Utmost OCXO Solutions Based on the IHR Technology

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Abstract— **The internally heated quartz resonators (IHR) for a long time had been an attractive solution for development of small size fast warming-up low power OCXOs. However in the frequency stability and phase-noise level they yielded noticeably to conventional OCXO designs based on the external oven structure. Along with complexity of the manufacturing process that restricted application of the IHR technology by the low and intermediate stability oscillators intended for portable battery supply devices. The present paper reports of creation of a new generation of the miniature low power OCXOs based on advanced IHR technology possessing excellent frequency stability and phase-noise parameters feasible heretofore only with high-end conventional OCXOs.**

I. INTRODUCTION

The IHR technology utilizing the idea of integration in the crystal resonator volume of part or whole oven control system was invented more than 40 years ago and proved to be the most efficient technique to reduce power consumption, sizes and warm-up time of OCXOs [1-3]. The unique features of the OCXOs built on the IHRs made them very attractive for different mobile and battery supply applications where the frequency stability and phase-noise level of commonly used temperature compensated crystal oscillators (TCXOs) were insufficient to meet the growing requirements.

However the IHR concept along with evident advantages revealed some serious shortcomings restricted its rapid proliferation in OCXO constructions. One of the weaknesses of the novel devices was their insufficient temperature stability normally limited by 0.1ppm due to influence on the frequency of the unheated oscillator circuitry and for essential thermal gradients arising in the heated crystal plate enclosed in miniature IHR volume. Another serious problem associated with the new technology was high sensitivity of the IHR parameters on vacuum level inside the packaging and complexity of maintenance of the high vacuum conditions during the whole IHR lifetime. This problem was aggravated at designing miniature fully integrated IHRs accommodating inside numerous electronic and constructive elements at that having no space for deployment of a gas absorber.

The described difficulties during a long period had been seriously obstacles for developments of miniature low power high stability OCXOs in spite of permanent needs for such products. Essential progress in this field was attained with creation of the direct heated resonators (DHR) packaged in the TO-8 cold-welded vacuum holder which at about 1ccm volume accommodated inside the whole thermo-controller circuitry and provided 50ppb temperature stability at about 80mW power consumption [4].

Further efforts to improve temperature stability of the IHRs packaged in TO-8 holder had led to appearance of the indirect heated design where the crystal plate is enclosed in the internal micro-oven structure [5]. Basing on this technology a family of extraordinary OCXOs with DIP8 or DIP14 compatible sizes and less than 150mW power consumption had been developed and put into production. In spite of very small sizes and consumed power these devices provided at 10MHz operational frequency up to 20ppb temperature stability in (-40 +85°C) range, to 0.2ppb/day aging and low phase-noise level normally measured as -95dBc/Hz at 1Hz offset and -168dBc/Hz on the floor.

Although these frequency stability and the phase-noise values were quite satisfactory for most of traditional applications they still noticeably yielded to the parameters of the high-end conventional OCXOs that bounded expanse of the novel devices into the fields requiring extraordinary frequency stability and the phase-noise performance.

The present work reviews outcome of recent researches in the IHR technology that has resulted in development of advanced OCXO designs combining basic advantages of the IHR devices with very high frequency stability and very low phase-noise level being before the properties of the best high-end conventional OCXOs.

II. A DESIGN AND CHARACTERISTICS OF THE ADVANCED IHRS

As it follows from above consideration essential improvement of the temperature stability of the IHR requires high temperature accuracy of the crystal plate maintained by

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the integrated oven system as well as minimization in the plate of the thermal gradients dependent on the ambient temperature. Departing from these demands there was created the TO-8 packaged IHR design schematically depicted in the Fig. 1. It consists of the crystal plate with deposited film electrodes which is mounted by the metal clips on the ceramic substrate fixed in turn on the low thermal conductivity supporting construction erected on the TO-8 base. The ceramic substrate bears all the thermo-controller circuitry including the heaters and the temperature sensor providing its fast warming-up to the operational temperature point. Due to strong thermal couple of the crystal plate with the ceramic substrate and minimized thermal flows into environment temperature of the crystal plate is sustained close to the substrate temperature. For most uniform heating the plate can be capped by a metal cover thermally contacting to the ceramic substrate. The result of these construction features is better than 0.5°C temperature accuracy of the crystal plate within (-40 +85)°C range and less than 0.1C°/cm thermal gradients ensuring significant increase of the temperature stability reaching 3 ppb in the wide temperature range.

The low thermal-conductivity properties of the supporting structure and deep vacuum in the TO-8 case provide up to 1000K/W thermal resistance from the integrated oven to environment resulting in very low power consumed by the IHR even at high operational temperatures. For instance, the power consumption of the IHR operating at around 95°C point doesn't exceed 70mW at room temperatures and is less 140mW at -40°C.

As the thermal flows from the internal oven into environment to a great extend depend on vacuum level in the TO-8 volume degradation of the vacuum conditions during long-term operation of the IHR for possible outgasing from the internal components and materials can degrade noticeably its power consumption and the temperature stability. To prevent from these negative effects a special manufacturing process providing high vacuum in the TO-8 case after the packaging and during whole lifetime of the resonator has been developed. It includes comprehensive liquid cleaning and vacuum baking procedures, optimal cold-weld regimes as well as adequate testing and long-term prediction of the IHR parameters.

Achievement of high long-term frequency stability of the IHRs had demanded consideration of different construction and the process factors including the cut and geometry of the crystal plate, its mounting structure, the film electrodes

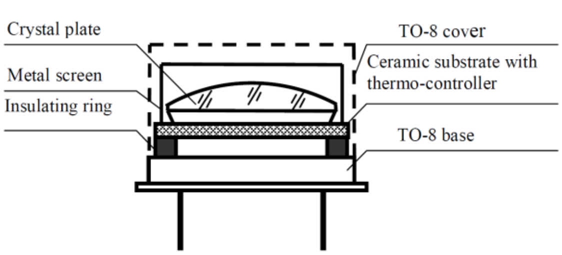

Figure 1. Design of the high stability IHR.

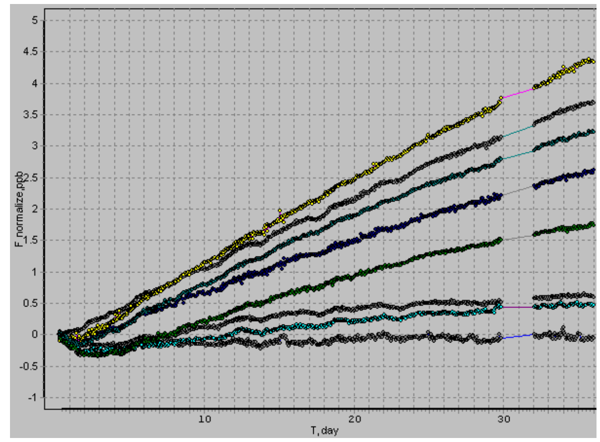

Figure 2. Typical aging curves of the SC-cut IHRs operating at 10MHz on the 5th overtone.

material as well as maintenance of deep vacuum in the IHR packaging. Optimization of this complex of the factors has led to noticeable improvement of the aging of the IHRs operating in the wide frequency range - from 8MHz to 120MHz – to the level of high-stability ordinary resonators. For instance the aging of the SC-cut IHRs operating at 10MHz on the 5th overtone reaches 0.1ppb/day and 20ppb/year (Fig. 2) that corresponds to the rate of the best conventional SC-cut crystals.

Dissipation of the whole start-up power in the ceramic substrate having strong thermal couple with the crystal plate provides fast warming-up of the latter that however doesn't convert directly in fast setting the IHR frequency due to influence of the thermal stresses arising in the plate during its fast heating. Usage of the stress compensated SC-cut crystal along with optimal mounting structure of the plate ensures almost total elimination of the gradient factor on the IHR frequency even at high start-up power values. Typical setting-up of the IHR frequency at 1.2W start power is depicted in Fig. 3 in comparison with the frequency setting for the DHR (direct heated resonator) utilizing the film heaters deposited on the plate [4]. As it follows from the plots the frequency of the new IHRs reaches the steady state with 0.1ppm accuracy after 30s and 0.01ppm accuracy within 50s after turn-on. These figures exceed noticeably the record 10s to 0.1ppm accuracy of the DHR designs reached however at about one-order worse temperature stability.

III. CONSTRUCTION AND PERFORMANCES OF THE HIGH-STABILITY OCXOS BASED ON THE ADVANCED IHR TECHNOLOGY

Integration in the IHR volume of the whole oven structure allowed substantial simplification of the OCXO construction at simultaneous reduction of its sizes and weight. The simplest and the smallest OCXO design consists of only TO-8 IHR unit mounted on the outer PC board with DIP8 compatible sizes and pins-out bearing the oscillator sustaining circuitry and other electronics (Fig. 4a).

Usage of the DIP14 compatible PC board (Fig.4b) provides additional space for the oscillator circuitry which can

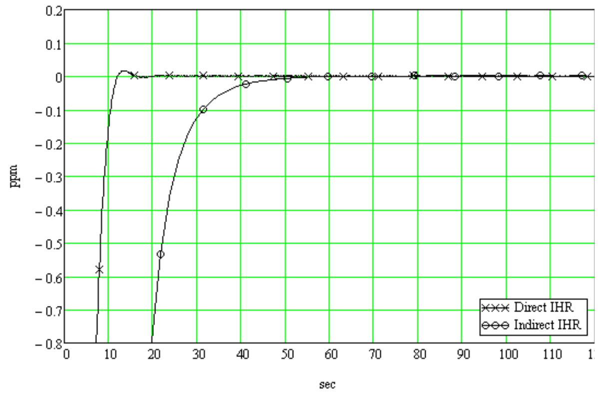

Figure 3. The utmost warming-up curves for the indirect heated and direct heated IHR versions.

Figure 4. (a) the DIP8 compatible OCXO design (15x15x10mm or 15x15x8.5mm); (b) the DIP14 compatible OCXO design (15x20x10mm or 15x20x8.5mm).

be used for deployment of the frequency multiplication stages to increase the output frequency or forming of the sine wave output. Both the DIP8 and DIP14 designs can be implemented in the SMD versions realized by proper bending of the wire leads. In case of severe environmental conditions with high humidity or salt mist, for instance, the OCXO content can be enveloped in standard steel case with 20x20x12mm sizes.

Technical characteristics of the OCXOs utilizing the IHR technology to a great measure depend on parameters of the IHR device. Thus the long-term stability and the warm-up time of the oscillators practically repeat these parameters of the IHRs.

The power consumption of the OCXOs differs from that of the IHRs only for the small portion dissipated by the sustaining circuitry and the voltage regulator. Operating in wide (-40 +85)°C range the new OCXOs consume less than 150mW at room temperatures. In more narrow range this value can be essentially reduced due to lowered internal operational temperature. Thus the OCXOs operating in (0-35)°C range (typical for the geological and geophysical submarine beacons operation) consume at 0°C only 60-65mW that is the level of the high stability TCXOs.

The temperature instability of the OCXOs is contributed from temperature instability of the IHR and of the not-heated sustaining circuitry with almost linear negative slope dependent on temperature sensitivity of the electronic components, electrical regimes and equivalent parameters of the resonator. Achievement of the highest temperature stability of the OCXOs had required therefore, besides minimization of the IHR instability, reduction of the temperature sensitivity of the sustaining circuitry. The latter was implemented by application of the “dynamic selection” technique for suppression of unwanted B-mode in the SC-cut resonator instead of usage of the selecting circuitry having essential temperature dependence [5]. These measures have led to increase of the temperature stability up to the limit of 5ppb in (-40 +85)°C and to 3ppb in (-30 +70)°C range at 10MHz operational frequency.

At rise of the operational frequency influence of temperature instability of the sustaining circuitry on the OCXO frequency grows with decrease of the resonator motional inductance. That results in degradation of utmost temperature stability of the OCXOs operating at high frequencies as depicted in Fig. 5.

The short-term frequency stability (STS) of the OCXOs based on the IHRs for a long time used to yield considerably to STS of the conventional OCXOs with external oven construction due to effect on the frequency of temperature fluctuations in the crystal plate induced by the internal heaters especially in the DHR designs [6]. Utilizing in the new IHR of the indirect heating method along with the stress-compensated cut and optimal geometry of the crystal plate has allowed essential improvement of STS of the oscillators. Nevertheless achievement of utmost STS values at the level of the high-end conventional OCXOs demands reduction of amplitude of the heating current noise by lowering the gain of the IHR thermo-controller circuitry. That however causes some degradation of the IHR temperature stability for rise of temperature deviations of the crystal plate vs. ambient temperature. The Fig. 6 indicates connection of Allan variance of the oscillators operating at 10MHz with the utmost temperature stability for different average times.

As one can see from the plots the most evident dependence of the STS on the thermo-controller gain is observed at 1s average time while the weakest one is at 0.1s due to filtering the high frequency temperature noise by thermal inertia of the IHR construction. Out of the experimental data at the top temperature stability of the OCXOs the STS is limited by $1x10^{-11}$ at 1s value which can be reduced to $2x10^{-12}$ only at relaxed temperature stability to 30-40ppb in (-40 +85)°C range.

Typical phase-noise plots of the OCXOs utilizing the advanced IHR technology are depicted in Fig. 7 for 10MHz

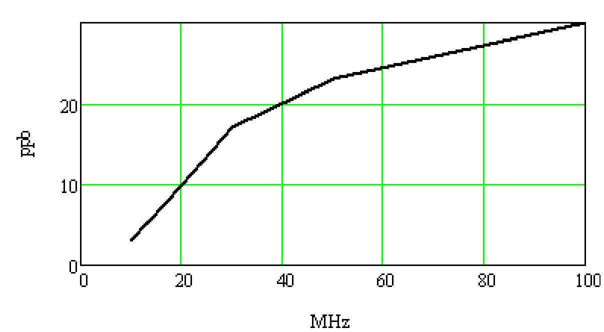

Figure 5. The utmost frequency stability of the OCXOs in (-40 +85)^{0}C depending on the operational frequency of the IHR.

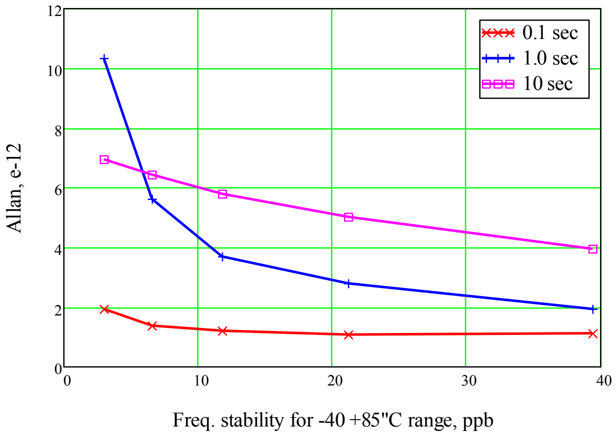

Figure 6. Allan variance of the OCXOs vs. average time at different values of the IHR temperature stability in (-30+70)°C range.

and 100MHz operational frequencies. At more than 1Hz offset from the carrier the phase-noise level approaches the figures of the low-noise 10MHz conventional OCXOs with -105dBc/Hz at 1Hz and -173dBc/Hz on the floor. However at closer than 1Hz it degrades as 35-45dBc/decade due to influence on the frequency of the power fluctuations in the IHR heaters.

The utmost performance of the OCXOs built on the advanced IHR technology are summarized in the table 1 for 10MHz operational frequency in comparison with best parameters of the high-end conventional OCXOs.

As it follows from the data the extreme values of the temperature stability, aging and phase-noise level attainable with the IHR oscillators are very close to the best figures of the conventional OCXOs. Combined with extremely low power consumption, very small sizes and short warm-up time that opens to the new oscillators the widest application field with expanse in the domains occupied heretofore entirely by the high-end conventional OCXOs.

TABLE I. UTMOST PARAMETERS OF THE HIGH-END OCXOS UTILIZING CONVENTIONAL AND IHR TECHNOLOGY.

Characteristics	Condition	The OCXO built on IHR technology	The OCXO with conventional oven design
Temperature stability, ppb	-30+70 °C	3	3
Aging per day after 30 days operation, ppb		0.1	0.1
Phase-noise level (dBc/Hz) at offsets:	1Hz	-105	-108
	10Hz	135	-140
	100kHz	-173	-173
Short-term frequency instability (Allan Variance), 10^{-12} at average time:	0.1s	1.13	0.76
	1s	1.91	1.55
	10s	3.95	2.31
Power consumption in the steady state, W	25°C	0.12	1.10
Warm-up time to 0.1ppm frequency accuracy, s	25°C	30	120
Volume, ccm		2	5

IV. ULTRA HIGH STABILITY OCXO DESIGN BUILT ON THE IHRS

Besides considered application in the low power high-stability miniature OCXOs the modern IHRs can be a unique means for creation of essentially new OCXO concept providing at miniature sizes extraordinary frequency vs. temperature stability. In such design radical gain in the temperature stability is realized by replacement of the ordinary crystal in the conventional OCXO structure by the IHR unit resulting in double heating of the crystal plate by the internal and outer ovens. In this construction the TO-8 packaged IHR is mounted on the cooper heat-sink heated by the external thermo-controller circuitry back side of which is thermally connected to the PC board bearing all the outer electronics of the oscillator (Fig. 8). This compact heating concept not assuming usage of sizeable double-oven structure provides extra-high temperature stability in 20x20x13mm case commonly used for packaging of most miniature conventional

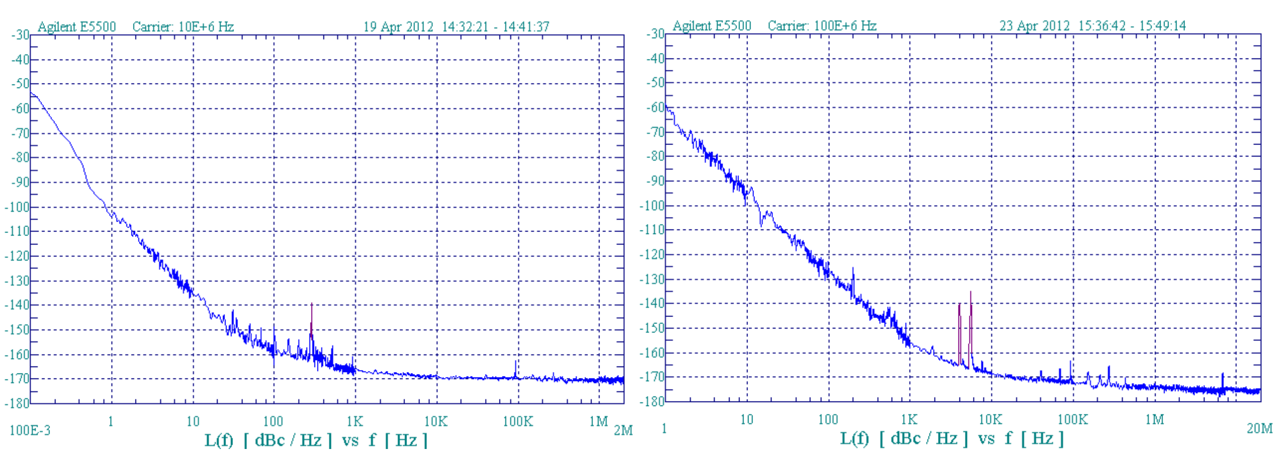

Figure 7. The phase-noise of the IHRs based OCXOs at 10MHz and 100MHz operational frequencies.

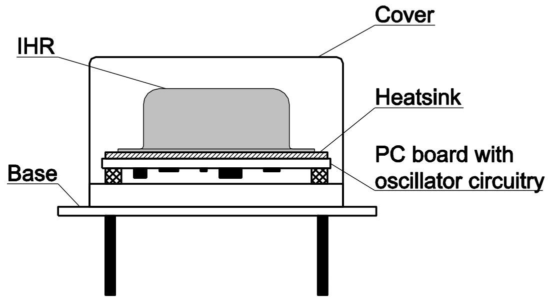

Figure 8. The concept of the IHR double-oven oscillator.

OCXOs.

Owing to the double heating of the crystal plate and ovenized sustaining circuitry the new OCXO exhibits as high as 0.2ppb frequency stability in (-30 +70)°C range. The long-term frequency stability of the new oscillators is entirely defined by the IHR stability which as was stated earlier reaches 0.1 ppb/day due to application of the 5th overtone crystal plate and improved manufacturing process. The STS of the oscillators reaches $2x10^{-12}$ at 1 s at reduced thermo-controller gain with however weak influence on the OCXO temperature stability.

The utmost characteristics of the IHR double-oven oscillator operating at 10MHz are summarized in table 2 in comparison with best parameters of small size conventional double-oven oscillators.

As it follows from the data the new oscillators utilizing the IHR technology has as twice as higher temperature instability and Allan variance than the conventional devices occupying at that about three times smaller volume and consuming lower power. At the same time compared to the high-end conventional oscillators (table 1) the new OCXOs exhibit about one-order better temperature stability at the same package sizes and power consumption.

V. CONCLUSIONS

The carried out researches and developments allowed creation of advanced IHR technology providing essential improvement of frequency stability of the OCXOs up to the level of high-end OCXOs utilizing the conventional oven designs. Possessing unique combination of very high frequency stability with extremely low power consumption, miniature sizes and short warm-up time the new OCXOs based on the IHRs are perfect solutions for various applications including those to present day occupied by the high-end conventional OCXOs.

Integration of the advanced IHR device with the conventional oven structure has yielded a novel OCXO concept possessing at very small packaging sizes ultra-high frequency stability being at the level of the existing double oven OCXOs.

TABLE II. COMPARISON OF THE DOUBLE OCXOS USING THE IHR AND TRADITIONAL OVEN CONCEPT.

Characteristics of OCXOs at 10MHz frequency	**IHR double oven OCXO**	**Conventional double oven OCXO**
Temperature stability in (-30 +70)°C, ppb	0.2	0.1
Aging per year, ppb	20	20
Allan variance at 1 s, 10^{-12}	1.9	1.5
Power consumption, W	1.1	1.5
Package sizes, mm	20x20x12	27x37x16

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