LaLI-POP: Lamp and Laser Integrated Pulsed-Optically Pumped Atomic Clock

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Abstract — Arguably, the rubidium atomic frequency standard (RAFS) is the workhorse of precise timekeeping in space, with the GPS RAFS one of the best atomic clocks now operational in any satellite system. However, the GPS RAFS is not perfect: 1) its short-term stability (*i.e.*, averaging times less than 10^4 seconds) is limited by the size of the atomic signal, and 2) its long-term stability (*i.e.*, averaging times greater than 10^5 seconds) is limited by frequency jumps caused by the light-shift effect. In both cases, the limitation of the RAFS's frequency stability traces to the use of an rf-discharge lamp for atomic signal generation and atomic system monitoring: low lamplight intensity results in small atomic signals, while lamplight-induced frequency jumps manifest as random-walk frequency noise. Though replacement of the lamp by a diode laser eliminates these RAFS problems, new laser-related problems arise in the *laser*-pumped RAFS. In particular, PM-to-AM conversion noise and intrinsic diode laser relative intensity noise can limit the device's signal-to-noise ratio. LaLI-POP solves these problems by combining the best of laser optical pumping with lamplight signal detection. A diode laser is pulsed on/off creating efficient optical pumping and hence large atomic clock signals, while microwave absorption is detected during the laser-off cycles by monitoring the vapor's transmission of lamplight. Since lamplight has insignificant levels of PM-to-AM conversion and relative intensity noise, large atomic signals are detected with very low noise. Moreover since the lamplight only needs to *monitor* the absorption and *not optically pump* the vapor, the lamplight intensity can be low, reducing the lamp's light-shift of the 0-0 resonance. Consequently, lamplight-induced frequency jumps should be much less problematic. In this presentation we provide a detailed theoretical estimate of LaLI-POP's short and long-term frequency stability, along with results from our initial experiments exploring the LaLI-POP concept.

Keywords—RAFS, vapor-cell atomic clock, POP clock, Rb atomic clock

I. INTRODUCTION

The traditional, lamp-pumped, rubidium atomic frequency standard (RAFS) is arguably one of the best space-qualified atomic clocks presently employed in operational space systems, and its physics package is illustrated in Fig. 1. Briefly, the RAFS's physics package consists of: 1) a Rb rf-discharge lamp, a filter cell, a resonance cell sitting inside a microwave cavity, and a photodetector [1]. After passing through the filter cell, the spectrum of the lamplight is shaped so that it can optically pump a vapor of ^{87}Rb atoms [2,3], creating a population imbalance between the Rb atoms' ground-state hyperfine levels. As a consequence, with few atoms in the absorbing state the lamplight reaching the photodetector is at a "high" level. When 6834.7 MHz microwaves are injected into the cavity atoms return to the (optically) absorbing state with a subsequent decrease in the transmitted light intensity. The lamplight reaching the photodetector is thus an indicator of the atoms' interaction with the microwaves, and is employed in a feedback loop to lock the microwave signal to the atoms' hyperfine resonance. The atomic-Q of this microwave transition is respectable (*i.e.*, ~ 10^7), and when combined with the vapor-cell's high signal-to-noise ratio (*i.e.*, SNR ~ $10^3 – 10^4$), short-term stabilities of $10^{-12}/\tau^{1/2}$ or better can be obtained and persist out to averaging times of 10^4 seconds and beyond [4,5].

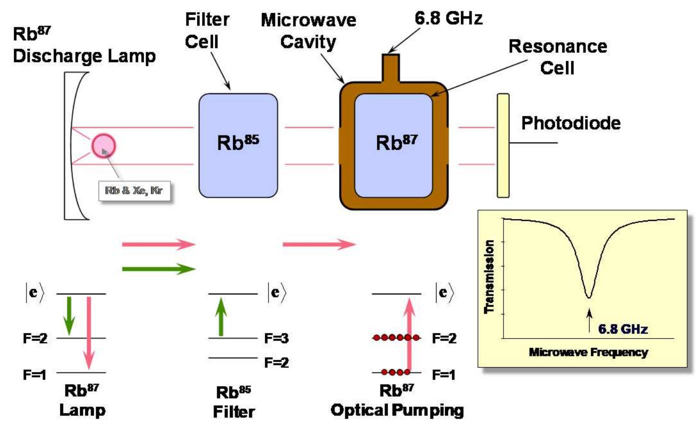

Figure 1: Block diagram of the traditional RAFS's physics package as described in the text.

There are two problems with this design: 1) the filtered lamplight has low efficiency for optical pumping (compared to that of singlemode diode lasers), resulting in SNRs that could be larger [6]. Further, lamplight jumps are now known to drive a RAFS's random-walk frequency noise via the light-shift effect [7]. Thus, it would seem that replacing the lamp with a pulsed diode laser could realize the full potential of vapor-phase systems for frequency standard metrology. Unfortunately, due to the diode laser's finite linewidth, laser phase-noise (PM) to amplitude-noise (AM) conversion can limit the diode-laser pumped RAFS's SNR [8] as can the diode laser's intrinsic relative-intensity-noise. It would therefore seem that neither the lamp-pumped nor the laser-pumped RAFS can realize the full potential of vapor-phase systems for frequency metrology.

II. ANTICIPATED PERFORMANCE OF LALI-POP

One solution to this problem is the Lamp and Laser Integrated Pulsed-Optically-Pumped RAFS: LaLI-POP. As illustrated in Fig. 2, LaLI-POP at one level is equivalent to the lamp-pumped RAFS: an rf-discharge lamp is operated cw and frequency-modulated microwaves are applied cw to the cavity. The difference is that the lamp is operated at low temperature (and hence low light intensity), while a diode laser performs optical pumping in a pulsed fashion. The lamplight's transmission is detected via a gated photodetector, so that only when the laser is off is the gated-photodiode signal employed for microwave frequency stabilization. In this way, larger clock signals are obtained as a consequence of diode laser optical pumping, while low noise levels are achieved via monitoring with lamplight. Moreover, even though a light-shift exists for this clock, the low lamplight level implies that the light-shift of the clock's frequency can be reduced significantly.

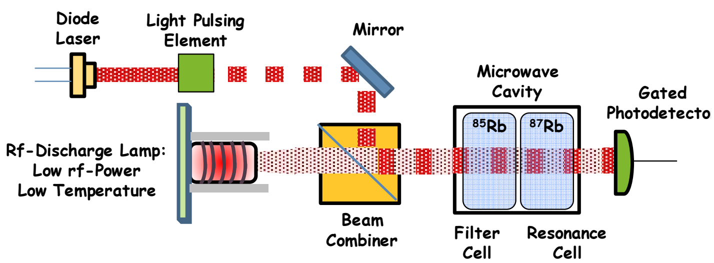

Figure 2: Block diagram of LaLI-POP as described in the text.

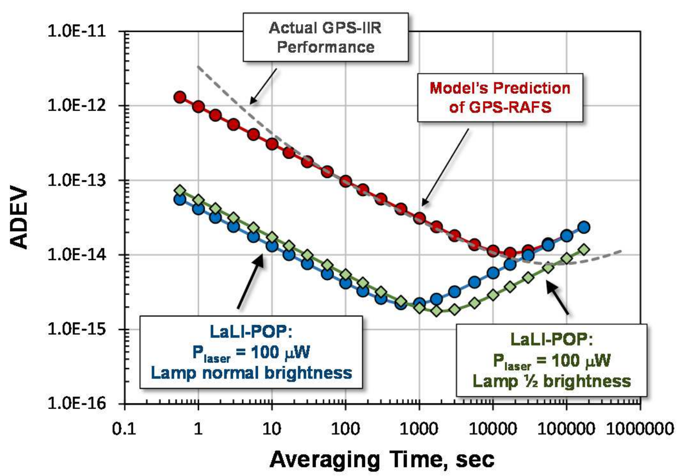

Figure 3: Anticipated Allan deviation (ADEV) of LaLI-POP. To verify our model's predictions, we first predicted the performance of the GPS-IIR RAFS using data supplied in Ref. [13]. With good agreement between test results and the model, we then predicted the performance of LaLI-POP operating at normal lamp brightness and ½ lamp brightness (*i.e.*, factor of two reduction in the clock's light-shift).

Using the Generalized Vanier Theory (GVT) of vapor-cell atomic clock signals [9-11], we modeled the anticipated Allan deviation for LaLI-POP. Signal levels came from laser optical pumping, and the clock's white-noise frequency instability was determined solely by lamplight shot-noise [12]. For LaLI-POP's random-walk frequency noise we assumed (similar to the GSP-IIR RAFS [7]) that long-term frequency instability derived from lamplight-induced jumps in clock frequency via the light-shift effect. The results of this analysis are shown in Fig. 3.

To test the model, we first used the GVT to predict the short-to-medium term performance of the GPS-IIR lamp-pumped RAFS. Input parameters for the clock signal were obtained from Riley [13]. Long-term random-walk frequency noise was assumed to derive from lamplight-induced jumps in clock frequency via the light-shift effect, and the parameters for the compound Poisson process of lamplight jumps [14] were obtained from Formichella *et al*. [7]. As Fig. 3 shows, the agreement between our model and the GPS-IIR performance is quite good, and provides confidence in the model's ability to predict LaLI-POP's frequency stability in both the short, medium, and long-term.

Assuming a singlemode diode laser with an output power of 100 µW, we computed the improvement in short-term frequency stability that laser pumping would provide. We assumed that the laser and photodiode could be pulsed on/off fast enough so that there would be negligible hyperfine-polarization relaxation during the laser-off cycles [15] and consequently no pseudo light-shift [16]. For the long-term, we assumed that lamplight jumps would induce frequency jumps via the light shift effect with the same amplitude and period as for the GPS-IIR clocks [7]. As Fig. 3 shows, there is significant improvement in LaLI-POP's short-to-medium term frequency stability compared to a GPS-IIR RAFS.

Clearly, for a lamp operating with the same output power as a GPS-IIR lamp there is no predicted improvement in LaLI-POP's long-term frequency stability compared to the GPS-IIR RAFS. However, as noted above the lamp in LaLI-POP only acts as a probe, and consequently it's light intensity need not be as high as the GPS-IIR lamp. Assuming that the lamplight is reduced by a factor of two, Fig. 3 shows a factor of two improvement in LaLI-POP's long-term frequency stability, while only a $2^{1/2}$ loss of frequency stability in the short term.

In addition to lowering the clock's light shift by operating with lower lamplight intensity, there may be a further benefit of the lamp's lower operating temperature. In other work conducted in our laboratory we have obtained evidence that the probability of lamplight jumps may be related to operation of the lamp near the so-called "ring-mode" to "red-mode" transition temperature [17]. Operating a lamp near this transition results in large signal-to-noise ratios, because the efficiency of lamp optical pumping is maximized [18]. However, if the lamp is only operated as a probe, and has no requirement for optical-pumping, then the lamp can be operated at a temperature away from the ring-mode to red-mode transition, which could result in lower probabilities for lamplight jumps. Thus, operating at lower lamp temperature might not just lower the clock's light shift (via lower lamplight intensity), but also lower the probability that lamplight-induced jumps in clock frequency will occur.

III. Preliminary Experiments

Figure 4 is a block diagram of our experimental arrangement for investigating the LaLI-POP concept. A VCSEL diode laser at 795 nm is tuned to the Rb D_1 optical transition: $5^2S_{1/2} – 5^2P_{1/2}$. Additionally, light from a natural isotope-ratio rf-discharge lamp passes through the resonance cell. Given the fact that the natural isotopic ratio of Rb is 72% ^{85}Rb and 28% ^{87}Rb, the lamplight primarily excites ^{87}Rb atoms in the resonance cell out of their F_g = 2 hyperfine ground-state [19]. Microwaves are applied to the vapor either with a horn or a microwave cavity.

The transmitted laser and lamplight are detected by two different photodiodes, and input to two separate lock-in amplifiers referenced internally to 137 Hz. Since there is no transmission signal at this frequency, these two lock-ins effectively measure low Fourier frequency noise on the laser and lamp transmitted light signals. Additionally, the lamp photodetector output is input to a storage oscilloscope for recording the lamplight transmission as the microwaves are tuned over the 0-0 hyperfine resonance. To distinguish the lamp's and laser's optical interactions, the lamp's photodetector has a 780 nm filter in front of it, so that this detector only monitors D_2 light from the lamp (*i.e.*, the Rb $5^2S_{1/2} – 5^2P_{3/2}$ transition).

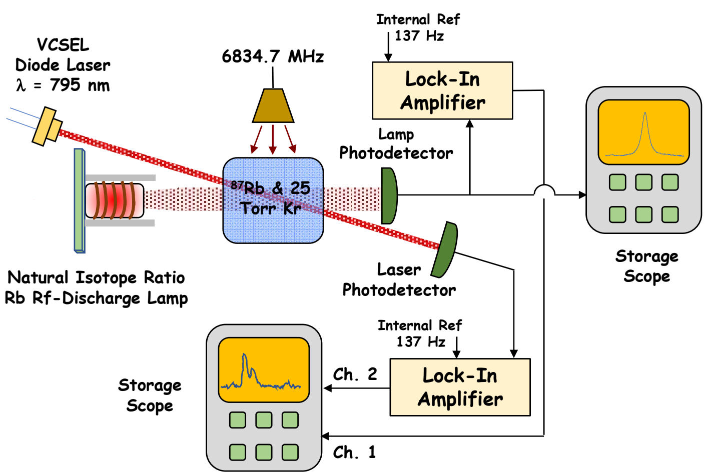

Figure 4: Experimental arrangement to examine the viability of the LaLI-POP concept. A VCSEL diode laser at 795 nm, exciting the Rb D_1 transition, optically pumps a vapor of ^{87}Rb in a 25 Torr Kr buffer-gas resonance cell. Given the natural isotope ratio of Rb, the lamp primarily excites ^{87}Rb atoms in the resonance cell out of the F_g = 2 ground-state hyperfine level. Two lock-in amplifiers internally referenced at 137 Hz allow us to monitor signal-noise for both the laser and lamp, and there is a 780 nm filter in front of the lamp's photodetector to isolate lamp and laser interactions in the vapor. As the microwaves are scanned across the 0-0 hyperfine transition the lamp's transmitted light intensity is monitored.

Figure 5 shows the transmitted lamplight as the microwaves are scanned across the ^{87}Rb 0-0 resonance. When only the lamplight is present (*i.e.*, the laser is blocked), there is a decrease in the transmission signal. This indicates that the lamp is still performing some optical pumping. Specifically, since the lamp's natural isotope-ratio yields greater optical excitation for ^{87}Rb atoms in the F_g = 2 hyperfine level than the F_g = 1 level [19], the lamp's optical pumping process is $|F_g=2\rangle \rightarrow |F_g=1\rangle$: microwaves induce atoms to *return* to the optically absorbing state with a subsequent decrease in transmitted light.

When the laser is tuned to the F_g = 1 hyperfine level, the lamplight shows a dramatic *increase* in the transmitted intensity. The laser's optical pumping process is $|F_g=1\rangle \rightarrow |F_g=2\rangle$, so that when microwaves are tuned to the ^{87}Rb 0-0 resonance atoms in $|F_g=2\rangle$ *exit* the state yielding greater lamplight transmission. Clearly, laser optical pumping is much more efficient than lamp optical pumping. Though the results presented in Fig. 5 are perhaps unsurprising, their experimental observation is nonetheless validating.

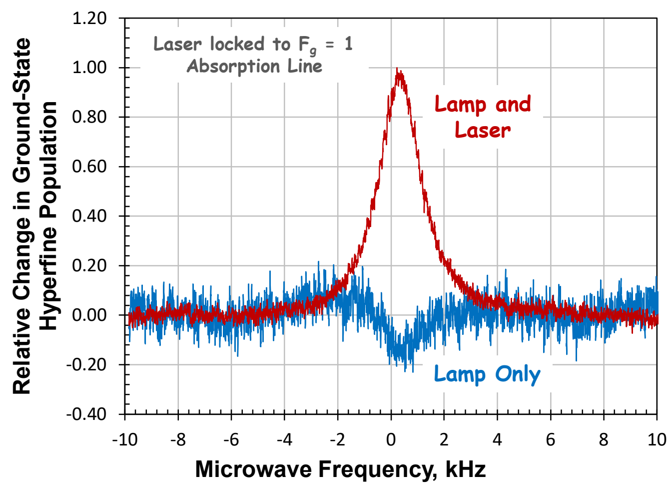

Figure 5: Change in transmitted lamplight as the microwaves are scanned across the 0-0 ground-state ^{87}Rb hyperfine transition. With only the lamp present, there is a decrease in the transmitted lamplight indicating that the lamp does some optical pumping: F_g = 2 → F_g = 1. With the laser present, there is a much greater increase in transmission, since laser optical pumping is associated with F_g = 1 → F_g = 2.

Figure 6 shows the noise on the transmitted laser light (red) and lamplight (blue) as the laser is tuned across the D_1 optical absorption line. The inset is an expanded scale to better illustrate the noise on the lamplight. In the figure, the noise has been normalized for both cases to the noise of the transmission with the laser far off resonance (lamplight and laser light separately). Thus, the figure shows the *increase* in transmitted lamplight and laser light noise due to the laser's resonant D_1 absorption. (The dashed gray curve shows the laser's relative absorption signal to orient the frequency scale.)

For the laser, the noise shows the classic "M-Shaped" pattern consistent with laser PM-to-AM conversion [8]. The noise on the lamplight shows something quite different, however. With the laser exciting atoms out of the F_g = 2 hyperfine level there is hardly any noise on the lamplight signal. However, for the laser exciting atoms out of the F_g = 1 hyperfine level there is clearly detectable increased transmitted lamplight noise. This is inconsistent with "standard" PM-to-AM noise conversion: for standard PM-to-AM noise conversion we should expect increased noise on the lamplight when the laser is tuned to *both* the F_g = 1 and 2 levels.

The data of Fig. 6 suggest that the lamplight noise is not arising as a consequence of laser-induced noise on the $5^2S_{1/2}$ – $5^2P_{1/2}$ coherence created by the laser. Additional experiments in our laboratory that are presently underway indicate that the lamplight noise arises as a consequence of *PM-to-AM induced optical pumping noise*: as the laser's phase noise induces absorption cross section fluctuations, there are concomitant fluctuations in the efficiency of laser optical pumping, which manifest as fluctuations in the population of $|F_g\!=\!2\rangle$ monitored by the lamp. We will be completing our experiments into this phenomenon in the next several months, and the results will be the subject of a forthcoming publication.

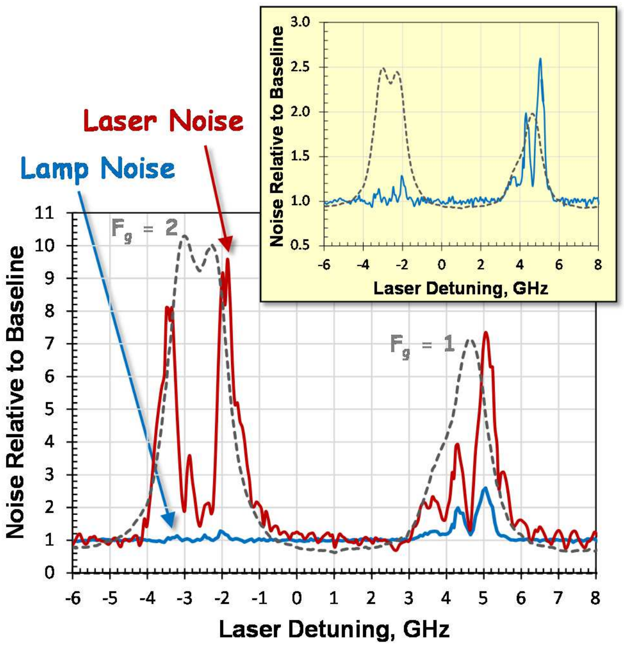

Figure 6: With the laser scanned across the D_1 resonance (absorbance shown as the gray dashed curve), the noise on the lamp and laser transmission signal is recorded.

IV. Summary

In this work we have introduced the LaLI-POP concept, where a pulsed diode laser optically pumps an ^{87}Rb vapor and a Rb lamp monitors the $|F_g\!=\!1, m_F\!=\!0\rangle \leftrightarrow |F_g\!=\!2, m_F\!=\!0\rangle$ hyperfine transition. Advantages of the LaLI-POP concept include the use of a laser for more efficient optical pumping and the elimination of (standard) laser PM-to-AM noise conversion, both of which should benefit the vapor-cell clock's single-to-noise ratio. There is, of course, a light-shift for LaLI-POP, since the 0-0 hyperfine transition is probed with the lamplight present. However, by operating the lamp away from the ring-mode to red-mode transition, the light-shift can be reduced, and we believe jumps in the lamplight (causing light-shift induced jumps in the clock frequency) may be significantly decreased.

We did discover an alternate pathway for laser PM-to-AM noise to affect the clock's signal-to-noise ratio: PM-to-AM induced optical-pumping noise. However, since optical pumping saturates at high laser intensity, the influence of this noise on LaLI-POP's performance will be nonlinear, and consequently might be eliminated by operating the laser at sufficiently high intensity. Nevertheless, this noise process will require further investigation, and that is presently where the efforts in our laboratory are focused.

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