A New Generation DSP-OCXO Using Crystal Temperature Sensor

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Abstract— **This paper reports on a development and tests of the DSP-OCXO (Digital Signal Processing-Oven Controlled Crystal Oscillator) using AT cut crystal high accuracy temperature sensor which consisting of two thermal equivalent crystals. For the applications of the small size base stations, the DSP-OCXO which has following features: 14 x 9 mm small size, 0.6 W maximum at +25deg.C low power consumption and +/-20 ppb maximum /-40 to +85deg.C high frequency stability vs. temperature has been developed.**

I. INTRODUCTION

As a background of needs on market requests, in fixed telecommunication network, such as wireless and optical network, a frequency reference clock which has features as follows. First, OCXO requires smaller less than 14 x 9 mm. And second, OCXO required higher frequency stability over -40 to +85deg.C wide operating temperature range.

For downsizing and high frequency stabilization of OCXOs, there are some real limitations by an aspect of crystal design [1], [2]. As conventional approaches of downsizing and high frequency stabilization, the doubly rotated cut crystal such as SC cut crystal has been used. However, it is hard to be realized to cut crystal's angle accurately with downsizing of OCXOs. So when using AT cut crystal which is single rotated cut, accurate temperature control has to be necessary in a crystal. In addition to that, oscillation circuit and other circuit have to been minimized by integrated circuits.

Also, in conventional design OCXO, thermistors have been used as a temperature sensor. However, when thermistors are used, there is a limitation to control of temperature. This limitation is caused by the variation of locational temperature distribution and the aging of devices.

From these backgrounds, in this paper, using AT cut crystal temperature sensor and DSP technology, 14 x 9 mm downsizing and less than +/-20 ppb high stability vs. temperature over -40 to +85deg.C have been achieved.

II. BASIS OF CRYSTAL TEMPERATURE SENSING

As the basis of crystal temperature sensor, the features of using crystal sensor are as follows. First, high accurate temperature measurement is able to be done. Because controlled object and a sensor are crystal and are in same place. Second, temperature sensor's resolution is very high (0.0001 deg.C) since temperature is detected as frequency but voltage. Temperature sensing by frequency is 10 to 100 times as robust as voltage detection against external noise. Third, extremely low aging as sensor. In conventional crystal temperature sensor, the detected temperature is varied by crystal's aging. However, in case of this proposed OCXO, by using the differential data between two frequencies, those aging are cancelled each other.

III. APPLICATION OF DSP TO OCXO

As mentioned above, for downsizing of OCXOs, many functions have to be integrated to one chip IC. In this paper, oscillation circuits, temperature detection and control circuit, control registers, output divider circuit were integrated to one chip IC. Also, DSP technology was used in temperature control circuit to establish easy adjustability and productivity.

IV. DESIGN OF OCXO

Figure 1 shows a functional block diagram of the OCXO. There are two key features in the block. First, temperature is detected from two AT cut crystals X1 and X2. The measured temperatures in the crystals are detected as the differential data between the crystals' frequencies. Second, temperature in the crystals is controlled appropriately by heaters in PI control loop. The control parameters have been determined and stored to the memories. Then after power-on, the parameters are loaded from the registers. In addition to that, the output frequency signal will be able to divide with ratios from 1/1 to 1/8.

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Figure 2 shows a functional block diagram of temperature detection in detail. The below left side figure shows the frequency deviations df_{x1} and df_{x2} (Each frequency deviations of crystals X1 and X2 from each nominal frequencies) vs. temperature. And the below right side figure shows the frequencies differential between df_{x1} and df_{x2}. This curve shows linear to ambient temperature. Additionally, this linearity is not depending on each crystal curves since these two crystal curves have same inflection temperatures. So the differential frequency between df_{x1} and df_{x2} is able to use as a temperature sensing. Then the frequency differential data is input to a phase detector, a loop filter and a DDS(Direct Digital Synthesizer) block. Finally, the temperature detection value is smoothed and output.

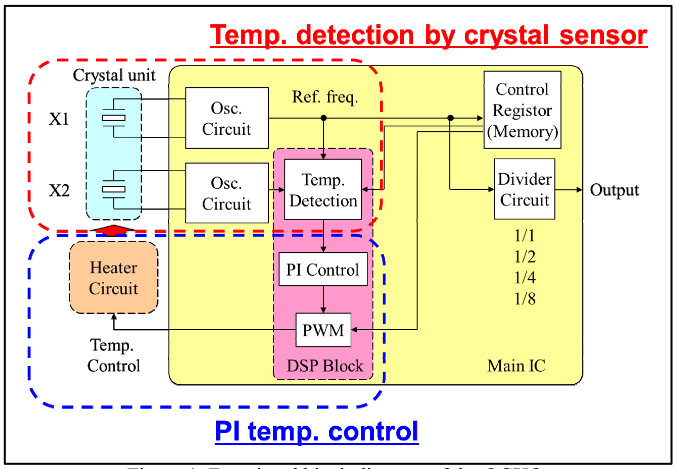

Figure 1. Functional block diagram of the OCXO

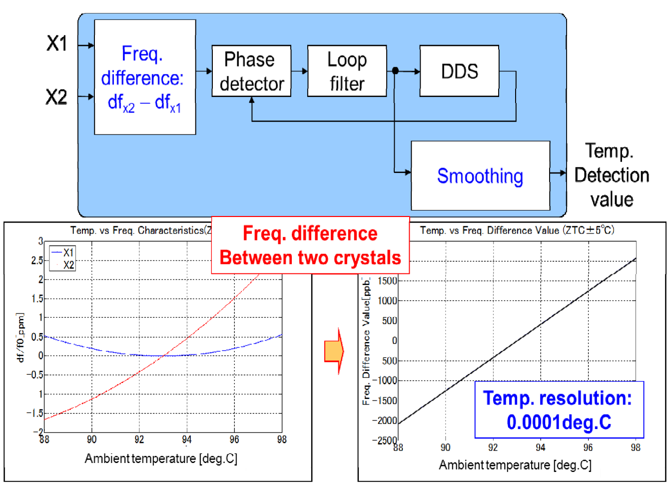

Figure 2. Functional block diagram of temperature detection by two crystals X1 and X2's frequencies.

In PI control, the temperature accuracy target is set to 0.02deg.C for an ambient temperature range of -40 to +85deg.C. Where, the temperature detection resolution is 0.0001 deg.C / bit, PWM bit number is 17 bits and the heater control resolution is 0.001 deg.C / bit from the below formula in a table 1.

Figure 3 shows the temperature control block diagram for explanation of PI control. The features are as follows. First, a crystal X1 is both an output frequency source and a part of temperature sensor. Therefore temperature at X1 is kept more stable. Second, by PI control, X1's temperature and frequency are more stable. Finally, the target temperature will able to be set, depending on crystal's zero temperature coefficients.

Table 1. Temperature accuracy target and other conditions

Temperature accuracy target: 0.02 deg.C

Ambient temperature	-40 to +85 deg.C (125 deg.C range)
Temperature detection resolution	Target: 0.0001 deg.C / bit
Heater control resolution	Target: 0.001 deg.C / bit A calculation formula : (Ambient temp. range) / 2 ^ (PWM bit number) (125 deg.C) / (2 ^ 17 bits) = 0.001 deg.C / bit

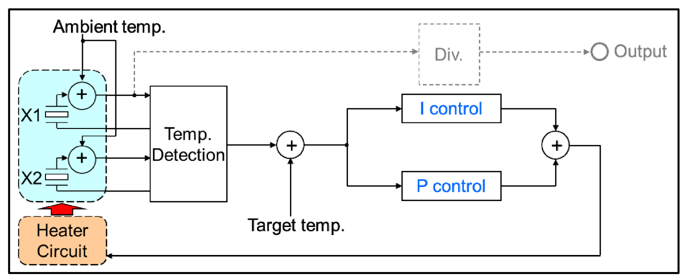

Figure 3. Temperature control block diagram for explanation of PI control

V. DEVELOPMENT AND DESIGN VERIFICATION

The development and design verification had been done by the following steps. First, finite element thermal analysis simulation was run. And then the OCXO structure was investigated and determined. Finally, PI control behavior was checked by the measurement of power consumption along with time and the variation of heater control temperature vs. ambient temperature.

Figure 4 shows an example of finite element thermal analysis simulation of an OCXO. As shown in the figure, temperature in a crystal was kept constant and within the target temperature range of 0.01deg.C. From this result, the structure of OCXO was finally determined as shown in figure 4.

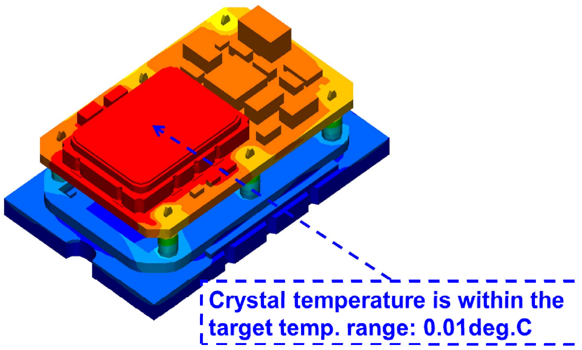

Figure 4. An example of finite element thermal analysis simulation

Figure 5 shows OCXO power consumption over time and figure 6 shows heater control operation in an OCXO. As shown in figure 5, in warm-up state, the power consumption in other words temperature control was vibrational, however, the power consumption was finally kept stable at around 1 min. by PI temperature control. Additionally, from figure 6, the amount of heater control temperature was changed in the range of +/- 0.020deg.C in almost direct proportion to ambient temperature changes. From these results, it is clear that PI temperature control in an OCXO had been done appropriately.

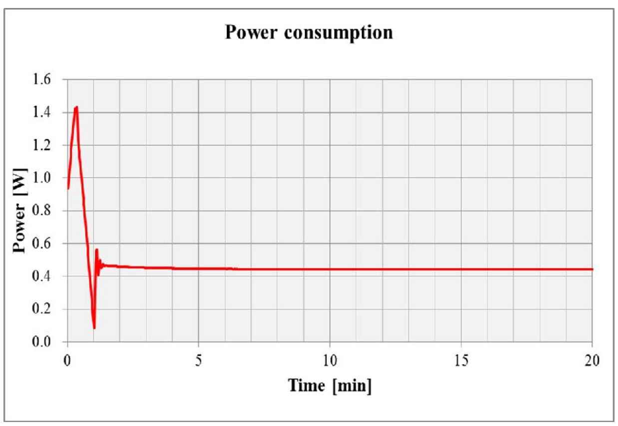

Figure 5. OCXO power consumption over time for the check of PI temperature control behavior

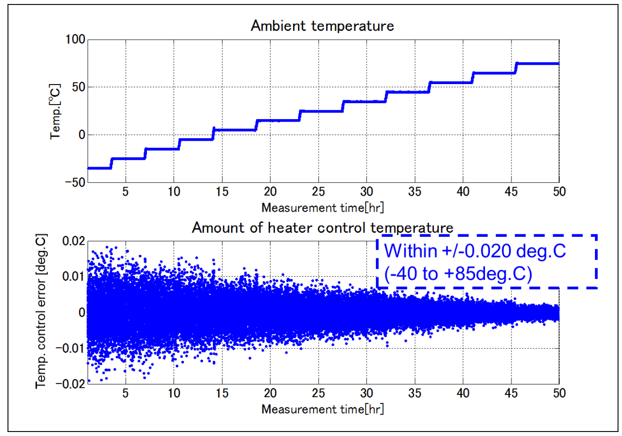

Figure 6. Heater control operation in an OCXO for the check of PI temperature control behavior

VI. Measurement Result

The features of the OCXO are as follows:

-SMD package

L: 14.6 mm, W: 9.7 mm max. H: 6.5 ± 0.2mm

-Frequency stability(Tempco)

±20 ppb max. / -40˚C to +85 ˚C

-Frequency range: 5MHz to 40MHz

-Power Supply: 3.3 V ± 5 %

-Power Consumption:

1.5 W max. (at warming up state)

0.6 W max. (at +25 deg.C steady state)

-Phase noise (f_{nom}: 19.2 MHz)

-78 dBc / Hz typ. (@1 Hz offset freq.)

-100 dBc / Hz typ. (@10 Hz offset freq.)

-127 dBc / Hz typ. (@100 Hz offset freq.)

According to the above, we have fabricated several nominal frequency OCXOs for the design verification.

Figure 7 shows the completed OCXO for the measurements. This OCXO's external structure is consisted of a metal cover and a PCB for SMD (Surface Mounted Device).

Figure 7. The fabricated OCXO and one cent coin for size comparison

Figure 8 shows the frequency stability vs. temperature characteristics in reference to frequency at +25deg.C. It shows ppb. (In the figured sample, -3.3 ppb at -40deg.C, +1.0 ppb at +85deg.C, f_{nom}: 38.88 MHz)

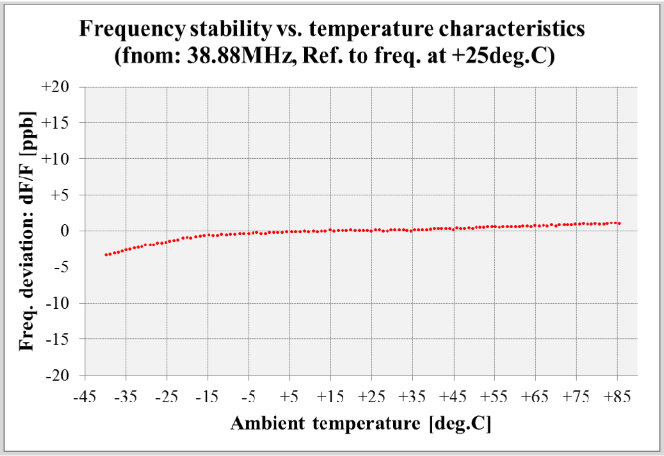

Figure 8. OCXO frequency stability vs. temperature

(In reference to frequency at +25deg.C)

As shown in figure 9, the power consumption at warm-up was 1.47 W, and 0.43 W at steady +25deg.C state.

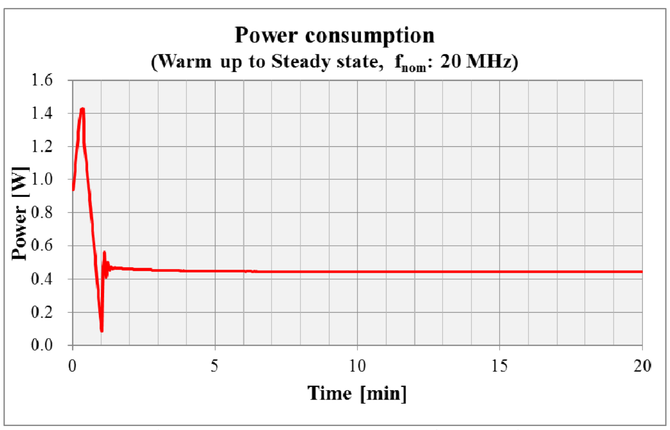

Figure 9. OCXO power consumption over time

Figure 10 shows single side band phase noise which was -78, -100, -127, -145 and -153 dBc/Hz at 1, 10, 100, 1k and 10kHz offset frequencies respectively (fnom: 19.2 MHz). Figure 11 shows Short term stability (Allan deviation) which was 3.3E-11 at τ: 1s.

From these results, even the OCXO with AT cut crystals have achieved these characteristics.

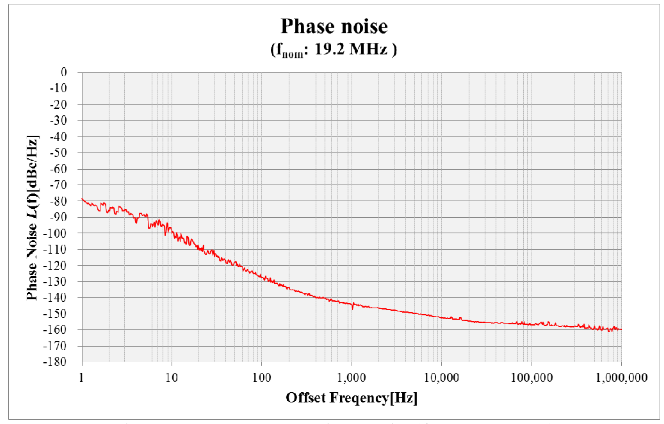

Figure 10. OCXO SSB phase noise(f_{nom}: 19.2 MHz)

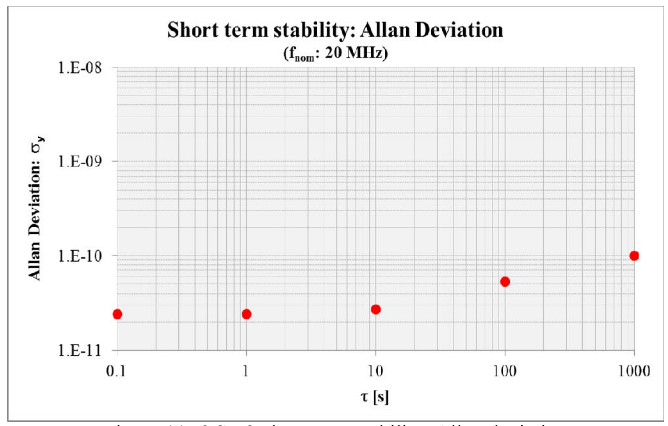

Figure 11. OCXO short term stability: Allan deviation
(τ: 0.1 to 1000 s, f_{nom}: 20 MHz)

VII. Conclusion

We have achieved the sophisticated design method of the 14 x 9 mm small size and high stability OCXO such as sub ppb frequency stability vs. temperature.

References

[1] Jaehyn Lim, Kyusun Choi, Hynsoo Kim, Thomas Jackson, David Kenny, "Miniature Oven Controlled Crystal Oscillator (OCXO) on a CMOS Chip", International Frequency Control Symposium and Exposition, IEEE, pp.401-404, 2006.

[2] Hyunsoo Kim, Thomas Jackson, Jaehyun Lim, Kyusun Choi, David Kenny, "Frame Enclosed Resonator for Miniature Oven Controlled Crystal Oscillator (OCXO)", International Frequency Control Symposium and Exposition, IEEE, pp.491-493, 2006.