THE CHIP-SCALE ATOMIC CLOCK – COHERENT POPULATION TRAPPING VS. CONVENTIONAL INTERROGATION

R. Lutwak, D. Emmons, W. Riley, and R. M. Garvey
Symmetricom – Technology Realization Center
34 Tozer Rd., Beverly, MA 01915, USA
E-mail: *RLutwak@Symmetricom.com*

Abstract

Symmetricom-TRC has undertaken a development effort to produce a prototype chip-scale atomic clock (CSAC). The overall architecture of the CSAC and, in particular, the physics package, must be defined early in the project, prior to the onset of a large-scale engineering effort. Within the constraints imposed by the performance goals of the project, we have recognized two possible schemes for interrogating the ground-state hyperfine frequency of the gaseous atomic ensemble: the conventional double-resonance technique and the coherent population trapping technique. In this paper, we describe a laboratory apparatus, which allows for* in situ *comparison of the two techniques, without the ambiguities associated with comparing data from disparate experiments. Data are presented comparing the short-term stability resultant of the two techniques, as well as environmental sensitivity to resonance cell temperature, laser intensity, and RF power.

INTRODUCTION

The Defense Advanced Research Projects Agency has initiated a program to develop a chip-scale atomic clock (CSAC) in order to provide accurate timing for lightweight man-portable instruments. The compelling applications for this technology are for synchronization of time-ordered encryption keys for secure communications and the rapid acquisition of P(Y)-code GPS signals, possibly in the absence of civilian GPS signals. The performance specifications that drive the design include short-term stability, $\sigma_y(\tau = 1\,\text{hour}) < 1\times10^{-11}$, with a total power consumption of less than 30 mW and overall device volume < 1 cm^3. Of these, we consider power to be the most fundamental in opening new applications for precise timing in portable military equipment. The stability requirement, equivalent to a white FM noise level of $\sigma_y(\tau) < 6\times10^{-10}\,\tau^{-1/2}$, appears reasonable based on theoretical predictions of decoherence rates in small cells **[1]**. Compared to existing atomic clock technology, e.g. small rubidium vapor cell devices, the stability goal is relatively undemanding. However, the size and power specifications are each more than two orders of magnitude smaller than any existing technology **[2]**. Fortunately, low power is consistent with small size.

In order to meet the stringent power requirement of the device, we have divided the power budget evenly among the three major subsystems: microprocessor and control electronics, RF generation, and the physics package. The 10 mW power budget dominates nearly all aspects of the physics package architecture, necessarily dictating a small (< 1 mm^3) volume gaseous atomic ensemble interrogated by a low-power semiconductor laser. We have elected to address an operational ambient temperature range of 0-50°C, which requires that the temperature of the physics package be stabilized at a somewhat elevated temperature, chosen to be 65°C. Assuming low thermal loss due to conductivity of the electrical leads and support structure, as well as negligible loss due to convection provided by vacuum insulation, the dominant heat loss mechanism is thermal radiation from the physics package to its environment. This drives the design towards the lowest possible surface area and, hence, a relatively small confined volume for the atomic sample. The thermal goals can be achieved with a 1 mm^3 resonance cell volume. This small volume, as well as the relatively low operating temperature, necessitates that we use atomic cesium, rather than rubidium, due to cesium's tenfold higher vapor pressure at 65°C. The fabrication and loading of such small cells with suitable reproducibility and cost-effective batch processing require novel fabrication techniques. This portion of the development effort, as well as the thermal isolation system and device packaging, is being undertaken by the MEMs fabrication center of Draper Laboratory.

A second key constraint on the overall architecture of the CSAC is the illuminating light source. In conventional cell-type rubidium frequency standards, the light source is provided by an isotopically filtered Rb_{87} RF discharge lamp, which typically consumes in excess of 1 watt. For this application, a much lower power optical source is required, e.g. a semiconductor laser. Standard cleaved-facet diode lasers typically dissipate in excess of 100 mW, due to relatively low conversion efficiency and, thus, are also too power-hungry for CSAC. Fortunately, a new class of diode laser, the Vertical-Cavity Surface Emitting Laser (VCSEL), has recently emerged from the laboratory into production for telecommunications applications. VCSELs and in particular, oxide-confined VCSELs have extraordinarily high efficiency and are able to produce the ≈100 μW of optical power necessary to achieve the CSAC stability goal while dissipating only 1-2 mW of drive power. Sandia National Laboratory has undertaken the development of an optimized VCSEL source for our CSAC development effort.

CONVENTIONAL DOUBLE-RESONANCE VS. COHERENT POPULATION TRAPPING

One key issue to resolve, prior to the onset of device engineering, is the method by which the ground-state hyperfine resonance is to be interrogated. All commercially available gas-cell frequency standards have employed the classical double-resonance method in which the population inversion, as measured by resonant optical transmission, is regularly interrogated by a magnetic field, oscillating at the hyperfine frequency, hereafter referred to as the "RF" method. A novel method has been proposed **[3]**, based on the phenomenon of coherent population trapping (CPT), in which the ground state coherence is measured, rather than its population inversion, by a pair of coherent laser sources, whose frequency difference is referenced to the hyperfine splitting. From a practical perspective, either technique could meet the requirements of the CSAC and each has perceived performance advantages and overall programmatic risk.

Figure 1, below, illustrates the relevant energy levels for understanding the RF and CPT interrogation techniques. In the conventional RF technique, the gaseous atomic sample is illuminated by an optical source, resonant with the D1 or D2 transition between one of the hyperfine ground states (the lower state in a lamp-pumped rubidium standard) and an absorbing optical state ($nP_{1/2}$ or $nP_{3/2}$). The transmitted optical intensity is monitored by a photodetector. In the absence of RF radiation, the absorption is limited by the depletion of the resonant ground state due to optical pumping. When RF radiation is applied, resonant with the ground state hyperfine splitting, the optically connected ground state is repopulated, leading to enhanced absorption (reduced transmission) when the RF frequency is tuned to the ground state hyperfine splitting. The impact of the RF on optical transmission, as a function of RF detuning, is indicated schematically in Figure 2(a).

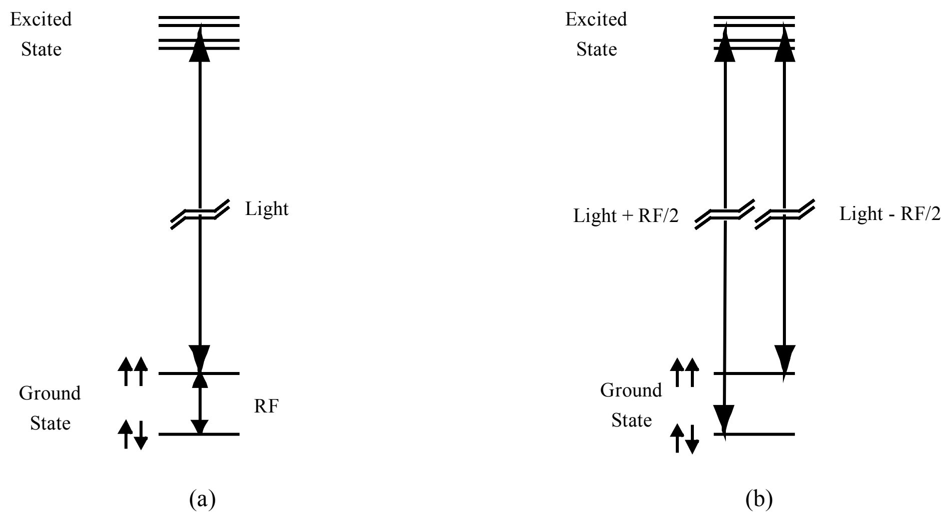


Figure 1. Relevant energy levels for (a) RF and (b) CPT interrogation.

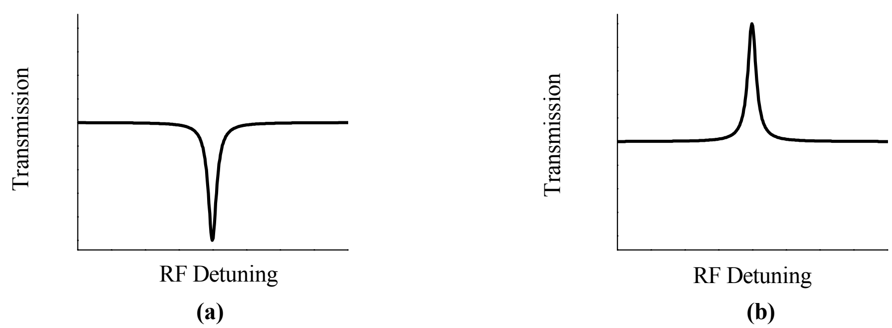


Figure 2. Resonance lineshapes for (a) RF and (b) CPT interrogation.

The energy level diagram shown in Figure 1(b) illustrates the CPT interrogation technique. In this approach, the atomic sample is simultaneously interrogated by a pair of collinear, circularly polarized laser beams, tuned so as that each couples one of the ground hyperfine states to the same optically excited state. It has been shown that, when the difference frequency between the two laser fields equals the ground state hyperfine splitting, a coherence is generated in the atomic vapor. Atoms participating in the coherence do not scatter light, resulting in increased optical transmission when the RF is tuned to resonance, as shown schematically in Figure 2(b). An essential feature of this all-optical interrogation technique is that the two laser beams be phase-coherent. Early laboratory observations of the CPT phenomenon utilized either separate laser systems, with a heterodyne phase-lock system, or a single laser followed by an electro-optical phase modulator. The recent advent of vertical-cavity surface emitting lasers (VCSELs), which exhibit extraordinarily high modulation bandwidths (> 10 GHz), permits the two coherent laser frequencies to be generated from a single source, by modulating the drive current to produce coherent sidebands separated by the hyperfine frequency. With such a directly modulated VCSEL source, the CPT interrogation technique could meet the power and size constraints for the CSAC.

The hardware implementations of the RF and CPT interrogation approaches are shown below in Figures 3(a) and (b), respectively. From a practical perspective, the two architectures are quite similar.

Implementing the CSAC with either approach involves common challenges associated with the small vapor cell and VCSEL source. The key differences are the need for a resonant RF cavity in the conventional RF technique, in order to provide a stable phase center for the interrogation, and the addition of a quarter-wave phase retarder (λ/4) in the CPT case, in order to circularly polarize the laser source.

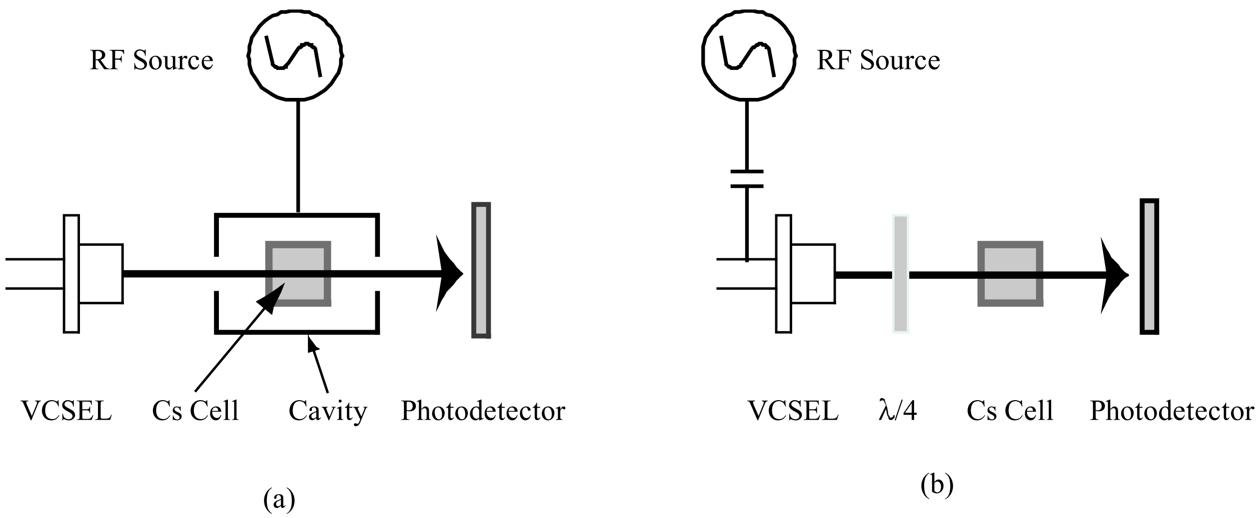


Figure 3. Hardware implementations of the (a) RF- and (b) CPT-interrogated CSAC.

From a programmatic perspective, each technique has advantages and disadvantages. The conventional double-resonance RF technique has been employed in laboratory and commercial rubidium frequency standards for over 30 years. Literally hundreds of thousands of units have been deployed and hundreds of technical papers have been presented, contributing to a nearly complete understanding of the major systematics and engineering considerations for the system. On the contrary, the CPT phenomenon has only recently been observed in the laboratory, the systematics and environmental sensitivities are only now being investigated, and a practical device has yet to be fully engineered. On the other hand, the fact that a phase-stable resonant structure is not needed for the CPT technique may well be an overriding consideration. The difficulty of creating a millimeter-sized RF cavity, resonant at 9 GHz, cannot be over-estimated. While several manufacturers have recently introduced sub-wavelength lumped-element cavities to produce relatively small rubidium frequency standards **[4]**, there is no clear path to reduce the size further, or to produce them with sufficient accuracy and consistency to enable batch processing of the CSAC. Practically, this presents a clear advantage for the CPT approach. However, the uncertainties associated with miniaturizing the CPT technology, which has yet to be realized in a practical system of any size, necessitate thorough consideration of its systematics, performance capability, and environmental sensitivities. This is a difficult task in that the available CPT data have emerged only recently from laboratory experiments, whose basic architecture (resonance cell, laser source, thermal control, etc.) generally bears little resemblance to the production rubidium standards on which our thorough understanding of the RF technique is based. Moreover, our understanding of both techniques is based on experience with rubidium, rather than cesium.

In order to practically assess the performance tradeoffs between the conventional RF and CPT interrogation techniques in cesium, we have developed a laboratory apparatus optimized for *in situ* comparison of the two technologies. This apparatus and preliminary results are described in detail in the following sections.

THE DUAL-MODE CSAC TESTBED

Figure 3, below, shows the key components of the dual-mode CSAC testbed, designed for near-simultaneous interrogation of the cesium ground state hyperfine resonance at 9.2 GHz by either the conventional RF or CPT techniques. Common to both techniques is the laser source, its intensity, collimation, and alignment; the resonance cell, containing cesium and a temperature-compensating buffer gas mixture as well as its temperature stabilization, magnetic field control, and shielding; and the photodetector and associated electronics. Rapid switching between the interrogation methods is accomplished by enabling either the 9.2 or 4.6 GHz synthesizer and removing or inserting the λ/4 phase retarder. Not shown in the figure are additional optics for laser collimation, isolation, and intensity and polarization control.

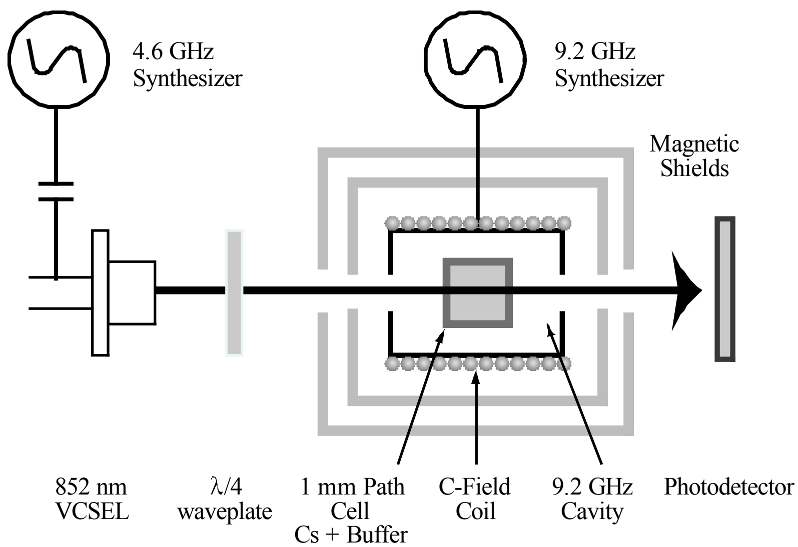


Figure 4. Schematic of dual-mode CSAC testbed.

The laser source is an 852 nm VCSEL, which operates in both single longitudinal mode and a single transverse mode of its cavity **[4]**. The VCSEL and aspheric collimation optic are mounted together within a temperature-stabilized brass housing. The laser beam is collimated to produce a 1 mm (FWHM) Gaussian beam at the resonance cell. The choice of 852 nm, which excites the D2 resonance line of cesium, is driven by the ready availability of VCSELs at this wavelength. Recent theoretical and experimental developments in rubidium have shown a nearly tenfold improvement in the strength of the CPT resonance line when excited on the D1 transition rather than D2 **[5]**. While this result has yet to be verified in cesium, it is likely that a similar improvement could be achieved in this system as well. In order to evaluate the corresponding improvement in cesium, the development of a VCSEL at 894 nm (cesium D1) will be pursued in a later phase of the CSAC development effort.

In order to produce the coherent sidebands necessary for CPT interrogation, a synthesizer, operating at ½ of the ground state hyperfine frequency ($\nu_{RF}/2$ = 4.6 GHz), is capacitively coupled to the VCSEL current leads. Figure 5, below, shows typical laser spectra, measured on a scanning Fabry-Perot optical spectrum analyzer, with the RF on and off. Note that nearly 75% of the optical power can be transferred to the first-order sidebands, separated by 9.2 Ghz, for efficient CPT interrogation.

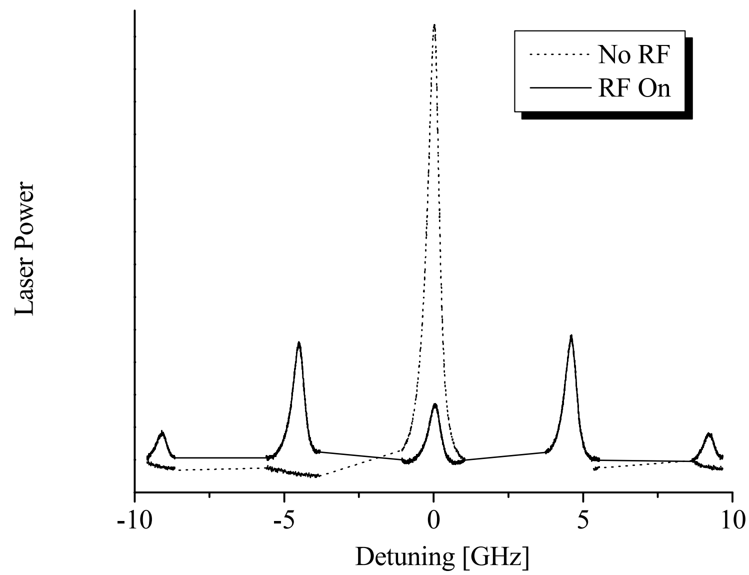
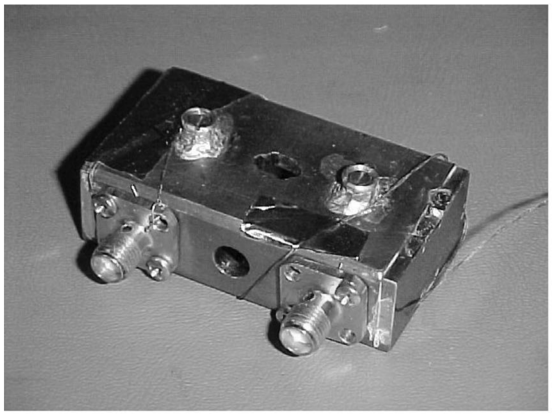


Figure 5. Laser spectra with and without 4.6 GHz RF drive.

The cesium resonance cell, shown below in Figure 6, is fabricated by conventional glass-blowing techniques. The inside dimensions of the cell are 3 mm x 4 mm x 1 mm path length. The 1 mm diameter laser beam passes through the broad face of the cell, effectively interrogating a cylindrical volume of comparable dimensions to that of the CSAC.

Figure 6. Resonance cell containing cesium and buffer gas mixture.

The resonance cell is supported on a removable mount within the RF cavity, which is temperature-stabilized to 0.1°C and enclosed within a double high-permeability magnetic shield. The resonance cavity is shown below in Figure 7.



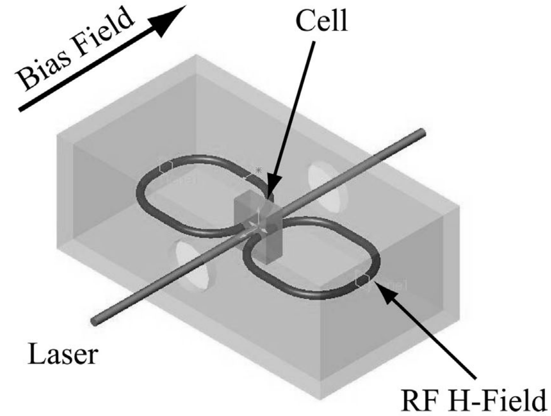


Figure 7. 9.2 GHz RF resonance cavity.

The defining feature of the RF cavity is that all of the RF H-Field, the laser Poynting vector, and the magnetic bias "C-field" are collinear. The cavity is fabricated from a length of thick-walled X-band waveguide, operates in the TE_{102} waveguide mode and exhibits a loaded Q ≈ 800.

Typical RF spectra are shown below in Figure 8. In both cases, the unattenuated laser power was roughly 100 µW, corresponding to a signal level of 600 mV. The resonance cell was operated at a temperature of 65°C, leading to 50% optical absorption.

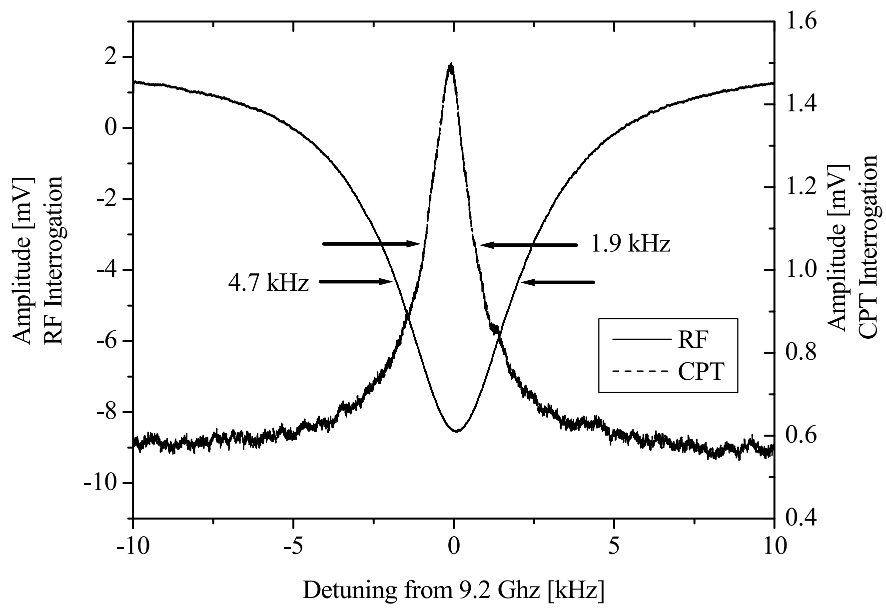


Figure 8. Typical RF spectra.

The RF spectra, shown in Figure 8, exhibit the key performance-limiting features of the RF and CPT interrogation methods. Note that, for the plot, the synthesizer detuning for the CPT case is multiplied by a factor of 2 in order to reference both spectra to 9.2 GHz. The conventionally interrogated linewidth is roughly 2X that of the CPT method, but the strength (depth) of the resonance feature is roughly 10X greater. In each case, the resonance signal level is much smaller than the background light level, ≈300 mV and the noise characteristics are entirely determined by the shot noise and laser frequency noise of this background signal. As a result, the signal/noise of the RF interrogation is roughly 10X that of the CPT interrogation. Thus, despite the twofold higher Q of the CPT interrogation, we expect the short-term stability of the RF interrogation to be 5X superior to that of CPT.

RF VS. CPT EXPERIMENTS

In this section we describe experiments, performed with the dual-mode CSAC testbed, to directly compare the performance of the conventional double-resonance interrogation technique with that of coherent population trapping.

SHORT-TERM STABILITY

The dual-mode testbed can be operated as a closed-loop atomic frequency standard by applying modulation to the RF, with depth equal to the linewidth (either 4.7 kHz or 1.9 kHz), and rate of approximately half that. An error signal is generated by synchronous detection of the modulation response of the physics package, integrated with a single-pole loop filter, and fed back to the ovenized quartz oscillator which serves as a reference to the synthesizer. The overall loop gain is adjusted to provide a time constant ≈ 1 second. Typical short-term stability data are shown below in Figure 9.

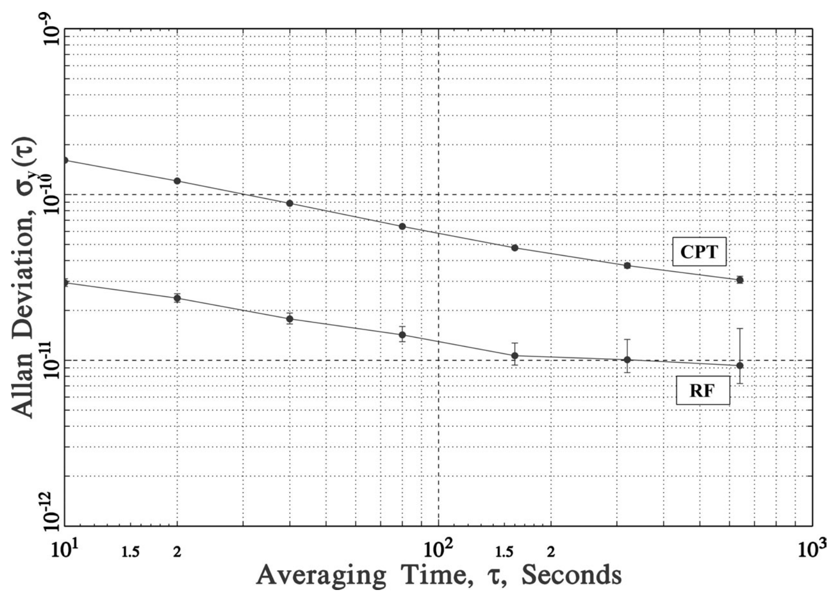


Figure 9. Typical short-term stability.

The stability measurements both exhibit the $\sigma_y(\tau) \propto \tau^{-1/2}$ behavior that typifies passively interrogated atomic frequency standards. As expected, the short-term stability of the RF-interrogation is roughly 5X lower than that of CPT, with a 1-second intercept of $\sigma_y(\tau=1) = 8\times10^{-11}$ vs. $\sigma_y(\tau=1) = 6\times10^{-10}$. Both techniques meet the stability requirements of the CSAC project, $\sigma_y(\tau=1) < 6\times10^{-10}$ and, while the CPT approach does so only marginally, we are confident that sufficient margin will be achieved with D1-line optical pumping, once 894 nm VCSELs become available.

RESONANCE CELL TEMPERATURE COEFFICIENT

In order to minimize coherence-quenching collisions between the cesium atoms and the cell walls, it is necessary to add a buffer gas to the resonance cell. Unfortunately, collisions between the cesium atoms and the buffer gas cause a shift in the ground state hyperfine frequency, which is approximately linearly proportional to the buffer gas pressure, and whose sign and magnitude are a function of the particular species involved. The problem is exacerbated in the CSAC, wherein the relative proximity of the cell walls necessitates a relatively high buffer gas pressure. For example, with a buffer gas comprised of 100 torr of pure N_2, the expected pressure shift is $\bar{y} = +1\times10^{7}$, with a temperature coefficient of $dy/dT = 10^{-8}/°C$ **[6]**. Fortunately, suitable buffer gases exist with opposite signs of pressure shift and comparable magnitude, enabling the composition of an optimized binary mixture of buffer gases such that the temperature coefficient of the resonance cell vanishes to first order. For the development and production of rubidium frequency standards, many buffer gas candidates have been extensively characterized and optimum mixtures have been developed. Unfortunately, very little data are available on cesium-buffer gas collisional shifts. Moreover, no experimental comparison has been made between collisional shifts under RF or CPT interrogation.

Resonance cells were constructed with a spectrum of total pressures and partial pressures of N_2 and Ar. The target mixture ratios were calculated based on the work of Strumia *et al.* **[7]**. Figure 10, below, shows temperature coefficient data for both the RF and CPT interrogation schemes with a balanced mixture of N_2 and Ar, and total pressure adjusted to effectively eliminate the linear temperature coefficient in the neighborhood of 65°C. The residual curvature reflects the temperature dependence of the individual temperature coefficients of the component gases.

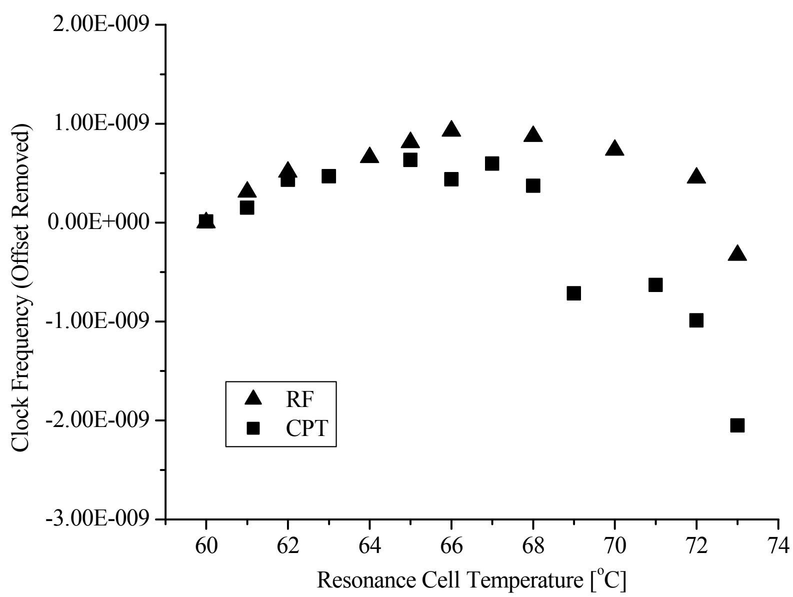


Figure 10. Resonance cell temperature coefficient with optimized binary buffer gas mixture.

LIGHT SHIFT

It is expected that the AC Stark shift, often called the "light shift," will be the greatest source of environmental sensitivity of the CSAC, regardless of interrogation technique. The light shift originates from the strong electric fields of the laser beam, which interact with the electric dipole moment of the cesium (or rubidium) atom, inducing a shift of the atomic energy levels and, hence, of the clock frequency.

In general, calculations of the light shift involve all possible electric dipole interactions between the atom and the laser field, though, generally, the effect is dominated by near-resonance transitions. In the case of RF interrogation, the light shift is dominated by transitions between the optically pumped ground state (F=4 in our experiments) and the hyperfine manifold of accessible upper levels (F=3-5 of the cesium D2 line). Previous work in laser-pumped rubidium standards leads us to expect near-linear behavior of the light shift in the low-power limit **[7]**. The case of CPT interrogation is considerably more complicated, involving at least two laser beams, resonant with and perturbing both ground states. These many light shift components have varying signs and amplitudes, and several authors have reported balancing the intensities of the two laser frequencies so as to eliminate the light shift to first order **[8]**. In the case of CSAC, wherein the two laser frequencies are generated by direct modulation of the VCSEL, there are additional laser frequencies perturbing the clock frequency due to the unsuppressed carrier as well as the second-order sidebands (see Figure 5). We have found that it is possible to optimize the RF power input to the VCSEL, such that the first-order light shift is largely eliminated, without sacrificing short-term stability of the CSAC. Figure 11, below, shows the experimentally determined light shift of both the RF and CPT interrogation methods, along with a linear fit to each data set. Note that in the CPT case, the linear component of the light shift is essentially zero to within the accuracy of our measurement.

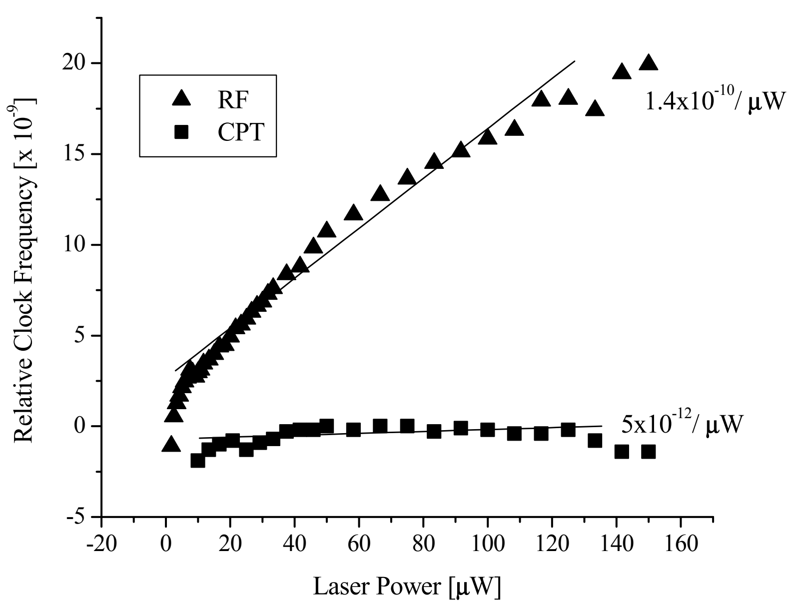


Figure 11. Light shift of RF and CPT interrogation.

RF POWER SENSITIVITY

Generally, the sensitivity of cell-type frequency standards to variations in the RF power level is small. In conventionally interrogated standards, variations in the microwave power produce a spatial dependence of interrogated atoms, as mitigated by the varying microwave amplitude at different locations in the cavity. If there exists, by other means, e.g. magnetic field gradients, a spatial dependence of the resonance frequency, variations in microwave power are correspondingly translated into clock instability. In the case of CPT interrogation, where the RF power level has been optimized to eliminate the light shift, the sensitivity can be much higher, depending on the sensitivity of the light shift to the RF power level.

The RF sensitivity of the dual-mode CSAC testbed is shown below in Figure 12.

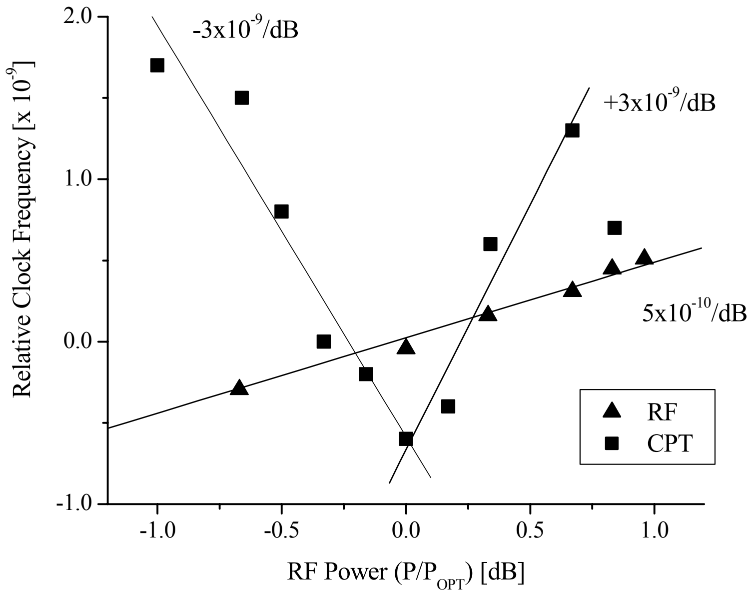


Figure 12. RF Power sensitivity.

As expected, the RF power sensitivity is relatively low under conventional interrogation. As described above, we believe the sensitivity is due to spatial variation of the resonance frequency across the cell, in this case due to magnetic field gradients, perhaps due to magnetic components in the RF connections to the resonance cavity. The sensitivity of the CPT interrogation is more problematic, due to the careful balancing of the laser sidebands necessary to eliminate the first-order light shift. Assuming the sensitivity is caused by an imbalance of two linear light shift components, we have assumed an independent linear shift on each side of the zero point and find the sensitivity to be $3 \cdot 10^{-9}$/dB in either direction.

CONCLUSIONS

We have performed *in situ* comparisons of the key performance parameters and environmental sensitivities of the conventional double-resonance interrogation technique with those of coherent population trapping in an apparatus that effectively mimics the operating parameters of the CSAC. We find that either interrogation method is capable of supporting the stability goals of the CSAC project. We have developed an optimized binary mixture buffer gas that effectively eliminates linear portion of the resonance cell temperature coefficient under either RF or CPT interrogation. We have measured the sensitivity of the CSAC output frequency to variations in optical intensity and RF power, and have found that the light shift can be eliminated to first order in the CPT approach by careful optimization of the sideband amplitudes. This comes at the expense of relatively high sensitivity to RF power variations.

ACKNOWLEDGMENTS

The authors wish to thank Tom English, of the Symmetricom TRC, for fabricating the cesium resonance cells for the dual-mode CSAC testbed. We are also grateful to John Kitching, of the National Institute of Standards and Technology, both for performing the theoretical analysis of decoherence rates in small vapor cells and for sharing his laboratory with us early in the CSAC program. This work is supported by the Defense Advanced Research Products Agency, Contract # NBCHC020050.

REFERENCES

[1] J. Kitching, S. Knappe, and L. Hollberg, 2002, *"Miniature Vapor-Cell Atomic-Frequency References,"* **Applied Physics Letters, 81**, 553-555.

[2] See, for example, the Symmetricom X72 (120 cm^3, 10W@25°C).

[3] N. Cyr, M. Tetu, and M. Breton, 1993, *"All-Optical Microwave Frequency Standard: A Proposal,"* **IEEE Transactions on Instrumentation and Measurement, IM-42**, 640-649.

[4] MODE Corporation, Product Number 8085-1000.

[5] M. Stahler, *et al.,* 2002, *"Coherent population trapping resonances in thermal ^{85}Rb vapor: D_1 vs D_2 line excitation,"* **Optics Letters, 27**, 1472-1474.

[6] F. Strumia, N. Beverini, A. Moretti, 1976, *"Optimization of the Buffer Gas Mixture for Optically Pumped Cs Frequency Standards,"* in Proceedings of the 30th Annual Symposium on Frequency Control, 2-4 June 1976, Atlantic City, New Jersey, USA (NTIS AD-A046089), pp. 468-472.

[7] G. Mileti and P. Thomann, 1994, *"Light-Shift Saturation in laser Pumped Rubidium Frequency Standard,"* in Proceedings of the 8th European Frequency and Time Forum (EFTF), 9-11 March 1994, Munich, Germany (VDI-Projekt und Service GmbH, Düsseldorf), pp. 377-384

[8] M. Zhou and L. Cutler, 2001, *"Theoretical and Experimental Study of Light Shift in a CPT-Based Rb Vapor Cell Frequency Standard,"* in Proceedings of the 32nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 28-30 November, 2000, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 311-324.