Highly Stable Miniaturized OCXO with Heater-Embedded Ceramic Package

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Abstract—This paper reports on the development of a highly stable miniaturized Oven Controlled Crystal Oscillator (OCXO) in the size of 9.7 x 7.5 mm consisting of heater-embedded ceramic package. The embedded heater layer establishes a symmetrical thermal field to achieve good temperature uniformity, which maintains the oven stability and reduces the power consumption. In addition, the SC-cut crystal is utilized for the proposed miniaturized OCXO to further improve the temperature stability, aging, and phase noise. As a result, this 9.7 x 7.5 mm OCXO has achieved temperature stability of ±3 ppb across -40 to 85 °C. Furthermore, we also demonstrated the proposed miniaturized OCXO could be complied with Stratum 3E requirements.

Keywords—Heater-embedded ceramic package; symmetrical thermal field; SC-cut crystal

I. INTRODUCTION

The forthcoming wireless communications (recently often referred to as fifth generation, 5G) and mobile technology are expected to operate at high-spectral-purity signals with higher communication quality. The low-power nodes (i.e., small cells, which may be employed indoors or outdoors) has shown their ability to satisfy the demands for 5G applications by achieving high dense deployment of infrastructure and providing cost-effective alternative for the system designers [1]. In addition, it also denotes that the requirements for the reference oscillators operating in small cells technologies require tight phase accuracy, low power consumption, and small-sized package.

However, conventional ASIC-based OCXO adopts the heat source embedded in IC [2], resulting in a thermally asymmetric structure with respect to the heat source between crystal and IC. This yields relative large thermal gradients from crystal to IC, thus degrading the oven control stability and leading to an insufficient heating capability. To overcome the abovementioned issues, we proposed a miniaturized OCXO consisting of heater-embedded ceramic package as shown in Fig. 1(a), which installs an IC and a crystal blank at two opposite sides of an embedded heater layer (resistive element), whereby the embedded heater layer establishes a symmetric thermal field, so as to achieve good thermal uniformity, maintain the oven stability and reduce the power consumption.

In this paper, the thermal behavior of the proposed thermally symmetric OCXO is numerically compared to the conventional ASIC-based OCXO using thermal modeling [3]. In addition, an AC-cut crystal is utilized to experimentally investigate the oven stability of the practical structure.

To further improve the temperature stability, aging, and phase noise [4, 5], we had developed a SC-cut crystal for the proposed OCXO. Finally, a highly stable miniaturized OCXO with the size of 9.7 x 7.5 mm consisting of a 6.0 x 3.5 mm heater-embedded ceramic package is presented. As a result, the performance of the proposed miniaturized OCXO has achieved temperature stability of ±3 ppb across -40 to 85 °C. Furthermore, we also demonstrated the proposed miniaturized OCXO could be complied with Stratum 3E requirements.

II. THERMAL ANALYSIS

A numerical model is implemented to investigate the thermal distribution in the OCXO as shown in Fig. 1(a), including a crystal blank, an IC, a heater embedded ceramic package, a PCB substrate, and a cover. First, the general heat
Conduction equation can be derived from the first law of thermodynamics as shown in below:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot \mathbf{q} = 0,$$

where \(\rho\) [kg/m\(^3\)] denotes the density, \(C_p\) [J/(kg·K)] is the heat capacity at constant pressure, and \(\mathbf{q}\) is the heat flux vector. Considering Fourier's Law of heat conduction gives:

$$\mathbf{q} = -k \nabla T,$$

where \(k\) [W/(m·K)] is the thermal conductivity.

Convective heat flux boundary condition is implemented to represent the outside wall of the cover, exposing to the ambient air environment:

$$-\mathbf{n} \cdot \mathbf{q} = h(T_A - T),$$

where \(\mathbf{n}\) denotes the normal to the wall, \(h\) is the heat transfer coefficient, and \(T_A\) represents the temperature of the ambient air. In this paper, the operating temperature of \(T_A\) utilized in the simulation is 25 °C. In addition, the power generating by the heat source is 0.42W.

As shown in the simulation result in Fig. 1(b), when the heat source generated from the embedded heater, a thermally symmetric temperature distribution between crystal \((T_X = 94.6\ °C)\) and IC \((T_J = 94.8\ °C)\) with respect to the embedded heater \((T_H = 95\ °C)\) is formed. However, using the heater inside the IC leads to an asymmetric thermal field as shown in Fig. 1(c). The temperature of crystal \(T_X\) and IC \(T_J\) is 91.2 °C and 95 °C, respectively. This indicates that a larger power is required to keep the temperature of crystal in the expected value, thus increasing power consumption and degrading reliability.

As shown in Table 1, the crystal-to-ambient thermal resistance \(\theta_{XH}\), heater-to-junction thermal resistance \(\theta_{HJ}\), and junction-to-crystal \(\theta_{JX}\) thermal resistance for the proposed thermally symmetric structure and the conventional ASIC-based asymmetric structure are calculated using the temperature distribution result from simulation. Firstly, the result of \(\theta_{XH}\) shows that the thermally symmetric structure is 8.1 °C/W larger than that of the asymmetric structure. It is noted that \(\theta_{XH}\) can be denoted as the thermal efficiency and should be designed as large as possible for OCXO. Secondly, \(\theta_{HJ}\) and \(\theta_{HJX}\) can be considered as the thermal uniformity in the ovenized structure, in which \(\theta_{HJ}\) and \(\theta_{HJX}\) should be as similar as possible to achieve more stable oven controlled ability. As a result of the thermally symmetric configuration, the thermal resistance difference \((\theta_{XH})\) between \(\theta_{HJ}\) and \(\theta_{HJX}\) is only 0.48 °C/W, which is much smaller than that of asymmetric structure (9.05 °C/W). By increasing the target temperature from oven controlled circuit of the asymmetric structure, the temperature variation of crystal compared to that of the expected value can be compensated. However, this temperature increment may induce an additional oscillation frequency change because the oscillation circuit in the IC is temperature dependence [6].

To further investigate the oven stability of the proposed structure, an AC-cut crystal as a temperature sensor is utilized. Fig. 2 shows the frequency output of AC-cut crystal with the ambient temperature when heater is turned off. Using linear fitting on the frequency data in Fig. 2 yields:

$$F(T_A) = 27.387T_A - 1111.7 \text{ (ppm)},$$  \hspace{1cm} (5)

where \(F\) (ppm) denotes the frequency. Then rearranging (5) gives the temperature function of frequency as below:

$$T_A(F) = 0.0365(F - 1111.7) \text{ (°C)}.$$  \hspace{1cm} (6)

Next, the heater is turned on and the frequency output is measured within the ambient temperature ranging from -40 to 85 °C. Using the frequency data referred to (6), the temperature stability of crystal is less than ±0.5 °C (solid line) as shown in Fig. 3.

<table>
<thead>
<tr>
<th>Thermal Structure</th>
<th>(T_H) [°C]</th>
<th>(T_J) [°C]</th>
<th>(T_X) [°C]</th>
<th>(\theta_{XH}) [°C/W]</th>
<th>(\theta_{HJ}) [°C/W]</th>
<th>(\theta_{HJX}) [°C/W]</th>
<th>(\theta_{JX}) [°C/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symmetry</td>
<td>95</td>
<td>94.8</td>
<td>94.6</td>
<td>165.7</td>
<td>0.48</td>
<td>0.95</td>
<td>0.48</td>
</tr>
<tr>
<td>Asymmetry</td>
<td>95</td>
<td>95</td>
<td>91.2</td>
<td>157.6</td>
<td>0</td>
<td>9.05</td>
<td>9.05</td>
</tr>
</tbody>
</table>

![Fig. 2. Frequency deviation of AC-cut crystal with the ambient temperature.](image)

![Fig. 3. Temperature stability of the proposed thermally symmetric structure.](image)
The proposed miniaturized OCXO in the size of 9.7 x 7.5 mm consisting of heater-embedded ceramic package with SC-cut crystal.

Figure 4 shows the practical appearance of the miniaturized OCXO in the size of 9.7 x 7.5 mm consisting of a 6.0 x 3.5 mm heater-embedded ceramic package and a SC-cut crystal is presented as shown in Fig. 4.

In addition, the IC temperature is also detected by measuring the temperature output from the sensor embedded in the IC as shown in the dashed line in Fig. 3, in which there is only 0.4 °C variation from -40 to 85 °C. As a result, owing to the thermally symmetric structure the maximum temperature error between crystal and IC is less than 0.8 °C (dotted line) shown in Fig. 3.

III. PRACTICAL PERFORMANCE

Based on the proposed concept, the practical appearance of the miniaturized OCXO in the size of 9.7 x 7.5 mm consisting of a 6.0 x 3.5 mm heater-embedded ceramic package and a SC-cut crystal is presented as shown in Fig. 4.

Figure 5 shows that the temperature stability of the proposed miniaturized OCXOs using 20 MHz SC-cut crystal could be less than ±3 ppb across -40 to 85 °C. In addition, the corresponding measured phase noise of -75, -106, -129, -150, -160, -161, and -162 dBc/Hz at 1, 10, 100, 1 k, 10 k, 100 k, and 1 MHz offsets are also demonstrated in Fig. 6.

Figure 7 shows the bias aging performance of the OCXOs operating at room temperature. First, we collected the first 14 days data plotted as bold solid lines in Fig. 7. Next, we adopted the aging model [7] using the measured data to simulate and to predict the aging behaviors in long-term perspective which is plotted as thin lines shown in Fig. 7. The results show the yearly aging performance is less than -60 ppb/year.

Furthermore, the proposed miniaturized OCXO is also complied with Stratum 3E requirements. First, the holdover phase movement ability under steady state condition is shown in Fig. 8, which is better than 1.5 μs for 4 hours. Next, the Wander test including MTIE and TDEV measurements with 1 mHz bandwidth filter is respectively shown in Fig. 9 and Fig. 10, showing that the proposed 9.7 x 7.5 mm OCXO could be complied with Stratum 3E requirements and ITU-T G.812 Type III clock.
Fig. 9 MTIE test result of the proposed 9.7 x 7.5 mm OCXO with 1mHz bandwidth filter.

Fig. 10. TDEV test result of the proposed 9.7 x 7.5 mm OCXO with 1mHz bandwidth filter.

IV. CONCLUSION

In conclusion, we have developed a highly stable miniaturized OCXO with the size of 9.7 x 7.5 mm consisting of heater-embedded ceramic package to establish a thermally symmetric structure. This concept can be effortlessly extended to other packaging sizes by replacing the cover and PCB substrate as shown in Fig. 1(a) to satisfy a wide range of application requirements, such as 25 x 22 mm, 14 x 9 mm, and 7.0 x 5.0 mm. In addition to the embedded heater design, the SC-cut crystal used in the proposed OCXO can further improve the frequency instability effect causing by the severe airflow condition from the outdoors application of small cells due to its greater temperature stability and lower frequency overshoot [4, 5].

REFERENCES