Low Noise Chip Scale Atomic Clock (LNCSAC)

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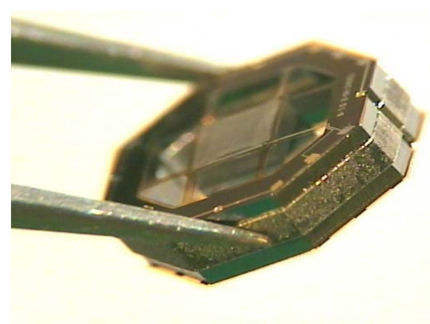
Chip Scale Atomic Clocks (CSAC) have provided a new capability in applications which had been previously been unrealizable due to the size, weight and power of atomic clocks. A CSAC requires approximately 100 mW of power within a 16 cm^2 volume. This is more than an order of magnitude reduction in size, weight and power (SWaP.) Although CSAC has the accuracy and stability of atomic clocks, trade-offs in the design lead to only modest performance for Allan Deviation and Phase Noise. External phase locked loops using conventional ovenized crystal oscillators (OCXOs) can address some of these performance limitations; however the power consumption and size of the OCXO obviates the advantages of CSAC. The Low Noise CSAC utilizes an indirectly heated crystal resonator oscillator within the atomic clock's control loop to optimize Allan Deviation and Phase noise. This design approach increases the power consumption and size modestly while improving the phase noise and Allan deviation significantly. This paper will provide a brief overview of CSAC, describe the design of the LNCSAC and show performance data along with the timing capabilities of the module

Figure 1: LNCSAC

The Microsemi CSAC reduces the size, weight and power by using coherent population trapping (CPT) of Cesium atoms in a 2 mm square and 2mm thick resonance cell using a vertical cavity surface emitting laser (VCSEL) and photo detector suspended in a vacuum package. The power consumption required to operate the physics package is approximately 15 mW. The low power is a result of the high thermal resistance of the tensioned polyimide suspension operating in a vacuum. Typical thermal resistance for the CSAC physics package is 7000 °C/W. The physics package is stabilized at approximately 85°C and adjusted to the optimum temperature to lock the laser's output wavelength to the Cesium resonance frequency.



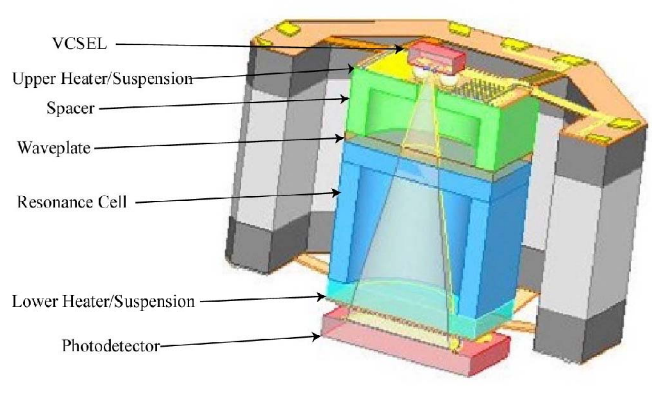


Figure 2: CSAC Physics Package

The remaining electronics, including power conditioning, microprocessor, microwave synthesizer, DSP and crystal oscillator carefully selected for performance and power constitute the remaining power budget. The standard TCXO used in the design is a low power, moderate performance device that requires approximately 7 mw of operating power.

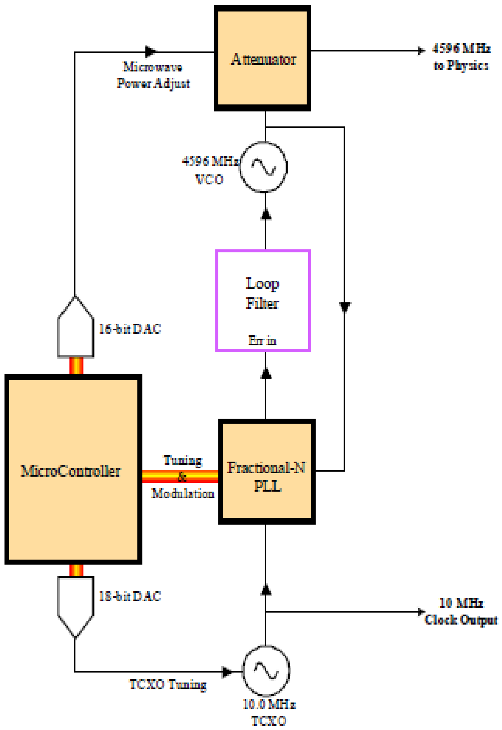


Figure 3: CSAC Microwave Subsystem

Microwave frequency synthesis is accomplished by phase locking a 4596 MHz Voltage Controlled Oscillator to the 10 MHz TCXO. The circuit uses a fractional-N synthesizer integrated circuit to generate the signal. A low power microprocessor controls the output frequency to a resolution of 2×10^{-12} along with amplitude levels to optimize performance. The control electronics use a single low power microprocessor, channels for analog to digital and digital to analog conversion, and a microwave synthesizer.

The LNCSAC replaces the TCXO with an oscillator that indirectly heats the crystal and partially ovenizes the electronics. The steady state power of this oscillator is 125 mW at 25°C. Software adjustments further optimize the frequency lock loop for phase noise and Allan Deviation. The measured performance improvements are as follows.

	CSAC 10 MHz	**LNCSAC 10 MHz**
Allan Deviation @ 1 sec. @ 10 sec.	 < 2.5e-10 < 8e-11	 < 2e-11 < 5e-11
Phase Noise @ 1 Hz @ 10 Hz @ 100 Hz @ 1 kHz @ 10 kHz @ 100 kHz	 - 50 dBc/Hz - 70 dBc/Hz - 113 dBc/Hz - 128 dBc/Hz - 135 dBc/Hz - 140 dBc/Hz	 - 87 dBc/Hz - 120 dBc/Hz - 140 dBc/Hz - 145 dBc/Hz - 150 dBc/Hz - 150 dBc/Hz

Table 1: 10 MHz LNCSAC Allan Deviation and Phase Noise

The improvement in phase noise is a combination of the selection of an ultra low power ovenized crystal oscillator, low noise internal voltage regulation and tailoring the loop time constant. The values in table one are data sheet values, performance is typically better. Allan Deviation or phase noise can be adjusted depending on the application.

Figures 4 and 5 show the effect of adjusting the time constants and the resulting change in performance.

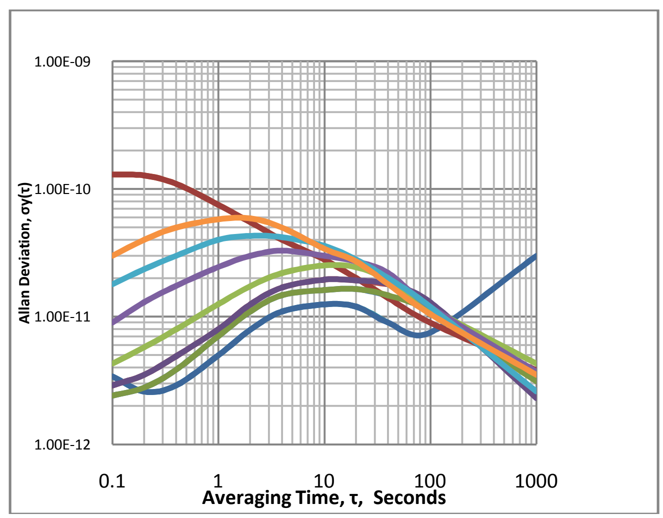


Figure 4: Allan Deviation Optimization

The red colored upper trace shows the performance of the device with the shortest time constant. Performance is identical to a standard CSAC. The dark blue colored trace at the bottom of the curves shows the effect of extremely long time constant. This performance is similar to the expected performance of the stand-alone OCXO with intermittent corrections from the atomic clock.

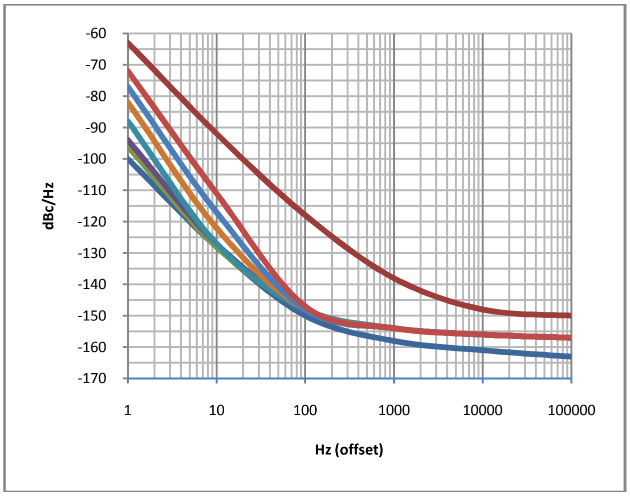


Figure 5: Phase Noise Optimization

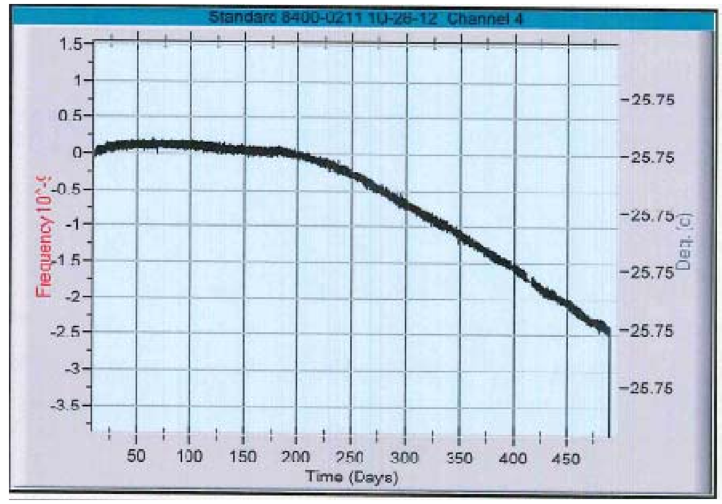


Figure 7: LNCSAC Long Term Aging

The phase noise plots, on the previous page show the same correlation. The LN CSAC can be adjusted in the factory with long time constant allowing for phase noise performance of significantly better than -90 dBc/Hz at 1 Hz.

The plot below shows measured output frequency of the unit from -20°C to 80°C; the total frequency variation is ± 1 x10-10.

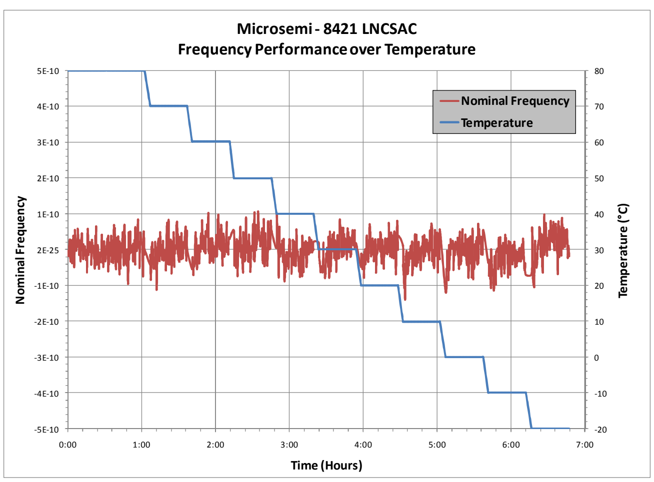


Figure 6: LNCSAC Frequency vs Temperature

One of the critical advantages of atomic clocks in comparison to crystal oscillators is the intrinsic accuracy. The LNCSAC has an frequency accuracy at shipment of $1x10^{-10}$ and a daily aging rate of less than 1×10^{-11} per day.

Frequency retrace, the accuracy of an oscillator prior to removing power and after the reapplication of power, of the LNCSAC shows a greater than 100 improvement. The retrace of the LNCSAC is $<5x10^{-11}$ in comparison to typical retrace of crystal oscillators on the order of 5×10^{-9}.

Although extremely useful as a frequency reference, the LNCSAC also provides timing capabilities in a manner similar to CSAC. The device has the ability to be steered with 1 pulse per second inputs and provide better than 100 ns timing accuracy at the output. CSAC/LNCSAC also provide time of day (TOD) output and extensive telemetry and state of health monitoring via a RS-232 serial input/output.

The ability to be synchronized to an external reference, typically a GPS receiver, allows for the CSAC/LNCSAC to be intermittently disciplined to improve the long term frequency accuracy or "clean-up" relatively noisy input references. This is particularly useful in battery powered applications.

A 100 MHz version of the LNCSAC is based on a similar design approach. The 100 MHz crystal oscillator provides the output frequency and is internally divided down to an intermediate frequency that the CSAC uses to generate a microwave interrogation signal. The frequency accuracy, aging, temperature coefficient represent significant improvements over comparable 100 MHz stand alone crystal oscillators. The device provides an excellent phase noise floor while maintaining the frequency accuracy and stability of CSAC. Most standard 100 MHz oscillators trade off RF performance for these parameters or require a phase locked loop with its inherent tradeoffs. For parameters such as temperature coefficient, Allan Deviation and aging, the advantages are more than 100-fold. The 100 MHz CSAC also maintains all of the timing capabilities of the 10 MHz variant.

	Typical 100 MHz OCXO	LNCSAC 100 MHz
Allan Deviation @ 1 sec. @ 10 sec.	 < 2e-10 < 2e-10	 < 2e-11 < 5e-11
Phase Noise @ 1 Hz @ 10 Hz @ 100 Hz @ 1 kHz @ 10 kHz @ 100 kHz	 - 65 dBc/Hz - 100 dBc/Hz - 130 dBc/Hz - 150 dBc/Hz - 165 dBc/Hz - 165 dBc/Hz	 - 65 dBc/Hz - 98 dBc/Hz - 132 dBc/Hz - 154 dBc/Hz - 170 dBc/Hz - 170 dBc/Hz
Input Power	1 to 2 W	300 mW
Temperature Coefficient	$< 1 \times 10^{-8}$	$< \pm 5 \times 10^{-10}$
Aging Rate	$< 1 \times 10^{-9}$ per day	$< 1 \times 10^{-11}$ per day

Table 2: 100 MHz LNCSAC Performance Comparison

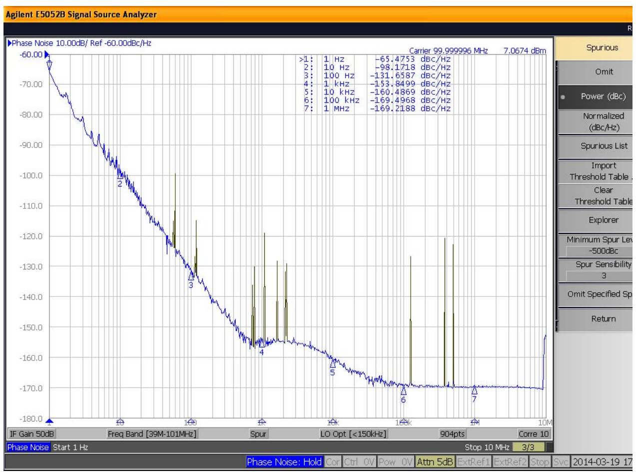


Figure 8: 100 MHz LNCSAC Phase Noise

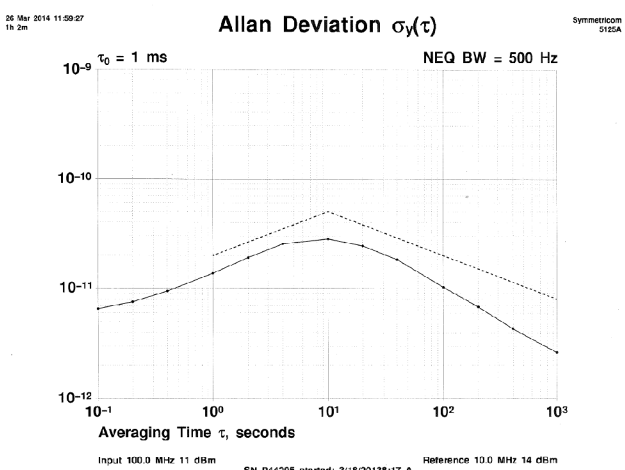


Figure 9: 100 MHz LNCSAC Allan Deviation

One additional advantage of the LNCSAC based timing references is the superior performance of the clock during vibration and shock. This is a result of the mechanically integrated physics cell. This cell is suspended under tension from the polyimide tethers provide shock immunity. Performance of CSAC, LNCSAC and ruggedized variants show specification compliant operation for Allan Deviation during vibration levels approaching 10 grms.

In summary, the LNCSAC combines the best attributes of CSAC, ovenized crystal oscillators and timing systems in a compact, extremely low power form factor. The LNCSAC is a portable time and frequency reference system.

References

[1] 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