THE IHROS AND ITS TEMPERATURE STABILITY.

Basic concept of modern IHR depicted schematically in Fig.1 was developed more than 10 year ago [1]. It contains inside the TO-8 vacuum holder the crystal plate with the film electrodes mounted on the ceramic substrate which bears the whole thermo-control circuitry and the metal screen covering the plate for better radiation insulation. The substrate, in turn, is fixed on the supporting mechanical structure which provides both thermal isolation of the internal oven from environment and proper mechanical durability of the construction. Excellent thermal isolation of the internal oven by deep vacuum degree inside the TO-8 holder and low thermal conductivity of the supporting structure ensure very small thermal losses resulting in extremely low power consumption of the IHR, about a tenth of the conventional OCXO consumption.

A structure of the OCXO based on the IHR concept is outlined in Fig. 2. In difference from traditional OCXO designs its sustaining circuitry is disposed on unheated outer PC board (fig.2) under ambient temperature conditions. Fig. 3 exhibits an exterior view of different OCXO models utilizing the IHR technology with the smallest one MXO37/8 approaching the sizes of the TO-8 holder.

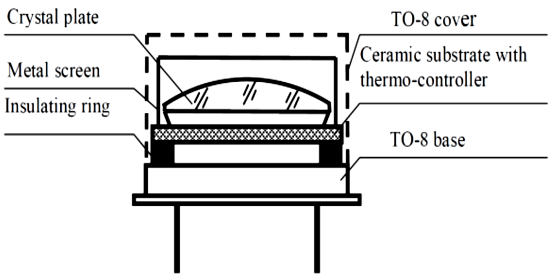


Fig. 1. Schematic drawing of the IHR structure.

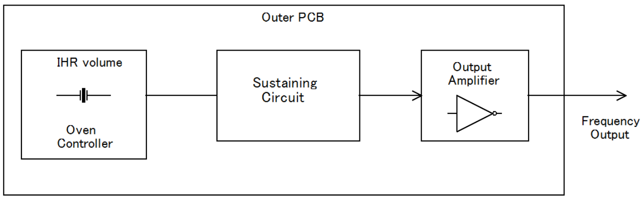
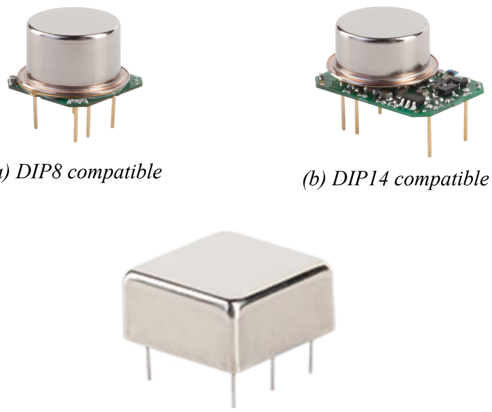


Fig. 2. Outline of the OCXO based on IHR concept



(a) DIP8 compatible

(b) DIP14 compatible

(c) Hermetically sealed in 20x20 mm case

Fig. 3. Exterior view of the IHRO designs: DIP8 compatible (a), DIP14 compatible (b), hermetically sealed in 20x20 mm case (c)

As it follows from the IHRO structure its temperature instability of the frequency is contributed from two main sources: temperature instability of the IHR and of the sustaining circuitry. To improve temperature stability of the IHR its internal oven structure and circuitry have been essentially modified to ensure high accuracy and uniformity of heating the bulky high overtone crystal plate. That has yielded to increase of the temperature control accuracy 0.1- 0.2˚C with proportional reduction of the thermal gradients over the crystal.

The unheated sustaining circuitry of the IHRO along with the buffer amplifier and voltage regulator contribute into OCXO temperature instability through variation of the excitation level, changes of reference voltage on the corrector and other factors. Degree of the influence depending significantly on impedance of the crystal and sustaining circuitry varies from 20-30 ppb at 10 MHz operation frequency to 0.3-0.5 ppm at 100 MHz.

For minimization of the circuitry factor there has been utilized the analog compensation network correcting the oscillator frequency in accordance with ambient temperature changes (fig.4). The compensation signal is produced by the temperature sensor disposed on the unheated board and biases the electronic corrector to provide minimal frequency deviation of the oscillator [2].

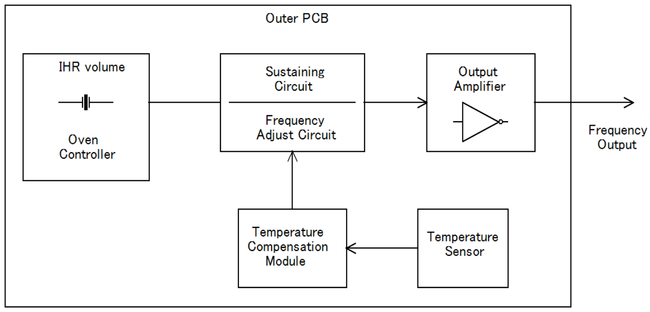


Fig. 4. The outline of temperature compensated IHRO structure.

The table below shows values of the temperature stability of modern OCXO models achieved with the improved IHR construction together with the effect of the temperature compensation technique.

TABLE I. TEMPERATURE STABILITY OF THE IHRO MODELS.

Type of the OCXO	**Operational frequency, MHz**	**Utmost frequency stability, (-40 +85)^{0}C, ppb**	
		No compensation	***Using compensation***
MXO37/8	10	10	2
	100	50	10
MXO37/14	10	5	1
	100	30	10
MXO37/R	10	5	0,5
	100	30	5

As it follows from the data the temperature stability of the DIP8 and DIP14 models is at the level of the high-end conventional OCXOs through attained at a few times smaller sizes and about one order lower power consumption. Meantime the MXO37/R oscillator exhibits superior frequency stability in wide temperature range attainable only with the double-oven OCXOs.

III. BASIC PERFORMANCES OF THE IHROs

The original construction features of IHRO concept determine essential difference of its basic performances from the conventional OCXO designs.

A. Power consumption

The power consumption providing most evident advantage of the IHROs over conventional OCXOs is almost entirely determined by thermal isolation of their internal oven structure from environment:

$$P = (T_o - T_a)/ R_t,$$

where P – the power consumption, T_o – IHR operation temperature, T_a – ambient temperature, R_t - thermal resistance between the integrated oven and environment characterizing thermal insulation of the IHR.

Owing to very small sizes of the internal oven and its excellent thermal insulation by the deep vacuum and low conductivity of the supporting structure the thermal resistance of the IHR can reach 1000 K/W. Power consumption of real IHR designs measured at 25^{0}C in dependence on ambient and operation temperatures is depicted in Fig.5.

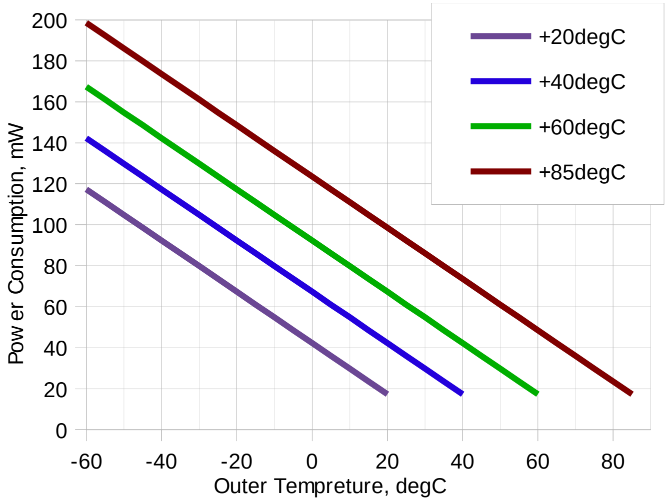


Fig. 5. Power consumption of the IHR at different operational temperature ranges.

As it follows from the plots very low power consumption is attained even at 90°C operation temperature used at wide operation temperature ranges while at narrow ranges the IHR devices ensure extremely low consumption values. That makes the IHROs a perfect solution for various battery supply devices, such as the high-end mobile radio or the underwater clocks. The latter operate in relatively stable sub-marine temperature conditions but are demanded for utmost frequency stability and the lowest power consumption.

B. *Warm-up time*

Very fast warming-up of the IHR construction (Fig.1) proceeds from very low thermal inertia of the internal heating system and its strong coupling with the crystal plate. Owing to these properties the IHR designs using the SC-cut plano-convex plates having low thermo-dynamic sensitivity ensure to 30 s warming-up to 0.1 ppm frequency accuracy that's at least three times faster than with conventional oven designs.

Significantly faster warming-up can be attained using *the composite heated IHR* version with the temperature sensor and the film heaters disposed directly on the crystal plate while the rest regulating elements are arranged on the supporting ceramic substrate [3].

The Fig.6 depicts warming-up curves for the indirect and composite IHRs utilizing the 10 MHz SC-cut crystal plate in dependence on the start-up power.

As it follows from the curves the composite IHR at 3W start power reaches utmost values of warm-up time: <15 s to 0.1 ppm accuracy and 20 s of 0.01 ppm accuracy operating at the room temperature. So fast warming up is result of almost "instant", within a few seconds, heating the SC-cut crystal plate to 90^{0}C operation point and its excellent thermo-dynamic properties.

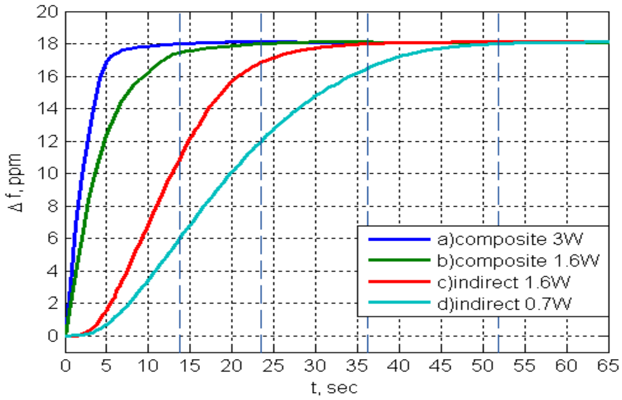


Fig. 6. Warming-up of the indirect (c, d) and composite heated (a, b) IHR versions vs. start-up power.

C. *Long-term stability*

The long-term frequency stability of a crystal resonator is a result of contribution of different intrinsic factors such as relaxation of the mechanical stresses in the crystal plate or sorption-desorption of residual substance on the film electrodes. The latter can be more significant factor in the IHR devices due to potential outgazing from different materials and components operating at high operation temperature in cold-weld sealed TO-8 holder.

The problem of preserving deep vacuum conditions inside the IHR volume has been resolved by choosing the "vacuum compatible" materials and effective vacuum cleaning the IHR structure before the cold-weld sealing. These measures along with utilizing high-overtone precision crystal plate have resulted in excellent aging performances of the IHROs, practically at the level of the high-end conventional OCXOs. The fig.7 displays the aging curves for a group of the 20 MHz oscillators built on the 5th overtone SC-cut IHR measured during one year operation time. The table 2 shows aging rate of these IHROs calculated after 1, 2, 3 months operation along with the first year total frequency shift.

Out of the data most of the IHRO units after 30 days operation provide 0.3 ppb/day rate and 0.15 ppb/day after 60 days. Total deviation of the frequency after the first year operation doesn't exceed 50 ppb that corresponds to the aging performances of the high stability conventional OCXOs.

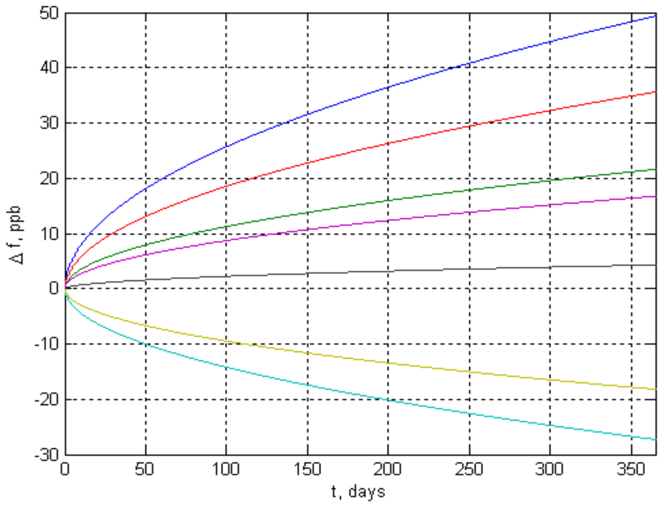


Fig. 7. Aging plots and statistic data for the IHROs.

TABLE II. AGING PARAMETERS OF THE 20 MHZ IHROS

Daily aging, 1x10^-10^			First year shift, ppb
After 30 days	*After 60 days*	*After 90 days*	
-1,5..+ 2,5	-1..+1,5	-1..+1,5	-30..+50

D. Phase-noise and Allan variance

The phase-noise level of the IHROs in the middle and far offset from the carrier is close to that of the low-noise conventional OCXOs for utilizing common sustaining circuitry and parameters of the crystal plate. Meantime at 0.1-1 Hz region the phase-noise level becomes rather sensitive to temperature fluctuations of the oven control system which produces frequency fluctuations of the resonator through the thermo-dynamic effect. The influence is more noticeable in the IHR oscillators for much lower thermal inertia of the internal oven system having strong coupling with the crystal plate.

To reduce the phase-noise degradation of the IHROs the amplitude noise of the internal oven was minimized by optimal choice of parameters of the thermo-control circuitry without sacrificing the temperature control accuracy. Low thermo-dynamic sensitivity of the IHR was ensured by usage of the SC-cut crystal plate having optimal geometry and mounting structure. The fig.8 displays typical phase-noise patterns measured with the IHROs operating at 10 MHz and 100 MHz fundamental frequency which obviously are close to the level of low-noise conventional OCXOs.

The short-term instability of a crystal oscillator can be determined from the phase-noise plot and also is influenced by the oven fluctuations factor. The fig.9 depicts utmost values of Allan variance vs. average time attained with the high stability MXO37R model.

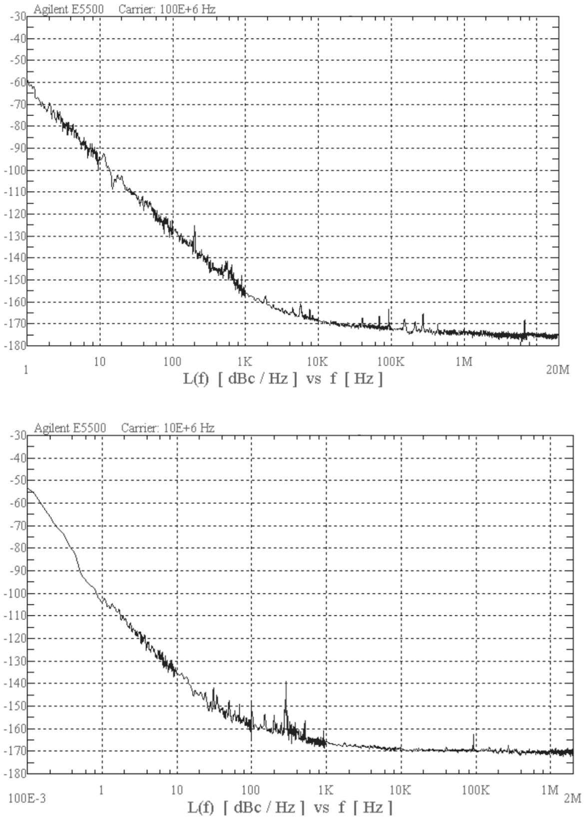


Fig. 8. Typical phase-noise level of 10 MHz and 100 MHz IHROs

As one can see the OCXO exhibits pretty good, to $1x10^{-12}$ / 1s, STS which is combined with 0.5 ppb in (-40 +85)^{0}C frequency stability and about 150 mW power consumption.

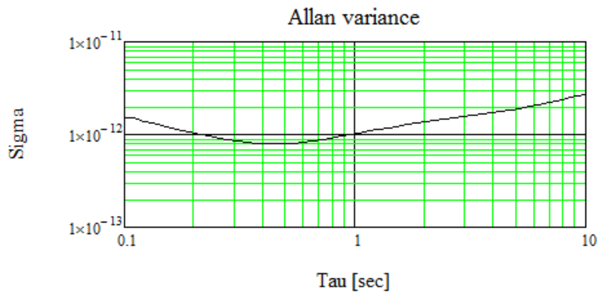


Fig. 9. Allan variance vs. average time for the MXO37/R model

E. Durability to mechanical factors

Portable and mobile radio-electronic equipment is often exploited in hard environmental conditions severe mechanical shocks and vibration. To withstand exposure to these factors the high durable MXO37D model has been created. Being implemented in the DIP8, DIP14 compatible sizes or 20x20 mm packaging the IHROs withstand up to 1000 g, 1 ms multiple shocks and 30 g, 0-2000 Hz vibration. In spite of robust IHR structure the OCXOs consume < 220 mW power and provide to 10 ppb frequency stability in (-40 +85)^{0}C range.

The acceleration or g-sensitivity of a crystal oscillator determines its phase-noise level under action of random or sine vibration and therefore is crucial parameter for various mobile applications with high demands to purity of the reference signal. To reduce sensitivity of the IHROs to acceleration low g-sensitivity IHR construction with optimized geometry of the crystal plate and the mounted structure has been developed. The new IHR design has enabled considerable reduction of the g-sensitivity, to 0.2 ppb/g for the worst direction at 10 MHz operation frequency and to 0.3 ppb/g at 100 MHz.

Farther reduction of the acceleration sensitivity has been attained by installation of the IHRO module in the outer anti-vibration structure arranged in “europack” case. The phase-noise pattern of this device operating at 10MHz under 8g RMS vibration is depicted in fig. 10 for three orthogonal axes. Calculated from these data the g-sensitivity is less than 0.05 ppb/g at higher 100 Hz offset while at above 300 Hz offset the vibration produces negligible impact on the phase-noise level.

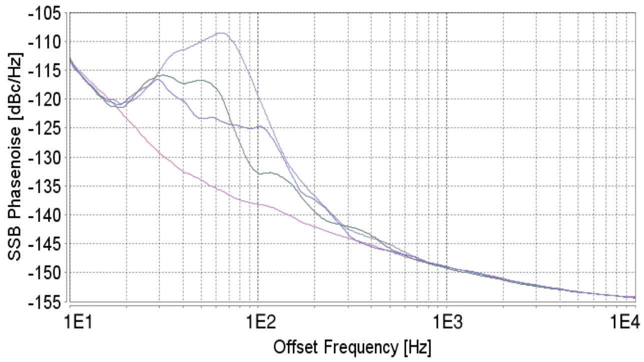


Fig. 10. Acceleration sensitivity vs. vibration frequency of the IHRO with outer anti-vibration protection.

F. *Summary on basic performances of IHROs.*

The basic performances of the OCXOs achievable with the up-to-the-date IHR technology are summarized in table 3.

TABLE III. UTMOST PERFORMANCES OF MODERN IHROS

Performances	**Indirect heated IHRO**	**Composite heated IHRO**
Operation frequency range, MHz	8-150	8-50
Temperature stability, (-40 +85)^{0}C	0.5 ppb	5 ppb
Aging per day (at 10 MHz), ppb/day	0.1	0.2
Allan variance, 1 s	$1x10^{-12}$	$5x10^{-12}$
Power consumption at 25 C, mW	130	
Warm up time to 0.1 ppm, s	30	15
G-sensitivity, worst direction, ppb/g	0.2	
Packaging	DIP8, DIP14, 20x20x12.6 mm	

Out of the data the modern IHROs provide for wide operation frequency range excellent frequency stability, low phase-noise level and high durability to mechanical factors, not yielding to the top level conventional OCXOs. At the same time, all the performances of the IHROs are combined with their extremely low power consumption, small sizes and very short warm-up time.

IV. CONCLUSION.

The many-years development work directed to improvement of the IHR technology has yielded a new generation of the OCXO devices combining very high frequency stability, low phase-noise level and high mechanical durability with extremely low power consumption, miniature sizes and very fast warming-up.

Owing to the extraordinary performances the modern IHROs are now a state-of-the-art solution for high precision timing and frequency control of various portable and/or battery supply systems which earlier had to compromise with usage of TCXOs, conventional OCXO or CSAC references.

[1] I. Abramzon, S. Baranushkin, A. Gubarev, O. Rotova, V. Tapkov, "High-Stability Miniature OCXOs Based on Advanced IHR Technology", Proceedings of the Joint 2007 European Frequency and Time Forum; 2007 IEEE Frequency Control Symposium., pp.242-245.

[2] Abramzon I. & Tapkov V. "Utmost OCXO Solutions Based on the IHR Technology", Microwae Journal, Vol. 57, No.4, April 2014.

[3] Igor Abramzon, “OCXO Designs Using Composite-Heating of the Crystal Resonator”, IEEE Transactions on Ultrasonics, Ferroelectrinics and Frequency Control, V.41(2), pp. 284-287, April 1994.