WHITE PAPER

High Performance Vapor Cell Raman Clock Development for Space Applications

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High Performance Vapor Cell Raman Clock Development for Space Applications

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Abstract

We propose to develop a vapor cell Raman clock testbed with three orders of magnitude higher performance than what has been currently achieved by chip-scale atomic clock technologies. We will investigate the metrological performance of our clock using an all-optical Ramsey excitation protocol for reducing light shift and attaining dephasing limited linewidth. We will develop an optimized design for the clock physics package using a computer-aided model and also develop an offset phase-locked laser system as a compact light source for producing Raman beams. A complete long-term frequency instability budget for our clock will be estimated under laboratory conditions. This effort will eventually lead the way towards a compact high performance vapor cell clock with long-term stability approaching the level of 10^{-15} at one day and providing advantages of portability, weight and reliability for space-based geodesy and fundamental physics studies.

1. Significance

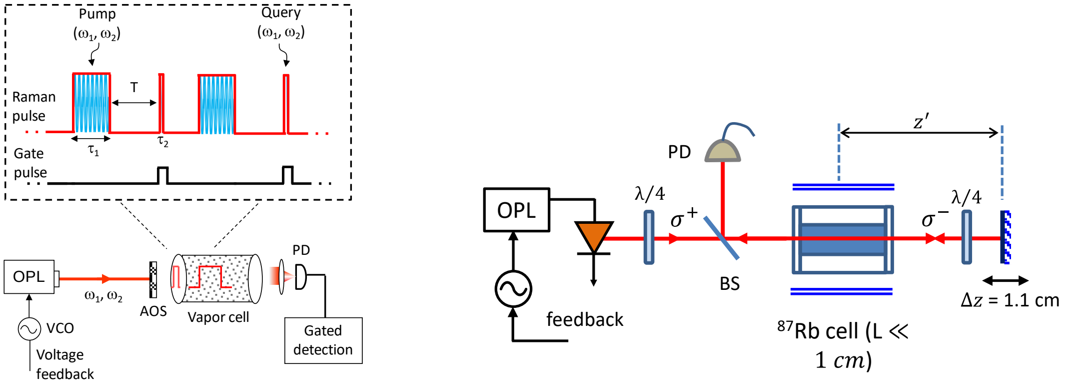
Atomic clocks are essential to a broad range of time keeping applications, including GPS, distributed networks, and communications etc. Highly stable and precise atomic clocks, if deployed in space, can be used in fundamental physics studies, such as measuring variations in fundamental constants of nature over time and performing tests of special and general theory of relativity [1,2]. It has been shown that a network of correlated atomic clocks in space can also be used in the ultra-light dark matter search [3]. The last decade has witnessed outstanding progress in optical clocks reaching fractional frequency uncertainties of 10^{-18} [4]. Although these highly stable and precise clocks are promising for ground-based applications, there are several technological challenges for using them in space. Laboratory versions of optical lattice clocks are still room-sized devices and operated under very stringent environmental conditions. The disadvantage of ion clock is only a single (or a few ions) can be used. Performance of these clocks rely highly on pre-stabilized laser sources and frequency combs. Trapping atoms with lasers in case of optical lattice clocks, also creates several insurmountable challenges.

On the other hand, portable microwave clocks using vapor cell can be easily deployed in space, as has been successfully done in global navigation satellite systems [5]. They meet the size constraint and power requirements of satellite-based systems. It is relatively easy and inexpensive to build a network of such clocks in space. Significant advancements have been made in miniaturizing these clocks. The design of miniature atomic clock (MAC) is based on compact integration of low-power vertical-cavity surface emitting laser (VCSEL), micro-fabricated rubidium or cesium vapor cell and photodetector into a single assembly. The physical mechanism for MAC involves coherent population trapping (CPT) [1] which provides the advantage of minimizing the clock's physical size and power consumption by eliminating the need for resonant microwave cavity. In the current state, MACs provide a reasonable frequency stability to enable portable and low-power applications in communication networks, jam-resistant GPS receivers, military radios and tactical UAVs etc. However, MACs are seriously limited in terms of long-term stability. In these types of clocks, fluctuations in experimental and environmental parameters are inherently converted to clock frequency fluctuations. One of the major sources that limits the long-term stability of MAC in particular, and vapor cell clocks, in general is the light-shift effect. Fluctuations in

VCSEL temperature, current and local oscillator power, and pressure-dependent frequency shifts further prevent MACs to reach long-term stabilities below 10^{-11}. Temperature changes in VCSEL are reported to produce clock frequency shifts by nearly 5 x 10^{-9}/K.

2. Concept

In this whitepaper, we discuss our plans to demonstrate a vapor cell-based Raman clock with high long-term stability approaching the level of 10^{-15} in a day without losing the advantage of its portability, weight and reliability for space applications. The proposed Raman clock will achieve high stability and accuracy by using a time-domain CPT-Ramsey interrogation scheme [6-9]. Our studies show that this technique can significantly reduce the light shift effect and produce high-contrast and narrow-linewidth Ramsey fringes which are not limited by the power broadening. This all-optical scheme does not require microwave interrogation which typically adds complexity and imposes a fundamental limit on the size-reduction. A compact offset phase-locked laser (OPL) system will be used to generate GHz frequency shifted beams for the proposed Raman clock. Monolithic DBR laser technology would allow us to design a compact OPL system with high spectral purity. Counter-propagating circularly polarized beams will be used to produce high contrast (> 50%) in the clock resonance. The proposed study will combine the advantages of CPT-Ramsey scheme and OPL system to demonstrate a vapor-cell based Raman clock with a short-term frequency stability reaching that to its fundamental photon shot-noise limit and long-term stability exceeding 10^{-15} per day. In the following section, we discuss some of the salient features of our all-optical CPT-Ramsey technique with the OPL system that will enable our development efforts for high-performance clock for space.



(a) (b)

Fig. 1 (a) Schematic showing the CPT-Ramsey in a vapor cell: AOS - acousto-optic switch, and VCO - voltage controlled oscillator and PD - photodetector, and (b) experimental geometry to be implemented for enhancing fringe contrast using counter-propagating σ^+ and σ^- polarized light. AOS for generating the pulse sequence is not shown in (b).

3. Technical Approach

A. CPT-Ramsey Scheme

CPT is produced by a continuous Raman excitation in a three-level $\Lambda -$system formed by two metastable ground-states coupled to a common excited state in an alkali atom. It can produce a narrow linewidth ‘dark state’ resonance. The linewidth of CPT resonance is fundamentally determined by the inverse of the ground-state coherence lifetime which could be tens of milliseconds in a vapor medium. However, in practice, the linewidth is broadened due to the higher optical power used in experiments to achieve higher contrast (or SNR) in the CPT resonance. The CPT-Ramsey scheme shown in fig. 1a can overcome this limitation. A pulsed excitation is used in the CPT-Ramsey scheme with a pulse sequence comprising of a long CPT (or preparation) pulse and a short query pulse. Ramsey interference is produced during the readout by the query pulse after an interaction-free evolution of the 'dark state' for time T. The fringe-width $\Delta\nu = 1/2T$ associated with Ramsey interference is thus, independent of the optical power used.

The frequency stability (or Allan deviation), $\sigma_y(\tau)$ of the atomic clock is estimated by $\sigma_y(\tau) = (\Delta\nu/\nu_0).(1/\mathrm{SNR})\,\tau^{-1/2}$, where ν_0 is the hyperfine (clock) frequency of the atom. The shot-noise limited SNR is given by $SNR = C\sqrt{\eta_d N}$, where C is signal contrast, η_d is the quantum efficiency of detector, and N is the average number of signal photons. The expected short-term stability of the proposed Raman clock can reach up to $10^{-12}\,\tau^{-1/2}$ which is calculated using parameters: $\Delta\nu$ = 100 Hz, $\nu_0 \simeq 6.8$ GHz for ^{87}Rb and $SNR = 1000$. Our experiments show that high contrast (≃ 30%) and narrow linewidth (< 500 Hz) Ramsey fringes can be produced using a centimeter-size, buffer gas (Ne) filled Rb-cell [6,9]. Further improvement in fringe contrast (> 50%) can be achieved by using counter-propagating σ^+ and σ^- polarized light in the rubidium cell as shown in fig. 1b. Moving the mirror reflecting the σ^- polarized light can change the relative phase between the dark states i.e. $|dark_{\sigma^+}\rangle$ and $|dark_{\sigma^-}\rangle$ at any fixed z-position in the cell, creating identical dark states. Atoms from that location can produce high contrast Ramsey fringes due to constructive interference of the two dark states. The cell length must be kept smaller than $\lambda_{hf}/4$ (i.e. close to 1 cm for ^{87}Rb) so that the phase variation of dark states can be considered small over the length of the cell and high contrast fringes can be generated even after spatial averaging. This condition is also consistent with the small cell-volume requirement for the proposed Raman clock.

The fundamental limit on long-term stability of the clock is imposed by the light shift (or AC Stark shift) [10,11]. One of the most important aspects of CPT-Ramsey scheme is reduction of light shift. For an ideal CPT excitation, the light shift should be zero as the atoms in the 'dark state' do not interact with the optical fields. However, a simple analysis shows that off-resonant excitations in a three-level Λ- system can produce a non-zero first-order light shift $\delta\omega_{\mathrm{LS}} = \omega_{\mathrm{hf}}\,.\,(\Omega_1^2 + \Omega_2^2)/(4\omega_{\mathrm{hf}}^2 + \Gamma^2)$, where Ω_i $(i = 1{,}2)$ represents the respective Rabi frequencies of the Raman beams, $\omega_{\mathrm{hf}} = 2\pi(\nu_{hf})$ and Γ corresponds to the total decay rate of excited state. This equation gives an oversimplified picture as it does not account for any additional frequency error which can result from CPT line-shape asymmetry and light shifts which are produced by multiple energy states in a real atomic system. When a VCSEL is used, it creates higher-order optical sidebands which modify the light shift due to off-resonant interactions. As we discuss below later, developing a compact OPL system will completely alleviate this problem.

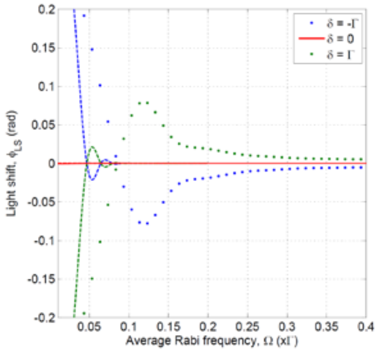


Fig. 2 CPT-Ramsey light shift calculated as a function of Ω of the Raman pulse for laser detuning $\delta = 0$ (red) and $\pm\Gamma$ (blue and green). The following parameters were used in our calculations: τ_1 = 100 μs, T = 1 ms, τ_2 = 100 ns and $\Omega_1 = \Omega_2 = \Omega$.

Our investigations of CPT-Ramsey scheme revealed that the light shift can be significantly reduced by ensuring a sufficiently strong interaction with the Raman pulse [12]. Fig. 2 shows the calculated light shift as a function of average Rabi frequency of the Raman pulse. Light shift vanishes when the laser detuning is set to zero which is difficult to achieve in a real experiment. For a non-zero laser detuning (i.e. $\delta = \pm\Gamma$), oscillations in light shift are observed. By choosing a higher Ω for the Raman pulse, the amplitude of the oscillation diminishes due to strong interaction. The clock frequency error caused by light shift depends on the laser detuning. Assuming that the laser detuning can be tightly controlled by an electronic servo, we expect that a fractional stability better than 10^{-12} can be achieved in our Raman clock. We believe that the CPT-Ramsey will provide a competing pathway for designing and developing a high-performance Raman clock using a centimeter-size rubidium cell. Next, we briefly discuss our plan to develop a compact offset phase-locked laser system and some design aspects of the Raman clock.

B. Compact OPL System

A compact bichromatic laser system which can stabilize relative laser frequencies at GHz frequency-difference will be developed. Monolithic, fiber-pigtailed DBR lasers with $< 1\, MHz$ linewidth will be used to build the offset phase-locked laser (OPL) system shown in fig. 3. The relative phase between the master and the slave laser will be locked to the optical beat note at 6.834 GHz ^{87}Rb hyperfine frequency using a phase-locked loop (PLL) chip. The OPL system will provide higher phase and frequency stability, desirable optical power and polarization control for the Raman beams, and can be integrated on a photonic-integrated circuit with fiber-delivered light output. The spectral purity of OPL output can be improved using low-noise Libberecht-Hall current drivers for the DBR lasers. We plan to develop an experimental testbed for the Raman clock. Computer-aided model will be used to properly design the clock physics package. Effects of environmental factors and physical parameters e.g. temperature, magnetic field, and buffer gas pressure will be mitigated for reaching higher stability. The cell physics package will consist of 1 cm long buffer gas-filled Rb-cell, high magnetic shield enclosure (attenuation > 60 dB), field coil, and ac heating with temperature control etc. Various servo controls will be implemented using FPGA boards. We will systematically investigate all major sources of frequency errors in the clock prototype. We will also study the role of the buffer gas mixture for canceling the first-order (linear) temperature-dependent shift and determine the gas pressure ratio needed for the mixture to cancel the temperature-dependent shift while elevating the operating temperature between 30 – 50^{0}C.

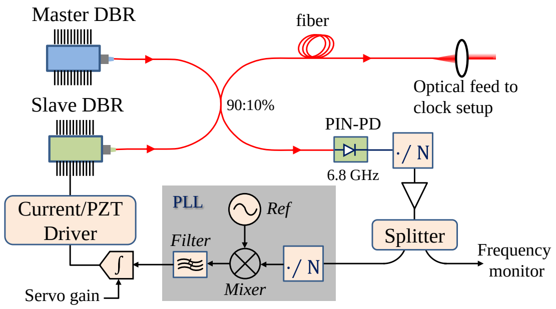


Fig. 3 Schematic of a compact fiber-pigtailed OPL system.

4. References

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