Ruggedized Rubidium CPT Clock Platform

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***Abstract*—This Since their introduction to the commercial market in 2008, microwave atomic clocks using a Coherent Population Trapping (CPT) approach have provided a smaller size, lower power alternate to Rb lamp clocks[1]. By eliminating several complex assemblies, specifically the lamp and microwave resonator, CPT clocks have been able to leverage economies-of-scale and provide a board-mountable, low-cost atomic clock to applications like handheld test equipment and telecom infrastructure.**

More recent iterations of CPT clocks have addressed early technical challenges, such as a reliable and rapid lock acquisition time, as well as integration of low noise electronics to improve overall stability metrics such as Allan Deviation (ADEV), phase noise and temperature stability (TempCo)[2]. CPT clock performance now approaches the performance of commercially available lamp technology.

Recently, CPT clocks have turned towards ruggedization to meet the demanding environmental and performance requirements of aerospace and defense applications.

This paper discusses the challenges and development of a low-profile Rb oscillator platform that leverages CPT cost, size and power reductions into a ruggedized design. This design is intended to offer a wider temperature range compared to commercial variants by employing a novel approach of integrating a Thermo Electric Cooler (TEC) into the Rb cell assembly, with a goal of surpassing a range of -40 to +85°C. The design is also intended to accommodate several options including improved short-term stability (ADEV and phase noise) and radiation tolerance. The latter to be addressed in subsequent projects with an approach similar to products such as the space Chip-Scale Atomic Clock (CSAC), which minimally modifies and screens by manufacturing lot to achieve radiation goals while maintaining a low cost. The improved short-term stability variant is to be addressed by leveraging the latest in low-power Evacuated Miniature Crystal Oscillator (EMXO) technology and integrating it into the control loop. The baseline ADEV performance is anticipated to meet 2 x 10^{-11} at Tau = 1s, while the low noise variant has a goal of 2 x 10^{-12} at Tau = 1s with a phase noise of -100 dBc/Hz at 1Hz. Experimental results and progress will be shared.

Keywords—rubidium, rugged, CPT, clock, oscillator

Figure 1: Miniature Atomic Clock (MAC) model SA5X

I. Introduction

Coherent Population Trapping (CPT) atomic clocks based on the innovations of Northrop Grumman (formerly Westinghouse) and NIST in the 1990's that demonstrated excellent performance in compact form factors previously unattainable. The technology al-lowed for the replacement of conventional lamp-based excitation of the Cesium or Rubidium atoms, with a Vertical Cavity Surface Emitting Laser (VCSEL). The technique of modulating the laser at one half the conventional microwave interrogation frequency simplified frequency synthesis and significantly reduced the size weight and power (SWaP) of the atomic clocks physics package. Microchip, along with partners Draper Laboratories and Sandia National Laboratories developed the Chip-Scale Atomic Clock (CSAC) in the early 2000s and released the first commercial product in 2011. During the development of CSAC, a derivative higher performance design was developed that traded off volume and power for improved performance. The product was designated the Miniature Atomic Clock (MAC).

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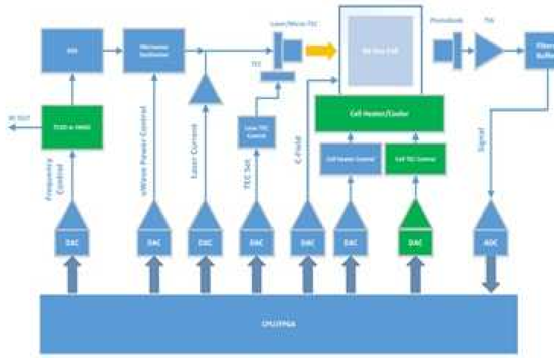

Figure 2: MAC / 8300C Block Diagram

II. The MAC

The first-generation MAC was commercially released in 2009 as the model SA3X. Subsequently, an updated version of the MAC was released in 2019[4], as the model SA5X. Key improvements included improvement of the reliability the thermal control of the VCSEL, separating the microwave synthesizer and laser on a unique PCB assembly to reduce cross-talk and im-prove phase noise, leveraging an FPGA for precision timing and direct digital synthesis, attention to power supply filtering and isolation, optimizing the laser controls to reliably lock over a wide range of temperature, improvements in

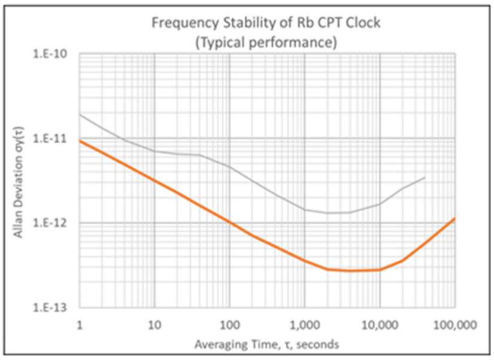

Figure 3: Frequency Stability Comparison

the temperature compensation algorithms and reduction in the aging. A simplified block diagram is shown in figure 2. The items in green represent additions to the design called the 8300C. A variant of the SA5X was developed for installation into low profile VPX modules and has been qualified and fielded into military aircraft. The result of these changes im-proved frequency stability, temperature stability and consistent lock over all operating temperatures. Figure 3 shows the improvement of the performance of Allan Deviation of this next generation design. The orange line represents measured performance of the SA5X vs the SA3X in grey. The improvements on the flicker floor, beyond 10,000 seconds, is particularly significant and of critical importance for applications requiring long term frequency stability. The flicker floor is representative of a factor of 3 improvement in temperature stability. Temperature stability of the SA5X is typically less than 3 x 10^{-11} over the operation temperature range of -40 to +75°C. The resulting design has demonstrated 300 ns of holdover in benign, stable temperature environments.

III. Ruggedized Approach: The 8300C

Microchip's experience in developing time and frequency systems for industrial and military applications, motivated the development a new platform for military applications, designated the 8300C. The design maintains the low profile, < 0.7" or 18 mm, of the SA5X with a slightly larger footprint that allows for the inclusion of a TEC, low phase noise EMXO, and future capabilities.

The chassis is available in a hermetic package for enhanced reliability with a coaxial connector for low noise connectivity.

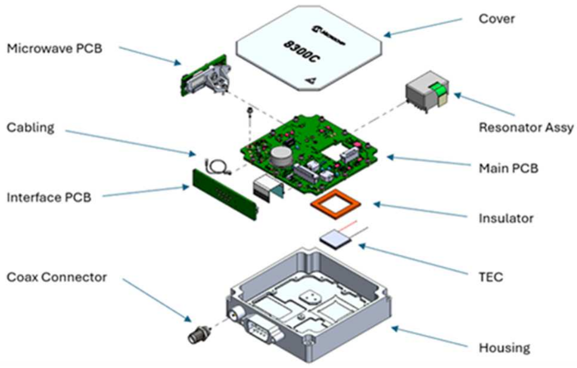

Figure 4: 8300C assembly

Referring back to figure two, the 8300C shares much of its architecture with the SA5X. The key differences be-tween the new design and the SA5X is the option of substituting the EMXO in place of the standard TCXO to improve phase noise, the transition to a Microchip IGLOO® 2 FPGA and other Microchip com-ponents, the TEC attached to the resonator assembly, and a more reliable connectorized hermetic housing.

A. EMXO

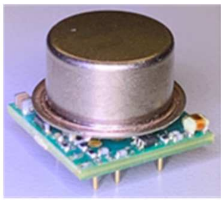
Figure 5: EMXO

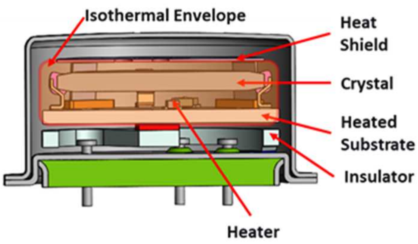

Figure 6: EMXO crystal assembly

The EMXO allows the module to achieve significantly improved phase noise and short-term frequency stability. The EMXO is a low power ovenized oscillator that controls the temperature of the 3rd overtone SC cut crystal and elements of the oscillator circuitry within an evacuated enclosure to minimize power consumption. Figure 5 shows an EMXO as a standalone device and the cross section of the crystal/oven assembly. Because the intrinsic frequency stability of the 8300C is typically better than 1 x 10^{-11} at one second time intervals, the system can be optimized to demonstrate superior performance. Figure 7 and 8 show measured phase noise and frequency stability of the combined system of a prototype device. The combined low noise 8300C shows Allan Deviation below 3 x 10^{-12} at one second, and below 5 x 10^{-13} for a flicker floor. The measured phase noise on at 1 Hz is -98 dBc/Hz and a floor of -160 dBc/Hz. This design provides a viable path toward project goals of 2 x 10^{-12} Allan Deviation at 1 second and -100 dBc/Hz at 1Hz offset frequency for phase noise.

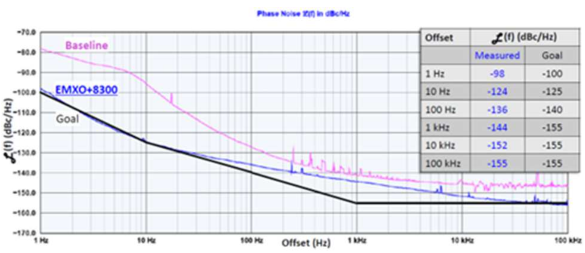

Figure 7: 8300C Phase Noise

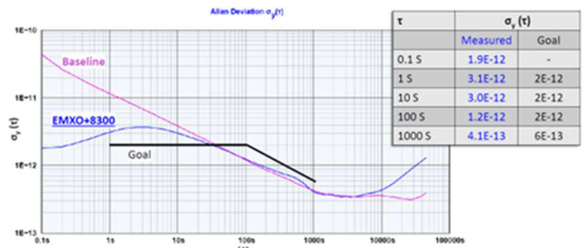

Figure 8: 8300C Allan Deviation

B. TEC

Military and industrial applications for frequency sources often require operating temperatures of -40°C to 85°C. This is a challenge for gas cell atomic clocks because the thermal rise from the baseplate increases the temperature of the atoms and buffer gas to a point in which performance is compromised. Many high performing rubidium clocks have maximum operating temperatures as low as 65°C or 70 °C. The 8300C uses a thermal electric cooler (TEC) to maintain the optimum cell temperature necessary while allowing the baseplate temperature to reach 85°C. Although the TEC requires power to stabilize the temperature, at higher temperatures the resonator oven, which is a conventional transistor heater, requires minimal power. As a result, the power consumption above 70°C only increases by 1.5W and the total power consumption is below the specification of 8W.

C. Radiation testing

Another critical emerging environment for atomic clocks are Low Earth Orbit (LEO) satellites. Microchip's Space CSAC is currently in use in several such applications, and its low power and reduced volume is critical for smaller satellites that have restrictions on power. However, in applications that require improved performance and additional power, a similarly qualified space 8300C may be necessary to support mission requirements. In order to validate the potential for the product, proof of concept testing was performed on standard SA5X units for the response to total ionizing dose to a level of 50 krad (Si). Like the update of the standard space CSAC, the TCXO was replaced with a radiation tolerant device, Microchip's TX-802. Testing was performed at the University of Massachusetts, Lowell, radiation testing facility and performance was demonstrated to 42 krads (Si.) During the testing, a manual reboot was initiated to make sure the clock remained capable of reacquiring atomic lock.

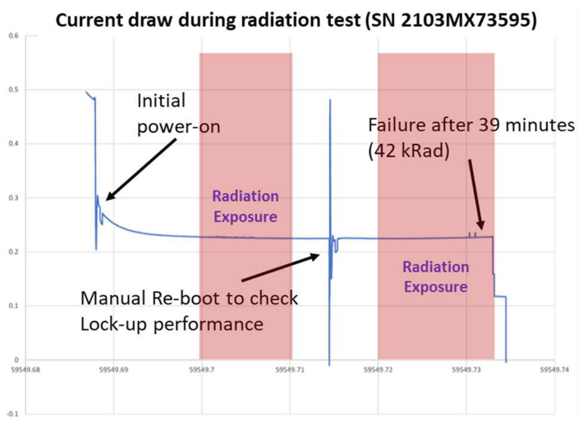

Figure 9: TID testing

The results of the radiation testing were encouraging and based on the results, plans are underway to offer a radiation tolerant version of the 8300C.

IV. Conclusion

In summary, the 8300C is based on the 2nd generation Microchip Miniature Atomic Clock and provides exceptional frequency and temperature stability, along with improved phase noise, wide operating temperature range and low aging. The packaging is designed to provide a flexible high reliability platform for industrial and military customers.

Figure 10: ADEV of prototype 8300C

REFERENCES

[1] John Kitching, "Chip-Scale Atomic Clocks" Johns Hopkins Applied Physics Laboratory Journal, 2018

[2] R. Lutwak, A. Rashed, M. Varghese, G. Tepolt, J. Leblanc, M. Mescher, D.K. Serklan and G.M Peaske, "The Miniature Atomic Clock - Preproduction Results," Proceedings, 2007 IEEE Frequency Control Symp., Geneva, Switzerland, May 29-June 1, 2007

[3] M. Stanczyk, S. Hampton, P. Cahs, M. Silveira, "Space CSAC: From Concept to Qualified Product", 2019 PTTI

[4] P. Cash, W. Krzewick, Paul Machado, K. Ricard Overstreet, Mike Silveira, Matt Stanczyk, Dwayne Taylor, Xianli Zhang, "Microchip Chip Scale Atomic Clock (CSAC) Technical Status, Applications and Future Plans", EFTF 2018

[5] W. Krzewick, J. Mitchell, J. Bollettiero, P. Cash, K. Wellwood, I. Kosvin, L. Zanca, "A Next Generation, Miniaturized Rubidium Atomic Clock Reference for Mobile, GNSS-Denied Environments", PTTI 2020

[6] P. Cash, I. Kosvin, H. Park, M. Stanczyk, M. Wacker, "Low Phase Noise Low Power Atomic Clocks", 2022 IFCS/EFTF