Discharge Lamps for Rb Atomic Clocks: The Role of rf-Power

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***Abstract*— Rubidium atomic clocks that fly on GNSS satellites employ the light from rf-discharge lamps for atomic signal generation and detection. In this application, the performance of the atomic clock and the capabilities of the navigation system depend sensitively on the lamp's stability. In order to better understand the mechanisms that might lead to instability in these lamps, and hence the satellite clocks, we studied the optical emission from a Rb/Xe lamp as a function of the lamp's rf-power. Surprisingly, we found that the electron density in the plasma was essentially independent of increases in rf-power above its nominal value (i.e., "rf-power gain"), and that the electron temperature was only a slowly varying function of rf-power gain. The primary effect of rf-power was to increase the temperature of the neutrals in the plasma, which was manifested by an increase in Rb vapor density. Assuming that increased Rb density proportionally increases the lamp's light intensity, we predict that the sensitivity of GNSS-quality Rb clocks to changes in lamp rf-power, $|\partial y/\partial[\Delta P_{rf}/P_{rf}]|$, is on the order of 1.0×10^{-14}/%.**

I. INTRODUCTION

Rubidium atomic clocks are arguably the workhorse of modern GNSS, and rf-discharge lamps play a primary role in the Rb clock's atomic signal generation [1]. Specifically, the lamplight is employed for optical pumping, which creates the necessary population imbalance between the atom's ground state hyperfine levels. Additionally, the lamplight's transmission through the atomic vapor monitors the atoms' interaction with the microwave field, thereby providing the clock-crystal's correction signal. Clearly, in order to achieve the required levels of frequency stability for GNSS applications, perturbations to the Rb atom's structure must be very well controlled, and one of the chief perturbations of that structure is the light shift [2, 3].

When an atom interacts with a near resonant optical field (e.g., the light from the rf-discharge), an induced, oscillating dipole moment is created in the atom. In second order, this induced dipole interacts with the optical field that created it, producing an atomic perturbation that shifts the atom's energy level structure. The strength of the perturbation is linear in the light intensity, and also depends on the specifics of the lamp's spectral emission. Consequently, the fractional frequency change in clock's output, Δy, due to the light shift is often written as

$$\Delta y = \alpha_{LS}(\Delta I/I_o), \quad (1)$$

where $\Delta I/I_o$ is the fractional change in the lamplight's intensity and α_{LS} is a lamp-spectrum dependent proportionality constant called the light-shift coefficient. Since the lamp spectrum is not expected to change significantly under modest lamp-parameter variations, α_{LS} will be considered a fixed constant in what follows.[1]

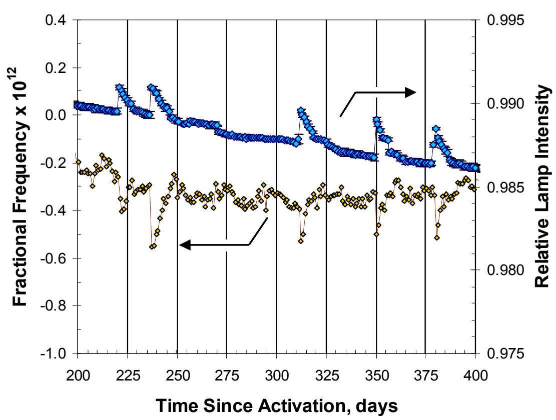

Figure 1. Illustration of the effect of lamplight intensity variations on the frequency of a GNSS Rb atomic clock.

To illustrate the significance of the light shift, Fig. 1 shows fractional frequency and lamp intensity data from a GNSS satellite [5]. Notice that there are discrete jumps in the lamp's

[1] Notwithstanding this assumption, we do note that temperature increases in the lamp can produce non-negligible radiation trapping [4]. In the case of radiation trapping, spontaneously emitted photons diffuse spectrally to the wings of the emission line, thereby significantly changing the lamp's emission spectrum.

light intensity that correlate with jumps in the clock frequency. Based on data like this from other GNSS satellites, the light-shift coefficient in a high-quality Rb atomic clock is about -1.4×10^{-12}/%. The light-intensity jumps lasted several days; they happened several times in the space of several months; and outside that few month interval (which occurred well into the lamp's "steady-state" operating life) they were not observed. This data provides a good example of the light-shift effect in a functioning Rb clock, as well as a powerful illustration of how little we know regarding the subtle (yet significant) behavior of rf-discharge lamps.

In the work discussed here, we examined rf-power induced changes in the characteristics of a low-temperature Rb/Xe ICP. In the following section, we describe our experimental arrangement, our analysis methodology, and our principle results. Then in Section III, we discuss the implications of our results with regard to the influence of lamp rf-power variations on the clock's frequency stability.

II. Experiment & Principle Results

The rf-discharge lamp (and its associated electronics) for these experiments were obtained from a commercial atomic clock: the glass bulb containing the plasma is thermally bonded into a metal base and placed within the induction coils of a Hartley oscillator ($f_{osc} \cong 70$ MHz and $Q \cong 85$ [6]). Thus the plasma, as part of a resonant circuit, plays a role in defining f_{osc} and Q, and as a consequence the rf-energy density for its own excitation. Though this nonlinearity enriches the physics of the discharge, it nonetheless complicates the situation. It is also unavoidable in our experiments, where the motivation is to understand the behavior of rf-discharge lamps *as employed in atomic clocks*. In addition to producing the rf-excitation, the lamp electronics regulate the temperature of the lamp's metal base, thereby providing the nominal lamp temperature [7]. Finally, we note that the construction of the rf-discharges employed in atomic clocks makes it difficult to employ a Langmuir probe: the discharge dimensions are quite small, and the probe would distort the plasma and the resonant circuit's characteristics.

Figure 2 shows a block diagram of our experimental arrangement [8], where the Pyrex glass bulb confining the discharge contained a rubidium (Rb) vapor in equilibrium with its condensed phase at about 70 °C along with xenon at a pressure of two torr. In order to supply additional rf-power to the discharge, a single loop "injection antenna" was placed around the glass bulb and connected to an external, amplified signal that was tuned to the lamp's nominal oscillation frequency. The tuning was accomplished by employing the rf-signal picked up by the small, single-loop antenna. With no additional power supplied to the discharge, the signal from this "pickup" antenna showed a bright line on the rf-spectrum analyzer at about 70 MHz. When additional power was supplied to the discharge two bright lines were observed on the spectrum analyzer, and we tuned the frequency of the external signal source until the secondary bright line's frequency matched the primary bright line's frequency. The optical signal was collected with a multimode fiber-optic cable and transmitted to a USB 4000 Ocean Optics spectrometer.

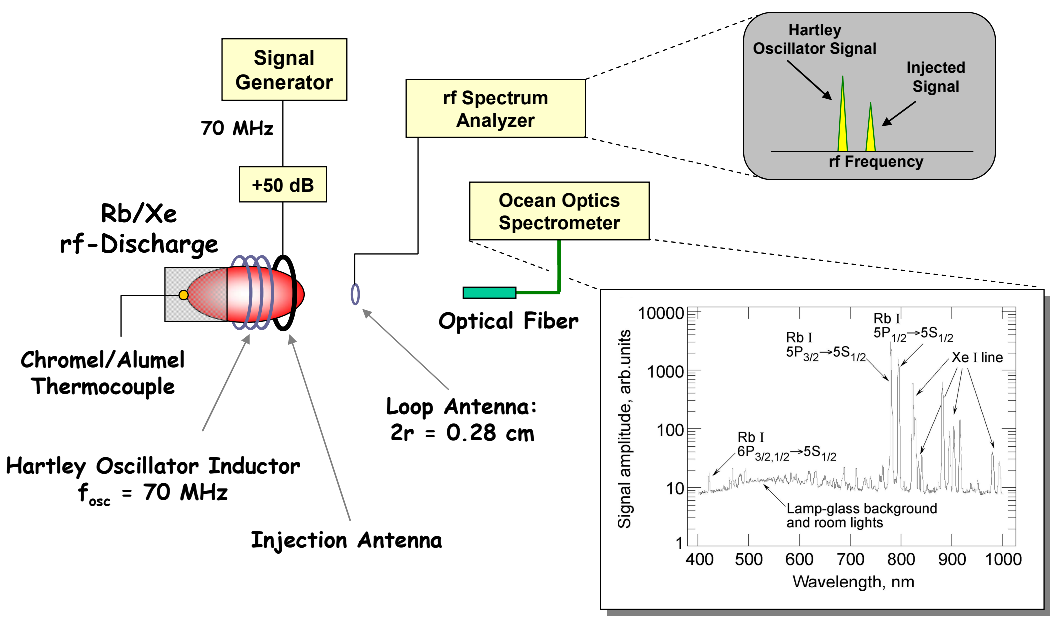

Figure 2. Block diagram of the experimental arrangement.

The "2nd resonance" of rubidium (Rb) corresponds to the transitions $6^2P_{3/2,1/2} \to 5^2S_{1/2}$, which have wavelengths of 420 nm and 422 nm, respectively. Due to the relatively small oscillator strength for this transition, it does not suffer from radiation trapping in the same way as the "1st resonance" transition (i.e., the two lines in the red at 780 & 795 nm, corresponding to the $5^2P_{3/2,1/2} \to 5^2S_{1/2}$ transitions, respectively). Consequently, the strength of this transition can be used to estimate the Rb vapor density, or equivalently the surface temperature of the liquid pool of Rb, which lies on the lamp bulb's wall.

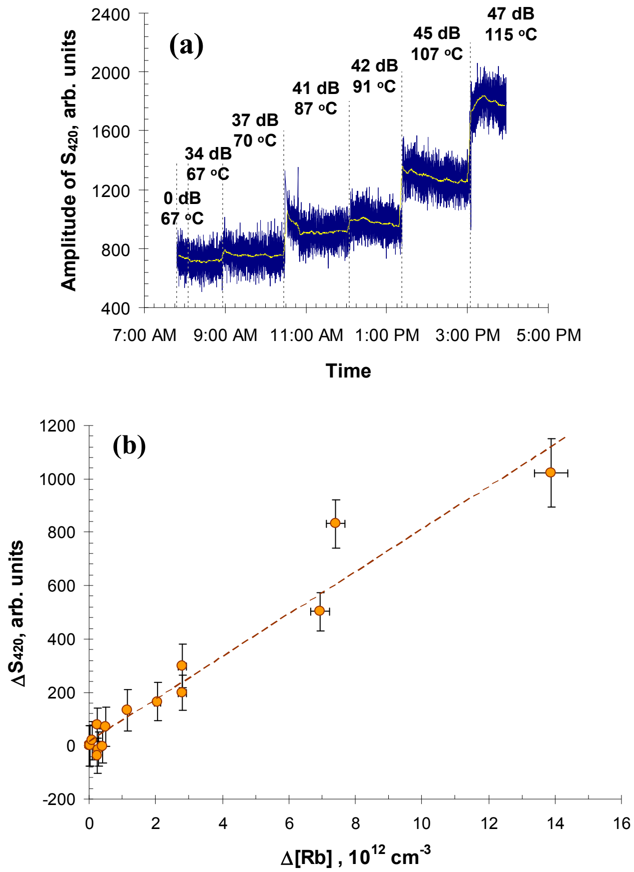

Figure 3. (a) During the course of a day, we changed the rf-power injected into the discharge and monitord the 420 nm Rb signal and the lamp temperature. (b) The change in 420 nm signal as a function of the change in inferred Rb density; the linearity of this data provides evidence that the electron density in the discharge is relatively constant as the rf-power is changed.

Figure 3a shows the change in the combined 420 & 422 nm signal strength (i.e., S_{420}) as we changed the rf-power driving the discharge. Figure 3b shows the change in S_{420} as a function of the (rf-power induced) change in Rb vapor density, inferred from the thermocouple reading. Together, these data demonstrate that we can use S_{420} to estimate the vapor-phase Rb density, [Rb]. More importantly, however, the linearity between ΔS420 and Δ[Rb] implies that the electron density in the discharge is relatively insensitive to changes in rf-power.

As discussed in Ref. 8, S_{420} should scale linearly with [Rb] and nonlinearly with the discharge's electron density, n_o. If n_o were dependent on rf-power gain (i.e., increases in rf-power above its nominal value), then n_o and [Rb] would be correlated; and this in turn would give S_{420} a nonlinear dependence on [Rb]. Thus, the linearity of Fig. 3b can only be explained if n_o is independent of (or at most weakly dependent upon) rf-power. This is a surprising conclusion, since the alkali number density is clearly changing with rf-power and one might have expected the electron density to scale with [Rb]. Nevertheless, in other experiments examining temporal fluctuations in electron temperature, which are not reported here (see Ref. 8), a similar conclusion is reached. Thus, as surprising as it may at first appear, we must conclude that the changes in rf-power that we induced did not appreciably change the total electron density in the discharge.

Using the Xe spectral lines, we estimated the electron temperature in the discharge as shown in Fig. 4. Briefly, we plotted several Xe spectral line strengths, S_{ij}, as a function of the transition's upper-state energy, ε_i, [8]; the slope of the resulting straight line was $1/kT_e$, where T_e is the electron temperature. As indicated in Fig. 3, we estimated the lamp bulb's wall temperature, T_w, by using S_{420}. (This is advantageous, since the thermocouple readings became erratic at high rf-power gain levels.) As one might have anticipated, we find that ΔT_w is (comparatively) sensitive to increases in the rf-power exciting the discharge, P_{rf}: $\Delta T_w \cong 0.25(P_{rf}/P_o)^{0.41}$. We also find that while T_e increases with P_{rf}, it is a very slowly varying function of P_{rf}: $T_e \sim \ln[P_{rf}]$.

Taken in total, our results suggest the following conclusions with regard to the effect of rf-power gain on Rb lamp operation.

- Increases in lamp rf-power above the nominal level have little if any effect on the discharge's total electron density.
- Increases in lamp rf-power above the nominal level have a slight effect on the discharge's electron temperature: $T_e \sim \ln[P_{rf}/P_o]$.
- Increases in lamp rf-power have their primary effect in heating the surface temperature of the liquid pool of Rb in the lamp, and hence increasing the Rb vapor density.

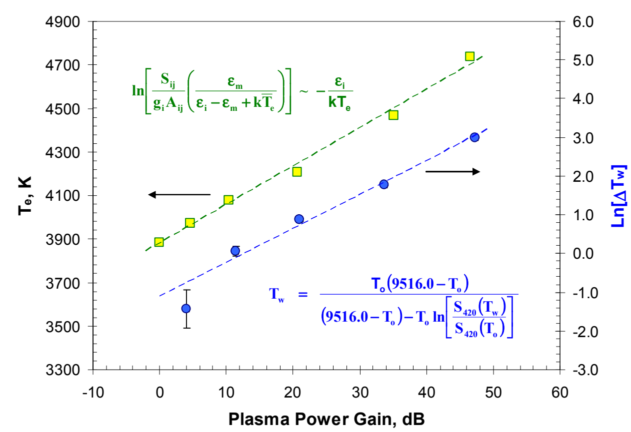

Figure 4. Squares show the discharge electron temperature, T_e, as a function of rf-power gain. T_e was determined by least squares fit of several xenon line strengths, S_{ij}, to the transition's upper state energy, ε_i [8]: g_i is the upper level degeneracy, A_{ij} is the Einstein A-coefficient, ε_m is a metastable energy for the multi-step electron excitation of Xe, and the nomial electron temperature is indicated with a bar. Circles show the change in wall temperature from nominal, T_o, as inferred from S_{420} [8].

III. Effect of RF-Power Gain on Clock Frequency

To infer the effect of lamp rf-power variations on atomic clock performance, we first employ the fact that rf-power gain has its primary effect on Rb vapor density, [Rb]. In particular, we generalize that observation to include *all* moderate variations in lamp rf-power about the nominal value, P_o; irrespective of whether these are increases *or* decreases in rf-power. Specifically, if we say that

$$T_w = T_o + 0.25\left(\frac{P_{rf}}{P_o}\right)^{0.41} \quad (2)$$

(ignoring the slight ¼ °C inconsistency at $\delta P_{rf} = 0$), we can expand Eq. (2) in a Taylor series about $\delta P_{rf} = 0$ in order to obtain

$$\delta T_w = \delta P_{rf}\frac{\partial T_w}{\partial P_{rf}} = 0.103\left(\frac{\delta P_{rf}}{P_o}\right)\left(\frac{P_{rf}}{P_o}\right)^{-0.6}. \quad (3)$$

The advantage of Eq. (3) over Eq. (2) is that it may be employed for both positive and negative changes in rf-power.

Then, using Killian's formula for the relationship between liquid Rb surface temperature and Rb vapor density [9], we have

$$\frac{\Delta[Rb]}{[Rb]_o} = \mathrm{Exp}\left[9514\left(\frac{1}{T_o}-\frac{1}{T_w}\right)\right]-1 \cdot \quad (4)$$

This becomes for small variations in liquid Rb temperature relative to the nominal temperature in Kelvin

$$\frac{\Delta[Rb]}{[Rb]_o} = \mathrm{Exp}\left[\frac{9514\times\delta T_w}{T_o^2}\right]-1 \cdot \quad (5a)$$

Finally, using Eq. (3) we have

$$\frac{\Delta[Rb]}{[Rb]_o} = \mathrm{Exp}\left[\frac{980}{T_o^2}\left(\frac{\delta P_{rf}}{P_o}\right)\left(\frac{P_{rf}}{P_o}\right)^{-3/5}\right]-1 \cdot \quad (5b)$$

To proceed, we assume that variations in Rb vapor density affect the intensity of lamplight, but not the spectrum (i.e., no increase or decrease in the degree of radiation trapping in the lamp); so that using Eq. (1) we have

$$\Delta y = \alpha_{LS}\left[e^{\left(\frac{980}{T_o^2}\left(\frac{\delta P_{rf}}{P_o}\right)\left(\frac{P_{rf}}{P_o}\right)^{-3/5}\right)}-1\right]. \quad (6)$$

Figure 5 shows the results of Eq. (6) for three different nominal lamp temperatures: 75 °C, 100 °C, and 125 °C. In all cases, we find that the clock's sensitivity to lamp rf-power variations is ~ -1.0×10^{-14}/%. Though small, this is certainly non-negligible, and gives one pause as to whether or not lamp rf-power variations might not have been the cause of the lamp intensity jumps illustrated in Fig. 1.

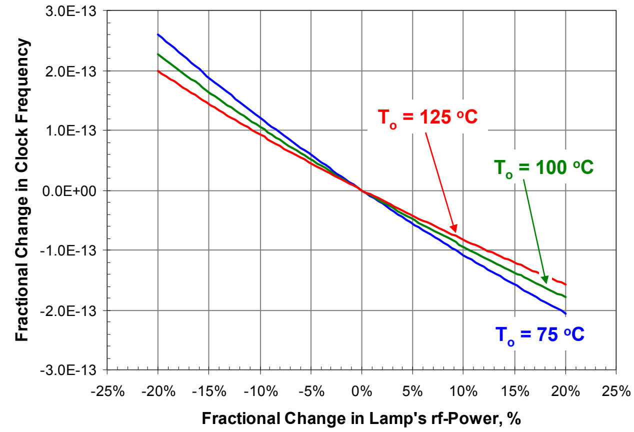

Figure 5. Estimation of the effect of lamp rf-power variations on Rb clock frequency.

IV. SUMMARY

In this work, we have examined the effect of lamp rf-power variations on the Rb rf-discharge lamp's operation. Principally, it appears that such power changes affect the Rb vapor density, and hence the intensity of Rb lamplight available for optical pumping. Concomitantly, changes in the intensity of the lamplight will affect the clock frequency via the light-shift effect, and we predict a clock sensitivity to lamp rf-power variations of ~ 10^{-14}/%.

ACKNOWLEDGMENT

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