QUANTUM™ SA.45s

White Paper

Leading-Edge Technology Enables a Chip Scale Atomic Clock

Microsemi

Power Matters.™

The Microsemi QUANTUM™ chip scale atomic clock (SA.45s) delivers the accuracy and stability of an atomic clock to portable applications for the first time.

Atomic clocks have enabled a world where ultra-precise timekeeping is now mandatory for communications, navigation, signal processing, and many other applications critical to a modern functioning society. However, as smaller, lighter, and more energy-efficient—in other words, more portable—versions of these systems have emerged, atomic clocks themselves have not followed the same trends. Why not? There are two reasons: First, legacy atomic clock technologies only scale so small. Second, even if you could make today's smallest atomic clocks significantly smaller than they are already (about the size of a deck of cards), they would still have serious shortcomings in portable applications, where battery power and ambient temperatures are real issues.

Enter the chip scale atomic clock (CSAC). This is not simply a miniaturized version of a bigger clock, but a reinvention. For example, rather than a cesium tube as a resonance cell, it uses a tiny, hollowed-out silicon cube filled with cesium gas. At one end is a vertical cavity surface-emitting laser (VCSEL) that shines a beam through the gas. At the other end is a photo detector that senses how much light gets through the resonance cell.

With a volume of 16 cm^3, the SA.45s is only one-third the size of other atomic clocks that are noted for their small form factor, and it is smaller than many oven-controlled crystal oscillators (OCXOs). While today's “low-power” atomic clocks consume 5 W in the steady state, the SA.45s CSAC's power consumption of <120 mW is a 40× improvement—a true breakthrough. Even most OCXOs consume 1.5 W to 2 W steady state, giving the SA.45s a 10×–15× advantage. And as a true atomic clock, the SA.45s has an aging rate of <9E–10/month.

Realizing a chip scale atomic clock with such small size and low power consumption required multiple innovations in multiple disciplines, including (among others) semiconductor laser technology, silicon processing, vacuum-packaging, and firmware algorithms.

The SA.45s CSAC enables a new class of atomic clock applications defined by portability. These applications include geophysical sensors, backpack IED jammers, backpack military radios, unmanned aerial vehicles (UAVs), and military GPS receivers. It offers longer battery life than previous technologies and maintains high accuracy without GPS or other external time references—all in addition to very small size and weight.

Chip scale is a brand new category of atomic clock, both in terms of the profile of applications for which it is suited, and in terms of the technology on which it is based.

The Atomic Clock Reinvented

The SA.45s CSAC employs coherent population trapping (CPT) to interrogate an atomic frequency. A laser illuminates atoms in a resonance cell with polarized radiation at two sidebands separated by the atomic resonance frequency. The atoms are excited to a non-scattering coherent superposition state from which further scattering is suppressed. The small size and low power of the CSAC is enabled by a novel electronic architecture, in which much of the functionality of conventional atomic clocks has been implemented in firmware rather than hardware.

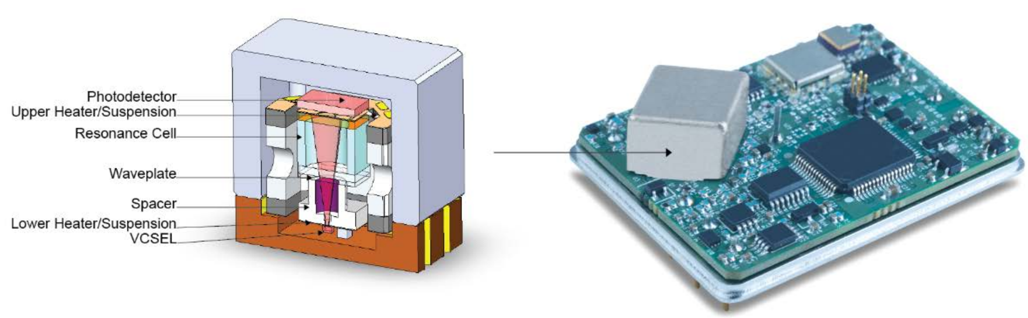
The SA.45s electronic hardware consists of a low-power digital-signal processor, a high-resolution microwave synthesizer, and analog signal processing. The microwave output is derived from a tunable crystal oscillator and is applied to the laser within the physics package to generate the two sidebands necessary for CPT interrogation. A photodetector detects light transmitted from the laser after it passes through the cesium vapor resonance cell. Based on the measured response of the atoms, the microprocessor adjusts the frequency of the crystal oscillator.

The microwave synthesizer consists of a 4.6 GHz voltage-controlled oscillator (VCO), which is phase-locked to a 10 MHz TCXO. This synthesizer enables the SA.45s to provide a standard RF frequency output at 10 MHz with the relative tuning between the TCXO and VCO digitally controlled with a resolution of better than 1 part in 10^{12}. For interrogation of the atomic resonance, modulation is applied through the microwave synthesis chain, thus avoiding the detrimental impact of modulation appearing on the TCXO output.

The SA.45s CSAC's performance is largely determined by the characteristics of the physics package. Short-term stability is determined by the atomic resonance line width and the signal-to-noise of the recovered signal. Medium-term stability is determined by the temperature stability of the physics package and by the stability of auxiliary servos that stabilize the laser power and wavelength, the microwave power, and the cell temperature. Long-term stability is determined by the long-term evolution of the properties of the laser and the contents of the resonance cell.

The following illustration shows a physics package composed of a center stack and a thermal isolation system.

Figure 1 SA.45s Physics Package



The center stack consists of a special-purpose VCSEL, the atomic vapor resonance cell, and the photodiode. The laser light, emerging from the VCSEL, diverges as it transits a cell spacer before passing through the resonance cell, and is detected on the photo detector. The center stack must be temperature-stabilized at a specific temperature, between 85 °C and 95 °C, which is precisely determined by the characteristics of the individual VCSEL device.

The function of the thermal isolation system is to support the center stack mechanically while providing a high degree of thermal isolation to the ambient environment, thereby minimizing the required heater power. The thermal isolation system consists of the upper and lower suspensions and the vacuum package. Vacuum packaging eliminates thermal loss due to gas conduction and convection. Thermal loss due to conduction is minimized through the design of the suspensions. The upper and lower suspensions are manufactured from a thin layer of polyimide film onto which the metal conductors that carry signals to and from the center stack are patterned.

The overall dimensions of the suspensions are chosen so that the center stack is suspended between two "drum heads" of polyimide. This architecture is quite sturdy, capable of surviving mechanical shock in excess of 1000 g (1 ms half-sine), and provides extraordinarily high thermal resistance (>5000 °C/W). Moreover, by patterning the electrical connections onto the polyimide, they do not need to be mechanically self-supporting, thus allowing their dimensions to be determined by electrical rather than mechanical requirements. This has the added effect of reducing heat load due to thermal conduction through the metallic, high-conductivity connections.

Obtaining a Precise Resonance Line

In CPT, the precision of the atomic resonance line is critical to determining clock stability—that is, a wide and blurry line is more difficult to lock to than one that is narrow and high-contrast.

Two key factors help determine resonance line quality: the choice of the optical transition for CPT interrogation and the VCSEL's cavity geometry.

Two principal optical transitions are available for CPT interrogation of the cesium ground state resonance. These two are termed "D1" and "D2," with principal optical transitions at λ=894 nm and λ=852 nm, respectively. Because the D1 transition has lower degeneracy in the excited optical state, it exhibits a narrower line width and higher contrast than D2.[1,2]

The VCSEL must operate in a single transverse cavity mode; its polarization must remain stable, and it must produce a wavelength that tunes to the atomic resonance across the CSAC's operating temperature range for the life of the product.[3] Meeting these requirements—for instance, to sustain an 894 nm wavelength resonance—calls for modifying the semiconductor processing steps commonly used to make the 850 nm oxide-aperture VCSELs prevalent in the telecommunications industry.

1. M. Stahler, et. al., "Coherent population trapping resonances in thermal ^{85}Rb vapor: D_1 vs D_2 line excitation," Optics Letters, vol. 27, August 15, 2002, pp. 1472–1474.
2. R. Lutwak, et. al., "The Chip-Scale Atomic Clock—Recent Development Progress," Proceedings of the 35th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, December 2–4, 2003, San Diego, CA, pp. 467–478.
3. D.K. Serkland, et. al. "VCSELs for Atomic Sensors," Proceedings of the SPIE. Vol. 6484, 2007.

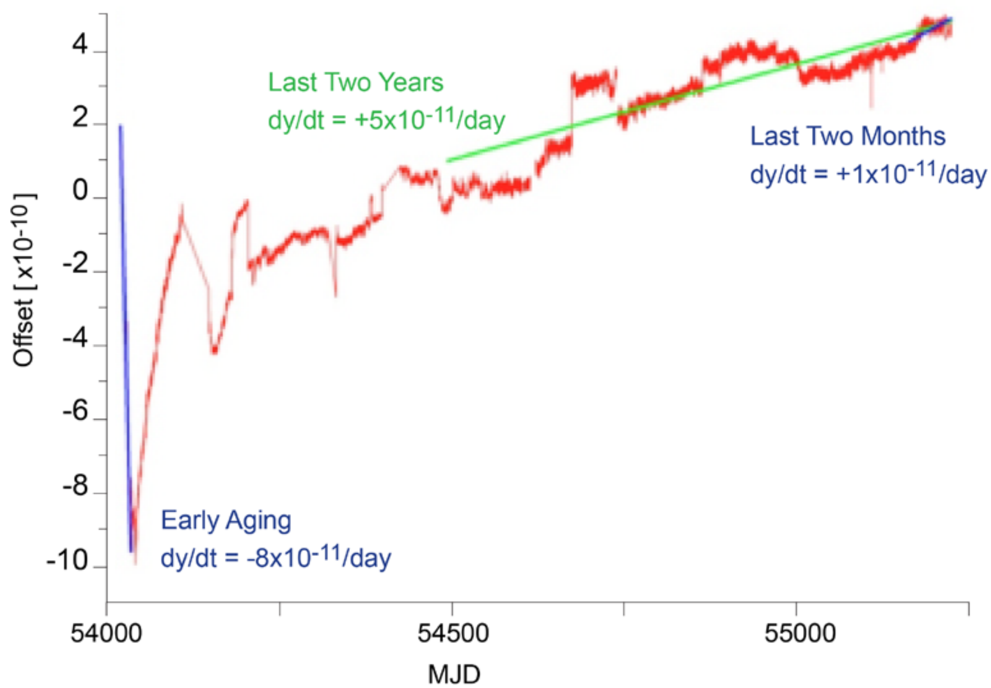
Performance Benchmarks

As innovative as the CSAC's design is, most users will gauge its value by its performance benchmarks. In summary, these include the following:

- 16 cm^3 volume
- 35 g weight
- ±5.0E–11 accuracy at shipment
- $\sigma_y < 1 \times 10^{-11}$ at $\tau = 1000$ sec short-term stability (Allan deviation)
- <9E–10/month aging rate
- <120 mW power consumption

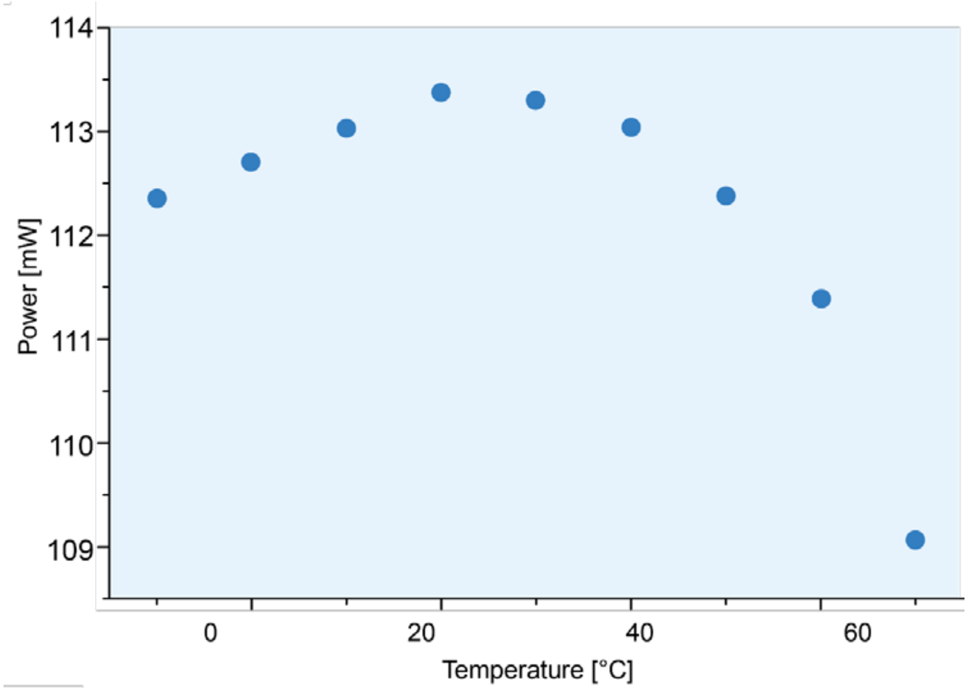
The CSAC's specifications for initial accuracy, short-term stability, and aging are all characteristic of atomic clocks—clearly a breakthrough given the SA.45s's size and weight. And while size and weight have obvious relevance to portability, frequency aging is of the highest importance to applications that may be cut off from GPS timing signals for long periods. These, too, are benefits of the physics package design. The following illustration shows the frequency aging of up to two years for the SA.45s.

Figure 2 SA.45s Frequency Aging



Portable applications are usually battery powered, which makes power consumption another key issue. Not only is the CSAC's power consumption very low, it varies very little over temperature and hardly at all during warm-up (which is very short compared to other atomic clocks). The following illustration shows variances in the SA.45s's power consumption over various temperature levels.

Figure 3 Power Consumption over Temperature



CSAC's Application Profile

In light of these performance benchmarks, the best fit SA.45s applications would be those where a TCXO or OCXO would do any of the following:

- Consume too much power
- Not be accurate enough
- Have insufficient holdover performance
- Be too large
- Be any combination of the above

Prime candidates fitting the CSAC's application profile include the following:

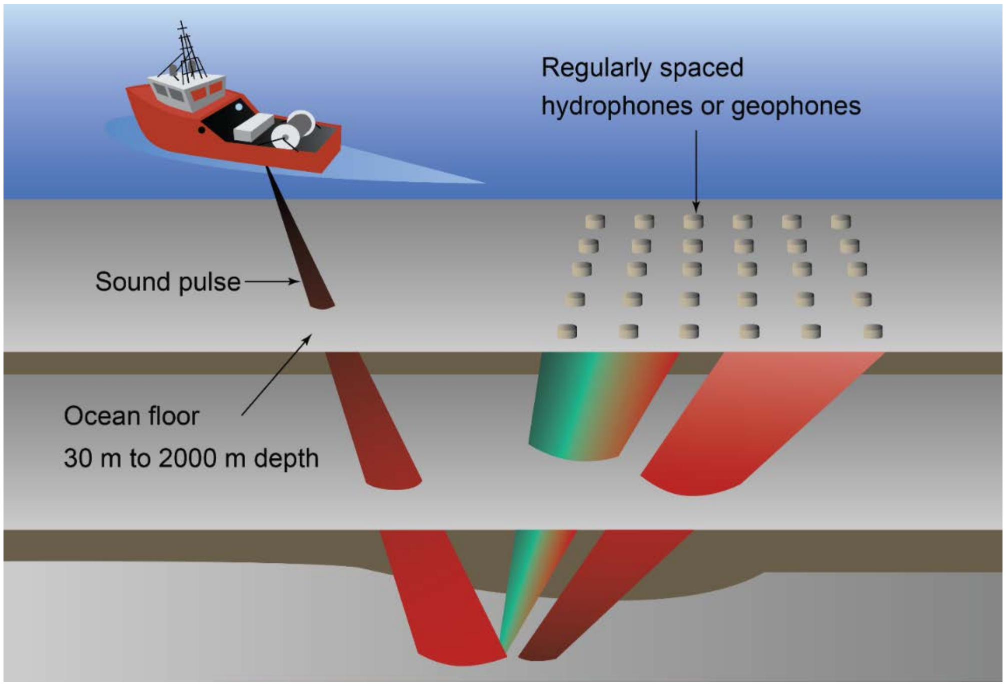
- Undersea seismic sensing
- Dismounted (backpack) IED jammers
- Dismounted (backpack) military radios
- Enhanced military GPS receivers
- Tactical unmanned aerial vehicles (UAVs)

Undersea Seismic Sensing

Several classes of underwater sensor systems rely on precise timing to be effective. Precise time from GPS is unavailable underwater, and so such sensors have generally relied on OCXOs for stable and accurate time stamping within the sensor.

Oil and gas exploration firms place a grid of geophysical sensors on the ocean floor to help determine likely spots where petroleum deposits are located. The following figure demonstrates an example of such a grid.

Figure 4 Reflection Seismology Application



Sensors can be dropped over the side of a ship or laid down by a remotely piloted vehicle. Each sensor typically includes a hydrophone, a geophone, and an OCXO or a TCXO that is used to time stamp the data received by the two other devices. The sensors can be independent or a cable can connect a row of sensors. Once the sensors are in place, a powerful air gun or array of air guns launches a sonic pulse from a ship. The ship moves in a pattern that allows the air gun to be fired from many different angles relative to the sensor grid.

Some of the pulse's energy reflects off the ocean floor and back to the surface, but the rest penetrates the ocean floor, travels through the layers of rock underneath, and eventually reflects back to the sensors where it is time-stamped. Once the ship has finished its predetermined pattern, the sensors are retrieved along with the time-stamped data. Because the sonic pulse travels at different speeds in different materials, the "bounce back" times are different based on which materials the pulse traversed. When this timing data is post-processed, it creates a picture of the layers of rock and sediment beneath the ocean floor, showing which locations likely hold oil or gas deposits.

Microsemi's SA.45s CSAC can greatly improve accuracy, reduce costs, and reduce the effects of temperature on sensor systems.

- Improved Accuracy from Lower Aging

  During a typical deployment, sensors can be underwater for several weeks at a time. This is because the ships and crews needed to deploy the sensors, take the measurements, and retrieve the sensors cannot always be optimally scheduled. Bad weather can also cause delays. Throughout the deployment, the OCXOs in the sensors are aging, producing a time-stamping error that varies as the square of the time underwater. The SA.45s's low aging rate (that can be 1/100th of even a good OCXO) greatly reduces these time-stamping errors.

- Lower Costs from Reduced Power Consumption

  Batteries are typically the biggest expense in these underwater sensors—and the number of sensors (and also batteries) in a typical grid is constantly increasing. Because the SA.45s consumes one-tenth to one-twentieth the power of an OCXO, it requires much less battery power, which means smaller and lower-cost sensors. Alternatively, sensor manufacturers can choose to retain the existing battery capacity and use the SA.45s to create sensors with much longer mission lives.

- Less Frequency Shift with Temperature

  Today, most marine geophysical sensors are calibrated to GPS on the deck of the boat before being dropped into the ocean. Because the water at the bottom of the ocean is often just a few degrees above freezing, the sensor can see a temperature change of 30 °C or more from its calibration temperature, causing a shift in frequency and a linear error in time. Some sensors use software models to correct for this error, but the best approach is to minimize the error to begin with. With a temperature coefficient of ±5.0×10–10 over its entire temperature range, the SA.45s can offer a 10× to 1000× improvement over the OCXO or TCXO alternatives typically used for this application.

Dismounted IED Jammers

Today's IED jammers have power requirements that can only be met by a vehicle's generator. In addition to lower power consumption, a dismounted jammer would also require key components to be smaller and lighter—exactly the combination of benchmarks on which the SA.45s surpasses an OCXO. Today's jammers also jam all signals, including friendly force communications. This can be overcome if all the jamming signals are tightly synchronized to allow pre-defined time slots in the signals ("look windows") where friendly force communications can get through. The SA.45s's high accuracy, even over wide temperature swings, can enable this level of synchronization, and can maintain it even during a lengthy absence from GPS.

Dismounted Military Radios

As new, higher-bandwidth waveforms (necessary for the explosion of data and video communications that the services are experiencing) are introduced, the amount of drift that is tolerable will decrease. This means that OCXOs and TCXOs may no longer be suitable reference oscillators. However, the SA.45s's atomic clock performance will meet these more demanding requirements. Its small size and low power consumption also make it very attractive for man-pack applications and it provides the stability needed to maintain network synchronization in GPS-denied environments.

Military Handheld GPS Units

Using the SA.45s as a time base, military GPS receivers can achieve greatly reduced time to subsequent fix (TTSF) for 24 hours or more. It also becomes possible to operate with only three satellites in view (instead of the usual four), a distinct advantage in many urban settings.

Tactical UAVs

Unmanned aircraft (drones) are always challenged in three areas where the SA.45s excels: size, weight, and power (SWaP). In some applications, the CSAC is attractive solely because its low power consumption simplifies thermal management issues when compared to conventional rubidium oscillators (~20 W in warm-up, ~10 W in steady state).

In addition, many UAVs rely on GPS, and the SA.45s CSAC can be disciplined by the 1 pps output from a GPS receiver, thus providing a stable signal that can be used by C4I or even SIGINT payloads. Furthermore, should GPS be lost due to natural interference or jamming, the CSAC provides a stable holdover signal that meets the requirements of even long-endurance missions.

The Next Era in Atomic Timekeeping

These examples offer a view into what the chip-scale era in timekeeping will look like. The SA.45s CSAC delivers the accuracy and stability of an atomic clock to portable applications for the first time—and does so within those applications' severe limits on power, size, and weight. It is comparable to other atomic clocks and surpasses OCXOs and TCXOs by wide margins in initial accuracy and aging.

Portable applications that had to settle for TCXO performance due to power constraints no longer must. Until the CSAC, the lowest-power atomic clock was Microsemi's own SA.3xm series, with a steady-state power of 5 W. The SA.45s uses 1/40th of that power. OCXOs offer better performance than TCXOs but are typically in the 1 W–2 W range. That limits their applications to those with large, heavy, and expensive batteries or where mission life is relatively short. Even then, they are a compromise when compared to a true atomic clock like the CSAC.

Then there are size and weight issues, which are always critical in portable applications. The SA.45s is much smaller than any atomic clock (one-third the size of the SA.3xm series, the next smallest), and is generally smaller than the OCXOs that approach its performance. The unit height is especially critical in many applications, and the SA.45s is only 0.45 inches high.

Finally, perhaps the most critical point is availability. The CSAC is not a laboratory prototype. It provides autonomous, reliable operation in production quantities today. That means that when it comes to the next era in atomic timekeeping, the clock is already running.

Table 1 Quantum SA.45s CSAC Options

Spec	Opt 001	Opt 003	Opt 004	Opt 006
Steady-state power consumption	<120 mW	<120 mW	<120 mW	<120 mW
TempCo	$\pm 5 \times 10^{-10}$	$\pm 5 \times 10^{-10}$	$\pm 5 \times 10^{-10}$	$\pm 5 \times 10^{-10}$
ADEV (Tau = 1000 s)	1×10^{-11}	1×10^{-11}	1×10^{-11}	1×10^{-11}
Warm-up time	<180 s	<180 s	<180 s	<180 s
Predicted MTBF	>100,000 hrs.	>100,000 hrs.	>100,000 hrs.	>100,000 hrs.
Operational temperature	–10 °C to 70 °C	–10 °C to 70 °C	–10 °C to 70 °C	–10 °C to 70 °C
Output frequency	10 MHz	16.384 MHz	10.24 MHz	5 MHz

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