Low Phase Noise Low Power Atomic Clocks

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Microchip Technologies has developed low power ovenized crystal oscillators and atomic clocks that enable applications requiring high performance in low Size Weight and Power (SWaP) Applications. Recently products have been improved and integrated into a single package. The atomic clock for this design is the Chip Scale Atomic Clock (CSAC SA65) and the ovenized crystal oscillator is the Evacuated Miniature Crystal Oscillators(EXX421.) Both oscillators use a vacuum as an insulator to maintain a constant temperature for the physics package in CSAC and the crystal assembly for the EMXO. Additionally, the electronic designs use power optimized architecture to minimize power and maximize performance.

Figure 1 EMXO and LNCSAC SA65

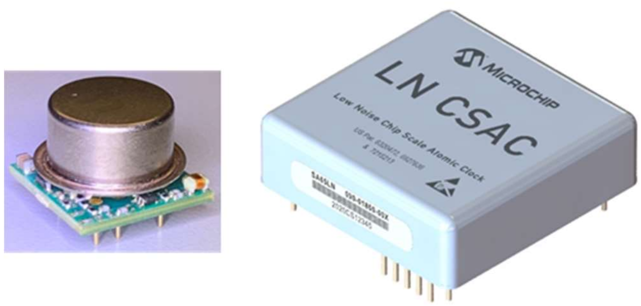


Figure 2 Evacuated Miniature Crystal Module (EMXM)

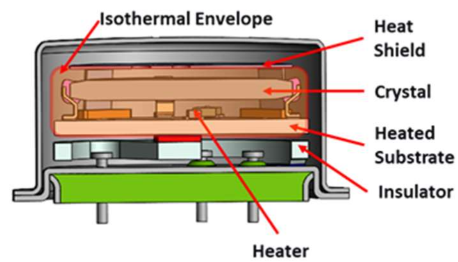
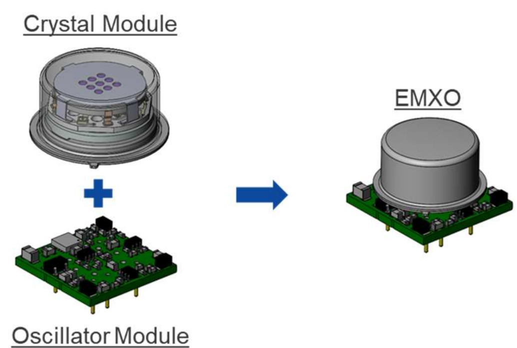


Figure 3 EMXO Oscillator Assembly



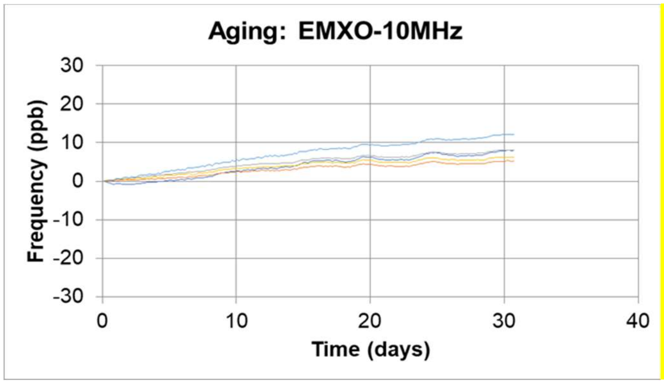
EMXO Design

The EMXO is comprised of an Evacuated Miniature Crystal Module (EMXM) and an Oscillator Module as shown in Figures 2 and 3. The crystal module contains the crystal resonator and oven heater circuitry. The oscillator module includes the oscillator sustaining, oven control and adjustment, output buffer, and voltage regulation circuitry Improvements in the latest release include further miniaturization of the crystal module and redesign of the mounting structure to minimize heat loss through the oven structure within the EMXM TO-8 hermetically sealed package.

The EMXO sealing process is critical to the long-term performance of the EMXO since the internal vacuum pressure of the device must remain stable to maintain proper performance throughout the intended mission life. Microchip has developed a novel package sealing process and the associated equipment to realize the assembly of the EMXM. The process partly involves the use of a hard-vacuum bake-out oven coupled with a controlled-environment glove box that ensures O_2, CO_2, and H_2O levels are less than 5 ppm.

The open-blank doubly-rotated crystal is 4-point mounted within a carefully designed isothermal oven structure to minimize gradients across the crystal. This results in improved frequency hysteresis and retrace compared to what has been attained with traditional design approaches. The oven design was facilitated by finite element thermal analysis software. The combination of these factors results in low-frequency aging consistent with a high-performance crystal oscillator. Figure 4 shows typically measured aging over a period of 30 days. Annual aging rates are 50 ppb.

Figure 4 EMXO Aging



Phase noise, a characteristic of the oscillator spectral purity, is optimized by balancing the crystal drive level and output amplifier topology in conjunction with the overall power budget. Measured phase noise is approximately -100 dBc/Hz at 1 Hz, and better than a -160 dBc/Hz phase noise floor. Figure 5 shows measured phase noise performance. Related to the phase noise is frequency stability, the EMXO's Allan Deviation is less than $1x10^{-11}$ for time intervals of less than 50 seconds, figure 6 shows this measurement.

Figure 5 EMXO Phase Noise

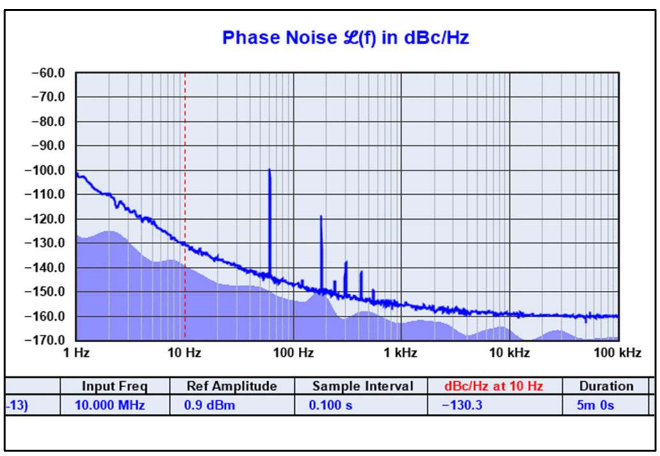
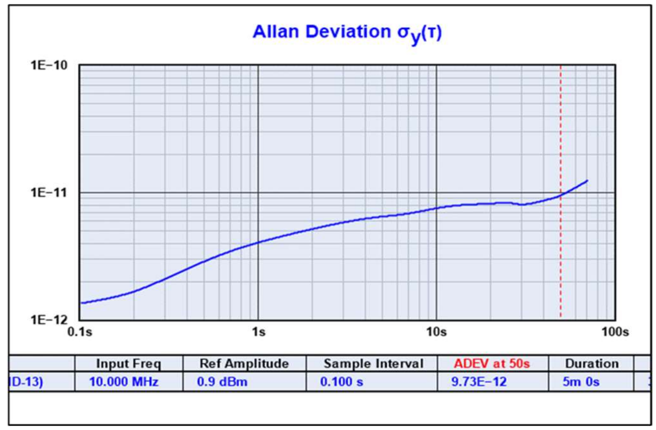


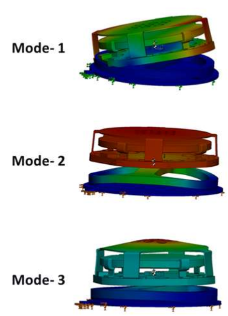
Figure 6 EMXO Allan Deviation



Mechanical Considerations

The ability of the EMXO to perform adequately during vibration is a key attribute in many industrial and defense applications. The sensitivity of crystals to vibration is a systematic challenge. A high level of sensitivity can increase the phase noise of an oscillator to a level in which the system does not operate properly. The EXMO crystal assembly was designed and analyzed to have mechanical resonances greater than 3 kHz. The modeling of the resonance was validated using the Finite Element Analysis shown in figure 7. This resonance is important because resonance frequencies of 2 kHz or lower amplify the response to standard random vibration environments. The phase noise of the EMXO in figure 8 confirms that the increase in noise is a direct result of the vibration input. Figure 9 shows the measured sensitivity per g in each of the three axes.

Figure 7 EMXO Mechanical Finite Element Analysis



Mechanical Resonance Mode	Freq (Hz)
1	3167.2
2	3620.4
3	3997.2

Figure 8 EMXO Phase Noise under Random Vibration

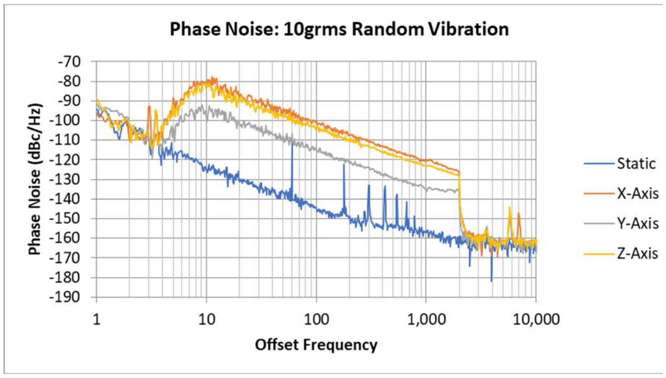
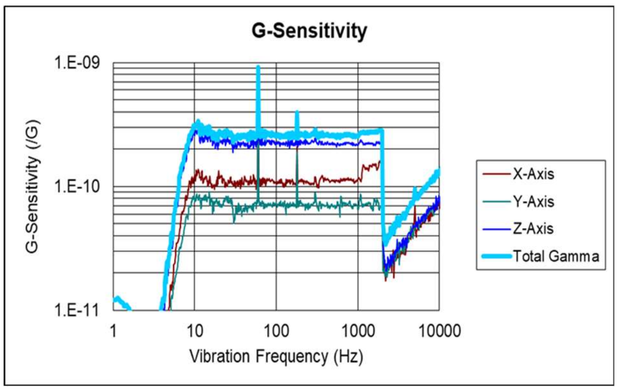


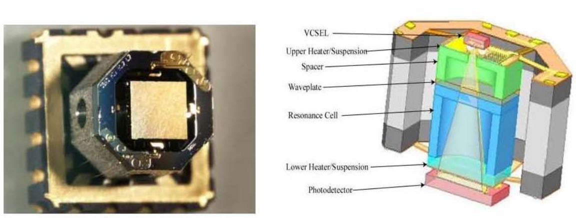
Figure 9 EMXO Measured Acceleration Sensitivity



In Summary, the EMXO demonstrates excellent phase noise of -130 dBc at 10 Hz, low aging of 50 ppb per year, compact size and low mass of less than 3 grams while requiring only 170 mW of power. The EMXO is ideally suited for applications that require performance in harsh industrial and military environments. In addition, the EMXO is an excellent choice embedded inside compact atomic clocks such as the CSAC SA65.

Low Noise CSAC Design

Figure 10 CSAC Physics Package



Microchip's CSAC technology utilizes MEMS technologies and assembly techniques to fabricate a physics package that delivers atomic clock performance while consuming less than 120 mW. The electronic and firmware design achieves performance consistent with other compact buffer-gas atomic clocks with minimal power consumption. The specifics of this core CSAC technology are described in references 1, 2, and, 4. The product designated the SA45 was released in 2011 and is utilized in many applications in commercial, defense, and space. The design was updated in 2021 to improve operating temperature to -40 to 80°C, decrease the frequency sensitivity by a factor of three and improve the time to lock by 30%. The new version, designated the SA65, provides increased holdover time in industrial and military environments.

CSACs frequency synthesis design, figure 11, is based on using a 10 MHz Temperature Controlled Crystal Oscillator (TCXO) as the local oscillator in the frequency generation chain that provides the 4.6 GHz signal and the output signal to the user. The LNCSAC replaces the TCXO with the EMXO along with the refinement of the output circuits. The result is the accuracy of an atomic clock and the output spectral purity of an Ovenized Crystal Controlled Oscillator (OCXO.) The LNCSAC output accuracy at shipment is $\pm 5 \times 10^{-10}$ and maintains an accuracy of $\pm 3 \times 10^{-10}$ over the operating temperature range. An additional feature of the LNCSAC is the inclusion of 1 pulse per second disciplining to an applied input. This results in a timing accuracy of ± 100 ns for the clock. The holdover accuracy, in the event of the loss of the input 1 PPS, is improved due to the CSACs environmental stability.

Figure 11 CSAC Frequency Synthesis Block Diagram

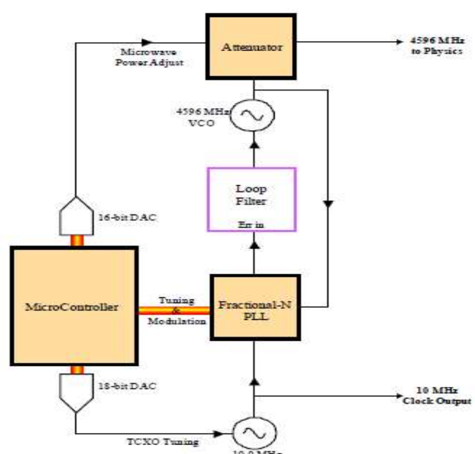
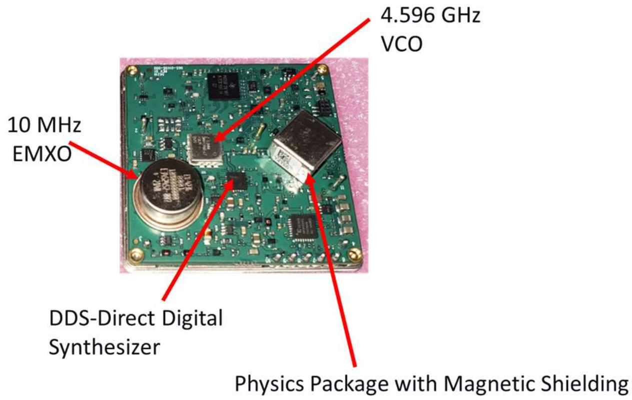


Figure 12 Photo of LNCSAC SA65



LNCSAC SA65 Hardware and Firmware Updates

The updates to the CSAC LN SA65 include the user option to increase the power applied to the physics package, thereby reducing the warm-up time by 30%. Design improvements include low noise voltage regulation for all circuits, optimization of the microwave coupling to the physics package, better laser control, enhancements to the Analog to Digital Converter (ADC) and signal recovery circuits, and the update to the 1 PPS functionality to support new GPS receivers.

LNCSAC SA65 mechanical design

The previous version of the LNCSAC included the low-power OCXO and a separate packaged CSAC in a larger package with a footprint of 2” x 2” (50.8mm x 50.8mm) with a height of 0.7” (17.8mm). The CSAC SA65-LN reduces the height to less than 0.5”(12.7mm) by integrating the EMXO crystal module directly to the printed circuit board(pcb). The mounting of the crystal to the pcb increases the resilience of assembly during vibration, and environmental testing confirms improved performance.

Figure 13 LN CSAC Side View

Performance Testing

The integration of the EMXO into the LNCSAC provides significant improvements in phase noise and frequency stability. Figure 14 shows measurements of -90 dBc at 1Hz and -155 dBc at 10 kHz. The 1 Hz phase noise is a product of the loop between the atomic line stability slope and the EMXO. The phase noise floor is a result of the design currently optimized for power consumption. Figure 15 indicates the measured frequency stability (Allan Deviation.) The unit measures less than 3 x 10-11 from 1 to 100-second offset. The EMXO improves the 1-second stability by a factor of four. The LNCSAC maintains stability below 1 x 10^{-11} beyond 200 seconds.

Figure 14 Phase Noise

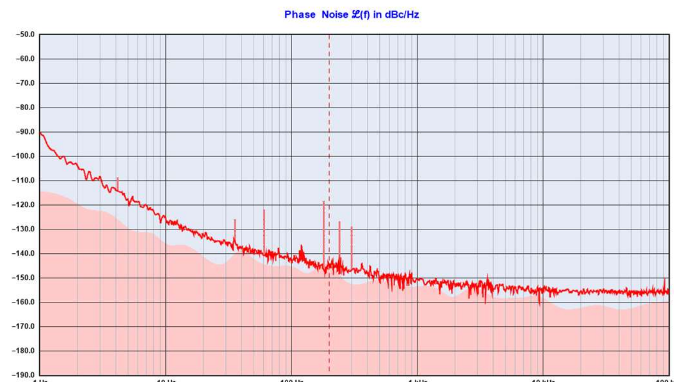
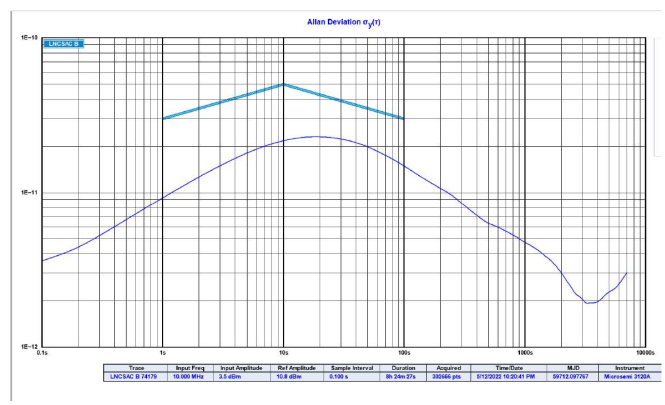


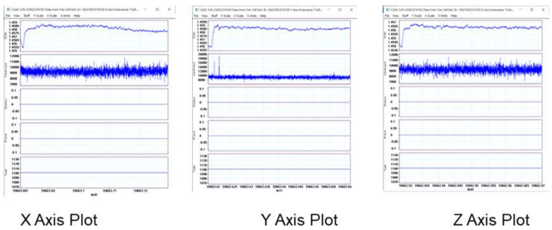
Figure 15 Allan Deviation



Environmental Testing

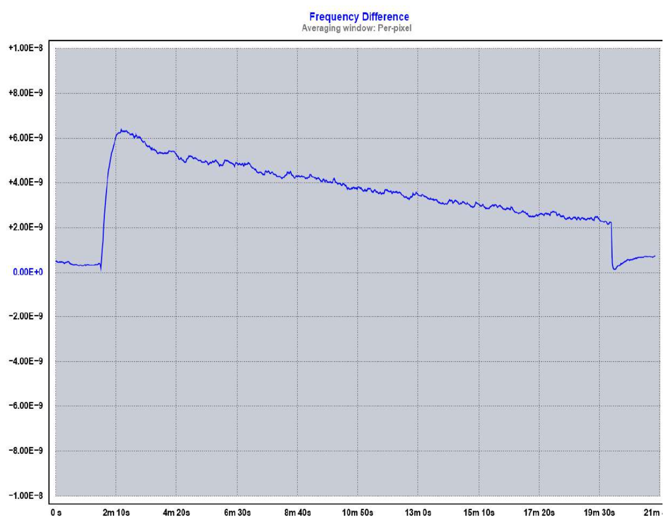
The vibration and shock sensitivity of CSAC is low because of the physics package design. The VSCEL, Cesium gas cell, and photodetector are directly attached to each other. As a result, compliant performance (maintaining atomic lock and frequency stability.) Random vibration testing on prototype units showed the ability to maintain lock for sixty minutes on each axis. The direct mounting of the EMXO crystal assembly to the printed circuit board improves performance during vibration. Mechanical rigidity is critical for optimized performance under vibration, the LNCSAC is ideal for these operational scenarios.

Figure 16 Operation during Random Vibration



Performance during exposure to radiation is critical for applications used in high altitude or LEO orbits. The predecessor Space CSAC SA45 is qualified to total ionizing dose of 20 krads(Si), minimum with characterization in SEE environments of 64 MeV-cm^2/mg. Initial testing of the LNCSAC SA65 demonstrated performance during 30 krads (Si) exposure. Subsequent testing will qualify and characterize SEE performance.

Figure 17 Radiation Testing 30 krad



Conclusions

Microchip has developed two new products: the EX-421 an ultra-low-power ovenized oscillator suited to applications in which low SWaP is required without compromising performance and the LNCSAC SA65 a low power atomic clock that provides high accuracy and excellent spectral purity. These clocks are optimized for SWaP and performance in many industrial and military applications.

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