Calcium Beam Optical Clock for Space-Based Precision Metrology

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Vescent Photonics, ColdQuanta, and the National Institute of Standards and Technology propose to develop a calcium-beam-based optical clock that has a viable pathway for near-term space qualification and can provide the frequency stability performance required to support precision metrology for tests of fundamental physics, worldwide timing distribution, and precision geodesy. Since time/frequency metrology offers the most precise physical measurement capabilities, ultra-stable atomic clocks positioned in the near-perturbation-free environment of an earth orbit have been proposed as unique tools for performing stringent tests of General Relativity and searches for Dark Matter/Energy [1]. To meet these scientific objectives, the atomic clock must have exceptional performance: a short-term fractional frequency instability of better than 1×10^{-16} $\tau^{-1/2}$ (where τ is the averaging time) and a clock uncertainty of better than 1×10^{-18}. Current state-of-the-art optical clocks based on lattice-confined neutral atoms currently provide this level of stability in laboratory settings but face formidable challenges in meeting field-deployed requirements for environmental ruggedness and low size, weight, and power (SWaP). An optical lattice clock requires five or more frequency-stabilized laser systems (not including the required optical frequency comb), some of which must operate at wavelengths and optical powers not yet conducive to low SWaP. Furthermore, the clock laser must have a sub-Hz linewidth, which involves stabilization to a sizable optical reference cavity and places further limitations on the achievable clock SWaP and ruggedness. We propose instead an optical clock based on interrogating a thermal beam of neutral calcium (Ca) with a single probe laser, thus greatly relaxing the laser system and physics package requirements. While not expected to compete against lattice clock performance, the proposed Ca beam clock is perhaps the simplest and most viable option for the rapid development of a space-based atomic clock that will still be sufficient for important tests of fundamental physics and demonstrations of other space clock applications.

The thermal Ca beam atomic clock utilizing Ramsey-Bordé atom interferometry has been shown to be one of the simplest yet highest performing single-laser atomic frequency standards [2]. With a single 657 nm laser, clock instability in the low 10^{-15} range at one second has been observed and adding a second laser at 431 nm has been shown to boost performance by more than a factor of 10 into the low 10^{-16} range at one second (Fig.1a). The atomic structure of neutral ^{40}Ca uniquely suits this desired performance range through its 400 Hz $6S_{1/2}$-$6P_{3/2}$ intercombination line. The 400 Hz linewidth can be interrogated by lasers with linewidths of 10's of Hz, as opposed to ultra-narrow Hz or sub-Hz clock transitions often used in cutting edge standards like optical lattice clocks or single ion clocks. This would considerably relax system environmental-isolation requirements (for the optical cavity used to pre-stabilize the clock laser), one of the most daunting technological challenges for a space clock mission. The 400 Hz linewidth is also broad enough that the clock transition can be excited with fairly low power lasers, with 10's of mW being sufficient to saturate the clock transition for laser cross-sectional areas supporting the thermal beam geometry [3].

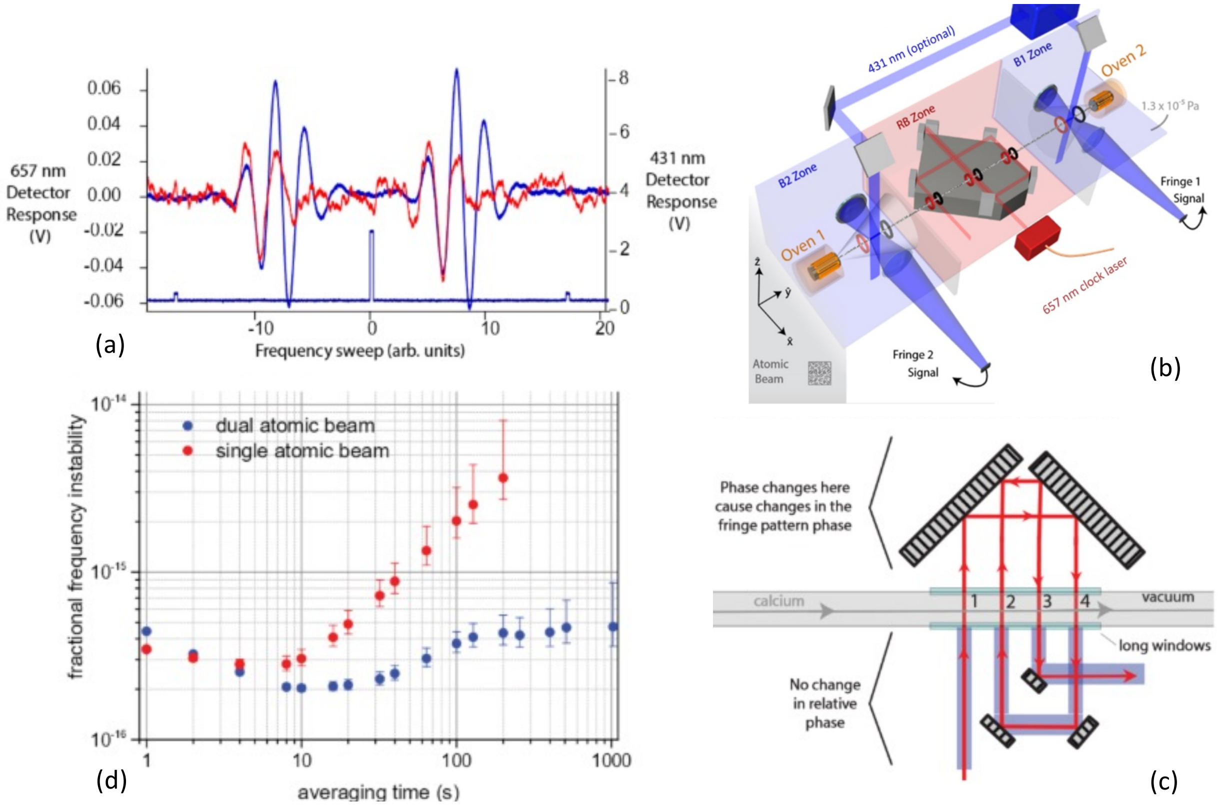

Figure 1: (a) Ca-beam Ramsey-Bordé (RB) interferometer atomic clock signal shown for both pure 657 nm detection and enhanced electron-shelving detection with an additional laser at 431 nm. (b) Ca-beam Ramsey-Bordé apparatus with counter-propagating atomic beams. The central RB zone and ovens are necessary for the single-laser implementation, and the optional 431 nm electron-shelving scheme is also displayed here in the B1 and B2 zones. The central gray structure is a monolithic optical system for phase-coherent, in-vacuum beam delivery. (c) Passive vibration and phase-noise cancellation via optical routing. A small fluctuation in the distance between two reflecting surfaces causes no phase change in the fringes for the path lengths high-lighted in blue on the bottom of the figure. (d) Frequency instability data for a ^{40}Ca-beam RB atomic clock for single and dual atomic beams.

The interrogation scheme suggested for use with the ^{40}Ca atomic beam is that of Ramsey-Bordé (RB) atom interferometry. In this scheme, an atom's wave function is split and recombined by a series of fixed laser beams that are directed by a monolithic in-vacuum optical element (Fig. 1b). Two counterpropagating atomic beams can be utilized to cancel a variety of inertial and thermal shifts that impact the phase of the clock signal fringes shown in Fig. 1a. Data has shown that the clock's performance, especially long-term, was greatly improved with counterpropagating atomic beams (Fig.1d). Generally, the optical paths created by the in-vacuum optical element also provide inherent phase and vibration sensitivity reduction through common mode cancellation, as depicted in Fig. 1c.

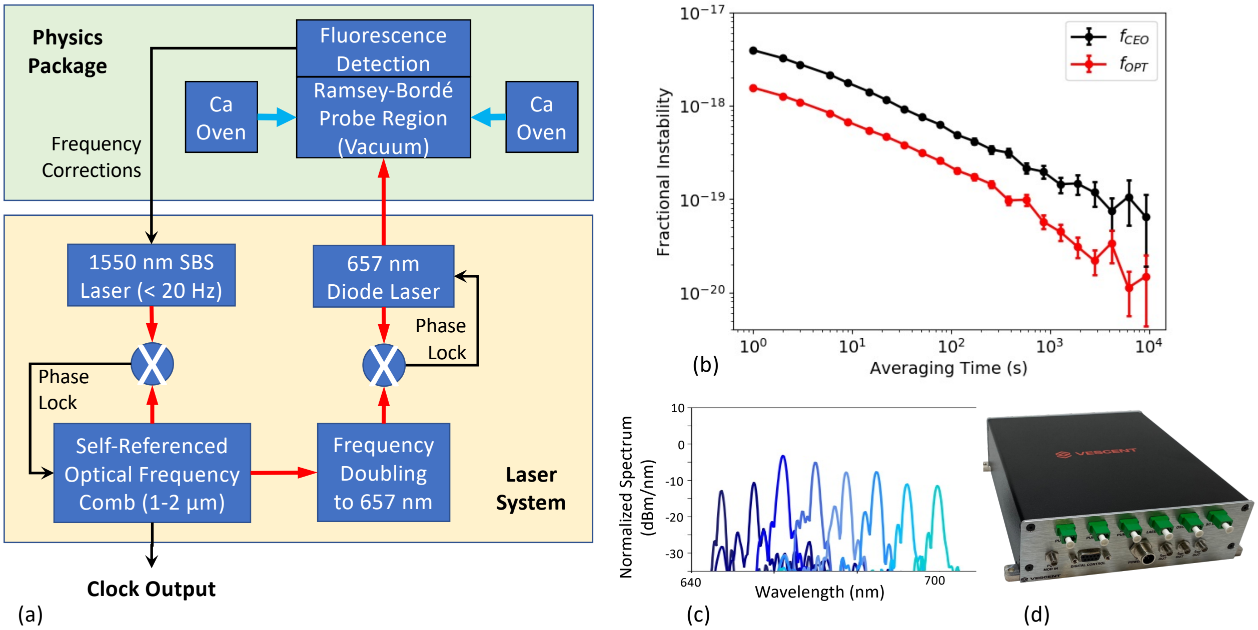

Figure 2: (a) Block diagram of proposed Ca beam clock. The phase lock signals are derived from optical heterodyne beat signals. The frequency stability of the narrow-linewidth SBS laser is transferred via the OFC to the 657 nm diode laser, which is used to probe the narrow Ca intercombination line. (b) In-loop frequency measurements (ADEVs) showing contributions of the OFC noise to the clock fractional frequency instability. (c) Efficient frequency doubling of the OFC over the wavelength range 650-700 nm, overlapping with the 657 nm clock laser. Optical power densities greater than -25 dBm/nm are sufficient for obtaining heterodyne beat signals with >35 dB signal-to-noise ratios for reliable phase locking. (d) Compact fiber-based optical frequency comb module with dimensions 20 cm x 18 cm x 5 cm.

A block diagram of the proposed clock is shown in Fig. 2a, showing how the Physics Package interacts with the Laser System. The Physics Package (to be developed by ColdQuanta) consists of two ovens that provide the counterpropagating thermal Ca beams into the RB atom interferometer housed in a vacuum system. Measured fluorescence from the RB interferometer acts as a frequency discriminator to provide feedback to maintain the laser system on the narrow-linewidth Ca resonance. The Laser System (to be developed by Vescent) provides two key elements of the optical clock: (1) the narrow-linewidth 657 nm laser for probing the Ca intercombination line, and (2) an optical frequency comb (OFC) that divides the optical frequency of the 657 nm clock laser to a useable radio-frequency clock output at about 100 MHz. The OFC is based on an erbium-fiber mode-locked laser that outputs a comb spectrum from 1000-2000 nm and employs the 1*f*-to-2*f* self-referencing method to control the carrier-envelope offset frequency. Frequency noise measurements of the OFC, shown in Fig. 2b, demonstrate that it can support optical clocks operating with fractional frequency instabilities at the 10^{-18} level, which is more than sufficient for the proposed Ca clock. Fig. 2c demonstrates that comb light at 1314 nm can be frequency doubled to 657 nm with sufficient power for tightly phase locking the 657 nm diode laser to the OFC. The entire OFC, including the frequency doubling, can be packaged in a compact module, shown in Fig. 2d, and is built from environmentally robust telecom components. Radiation-hardened versions of the comb optics have also been designed, built, and undergone initial ground-based testing for possible deployment on space-based platforms.

A requirement common to all optical clocks is a probe laser that has a linewidth narrower than the clock transition being measured. Clock lasers for state-of-the-art optical clocks are actively stabilized to sub-Hz linewidths by using large optical cavities (10-30 cm long) housed in a temperature-controlled vacuum system. However, these systems are relatively large and sensitive to vibrations. Reliable operation of cavity-stabilized lasers on vibration-prone mobile platforms presents the greatest challenge to developing field-deployed optical clocks. Fiber lasers based on stimulated Brillouin scattering (SBS) offer an alternative solution. All-fiber SBS lasers with < 20 Hz linewidths have been used to interrogate the 674 nm clock transition of a $^{88}Sr^{+}$ ion clock, achieving a short-term stability of 4×10^{-14} in one second without the use of an optical reference cavity [4]. Building upon this work, we envision phase locking the OFC to a narrow-linewidth SBS laser operating at 1550 nm, and, in turn, tightly phase locking a diode laser at 657 nm to the second-harmonic output of the OFC (see Fig. 2a). In this manner, the 657 nm clock laser acquires the narrow linewidth of the SBS laser and can effectively be used to probe the Ca intercombination line with adequate frequency resolution. This approach offers the tantalizing possibility of eliminating the need for an optical reference cavity, provided that the SBS laser frequency drift can be adequately suppressed by locking to the Ca RB interferometer. Should it be necessary to cavity-stabilize the SBS laser, the improved frequency noise performance of the SBS laser (as compared to an external-cavity diode laser) should relieve the stability requirements of the optical reference cavity and enable exploration of more SWaP-friendly cavity configurations.

We anticipate that the Ca beam clock would operate with < 100 W electrical power draw in a package size < 30 L and would have a short term (1-1000 s) performance near 1×10^{-15} with long-term performance ~ 10^{-14}. Addition of a second Ca laser (at 431 nm) would improve short term performance by another order of magnitude, requiring only a modest increase in SWaP and complexity. In either case, a spaceborne package would serve as a first step towards more complex optical clocks in space missions (including the critical step of evaluating optical cavity performance in a space environment). Moreover, the stability of the Ca beam clock would be sufficient to participate in clock searches for transient physics phenomena such as dark matter discontinuities, potentially outside of the shadow of the earth [5]. The significant advantage here is that the Ca clock system could be ready to fly years before their more complex trapped atom clock counterparts, thereby enabling critical tests of two-way optical links on a greatly accelerated time schedule (such links have yet to be demonstrated over distances beyond tens of km).

To prepare the Ca beam clock for space experiments, a modest ground program based on improving ruggedness, reducing SWaP, and finally space-qualifying the physics package and laser system would be required. We would anticipate that such advancements could be achieved in 3-5 years. We emphasize that the increase in technological readiness for these components would have great impact not only for future space clock missions, but also for ground-based applications including the highly sought objective of commercial optical atomic clocks offering orders-of-magnitude better stability than existing microwave atomic clocks.

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