Laser Polarization Noise & CPT Atomic Clock Signals

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***Abstract*— In the typical CPT clock, circularly polarized light creates a superposition state between the two $m_F = 0$ ground state sublevels via a common $m_F = +1$ (or $m_F = -1$) excited state. If the laser polarization suddenly changes, the common excited state will change (e.g., $m_F = +1 \rightarrow m_F = -1$). This introduces a transient into the CPT signal, which can degrade the clock's signal-to-noise ratio. Here, we present preliminary results from our experiments examining this issue. In particular, we find that a change in laser polarization leads to a transient change in the CPT signal via two processes. The first appears to be associated with the re-establishment of an equilibrium electronic spin polarization in the vapor, $\langle S_z \rangle$, which in a four-level model of the CPT signal can be thought of as a re-establishment of the "trapping state" population; the second process is still under investigation. Each of these processes has a unique timescale, and both will be important for understanding a CPT signal's response to laser polarization noise.**

I. INTRODUCTION

The intensity-optically-pumped (IOP) vapor-cell atomic clock and the coherent-population-trapping (CPT) atomic clock each have their own strengths. In the IOP clock the physics package consists of a diode laser, a glass resonance cell containing an alkali vapor along with a buffer gas, a microwave cavity housing the resonance cell, and a photodiode [1]. Light from the diode laser optically pumps the alkali, creating a population imbalance between the hyperfine states, and as a result the number of atoms in the absorbing state is reduced and the transmitted light intensity is maximized. If microwaves of the appropriate frequency are introduced into the cavity, atoms are forced to return to the absorbing state with a subsequent decrease in the transmitted light intensity. As is well known, this reduction in transmitted light is gainfully employed in the clock to lock the frequency of a quartz crystal oscillator to the atomic hyperfine energy level spacing. Obviously, one significant advantage of the IOP clock is its heritage: for the most part the physics of the clock's operation and the physical origins of important frequency shift processes are reasonably-well understood.

In the CPT clock, the microwave atomic signal is generated in an all optical fashion [2]. Sidebands are placed on the optical carrier at one-half the ground state hyperfine resonance frequency, and when the separation between the two sidebands matches the ground state hyperfine splitting, both levels are simultaneously coupled to the same excited state. In this situation, the excitation pathways destructively interfere, and with reduced absorption the transmitted intensity of the laser light increases. Again, the transmitted light acts as a monitor of the atom's interaction with a microwave frequency, and is employed to lock the frequency of a quartz crystal oscillator to the atom's ground state hyperfine splitting. An obvious advantage to this design is that the microwave cavity is eliminated. Hence, fundamental limits on the size of the device change from microwave wavelengths to optical wavelengths, and this has led to the recently realized chip-scale atomic clock [3]. Elimination of the microwave cavity has additional advantages, since with its removal go all microwave power shifts that can give rise to frequency instability [4]. In particular, effects like alkali surface migration on the resonance cell's glass walls, which affect the microwave cavity Q, are eliminated [5]. Moreover, fewer components usually translate into greater device reliability.

Though each of these devices has unique advantages, we should not overlook their common novelty: each uses diode lasers to generate an atomic clock signal. Though one might imagine that the use of diode lasers poses no new questions for the basic field/atom interaction, it must be remembered that in atomic clocks we are often considering signal-to-noise ratios in excess of 10^4. Thus, "small" noise processes can have very important consequences. As a case in point, it was originally thought that simply replacing the discharge lamp in a vapor-cell clock with a diode laser would lead to considerable improvement, and in fact atomic clock signals were seen to increase by an order of magnitude with the replacement… however, the noise increased by two orders of magnitude [6]. After several years of study, researchers finally came to realize that there was a subtlety to the basic field/atom interaction: the act of photon absorption invariably translates the field's phase noise into transmitted intensity fluctuations [7,8]. Moreover, recent work has suggested that a diode laser's mode partition noise may also be an important consideration for clock performance [9].

In the CPT clock, laser polarization is crucial to obtaining the clock signal. As an example, Fig. 1 shows a typical realization of the rubidium CPT clock. The laser light is circularly polarized and connects the (F=2, m_F=0) and (F=1, m_F=0) ground state Zeeman sublevels to the (F'=2, m_F=+1) Zeeman sublevel of the $5^2P_{1/2}$ excited state. This "lambda-system" coupling creates a coherence between the two $m_F = 0$ ground state sublevels, which is at the heart of the CPT atomic clock signal. However, if the circular polarization were suddenly to switch from right-circularly polarized to left-circularly polarized and then back again, a transient would be introduced into the CPT signal, which would manifest itself as clock-signal noise. Since VCSEL lasers are susceptible to laser polarization fluctuations [10], this potential noise process could be of considerable relevance to chip-scale atomic clocks.

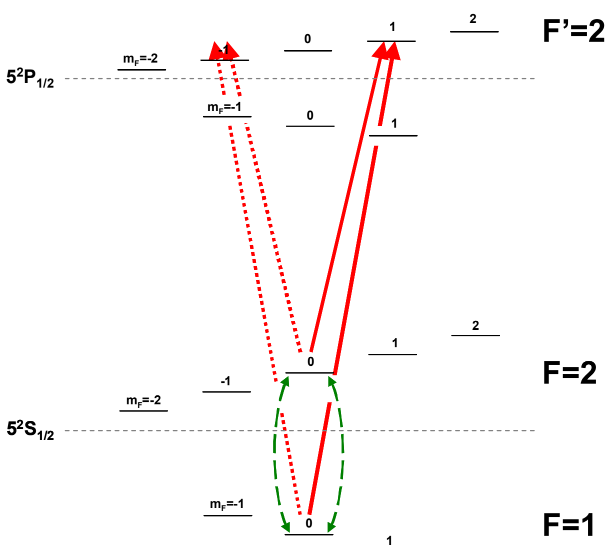

Figure 1. In an illustrative realization of the CPT clock signal process, the two $m_F = 0$ Zeeman sublevels of the ground state are connected to the $m_F = +1$ Zeeman sublevel of the excited state. A sudden variation in laser polarization will change the common excited state from $m_F = +1$ to $m_F = -1$, and will thereby give rise to transients in the CPT clock signal.

In the present work, we explore the nature of the transient change in a CPT atomic clock signal when the laser's polarization suddenly changes from right-circularly polarized to left-circularly polarized. As we will show, there appear to be two timescales inherent in this transient, which we will refer to as the γ_s-process (i.e., slow) and the γ_f-process (i.e., fast).

II. Experiment

Figure 2 shows our experimental arrangement. The output of a cleaved-facet Fabry-Perot diode laser passes through an electro-optic modulator, which places sidebands on the laser. (This is not shown explicitly in the figure, but is simply indicated as a 3.4 GHz signal input to the diode laser.) The modulated field then passes through a ferroelectric liquid crystal polarization switch that has a bandwidth of 10 kHz. This polarization switch can be thought of as a linear polarizer whose orientation changes by ninety degrees depending on an applied voltage. The field then passes through a quarter-wave plate, creating right or left circularly polarized light. The laser sidebands are first tuned to the CPT signal resonance, and we monitor the change in transmitted light intensity, I(t), with a photodiode, averaging the system's transient response to a polarization change using an averaging oscilloscope. The experiment is then repeated with the sidebands detuned by 1 MHz. Since the Doppler broadening is ~ 500 MHz, the laser sidebands are still in resonance with the optical transition, but at this detuning the coherent nature of the lambda transition is non-existent.

A real difficulty in the experiment relates to the data manipulation. We first extract the exponential attenuation coefficient of the vapor: $N\sigma L = \mathrm{Ln}[I(t)/I_o]$, where N is the number density of absorbing atoms, σ is the absorption cross section, and L is the length of the vapor. We then fit the attenuation coefficient to a sum of exponentials:

$$N\sigma L = A_o + \sum_j A_j e^{-\gamma_j t} \, . \qquad (1)$$

Theoretically, there may be a fairly large number of exponentials describing the transient in the case of Rb^{87} [11]. To determine the number of terms that actually do contribute to our transients, we perform a non-linear least squares fit to a variable number of summed exponentials. We constrain the number of terms in this sum by requiring that each exponential contribute more than 10 percent to the transient's amplitude. Our purpose with this constraint is to keep spurious terms, which might arise in the non-linear fitting algorithm, from too greatly influencing the results. Our experimental results consistently indicate that there are no more than two exponential terms contributing to the transient.

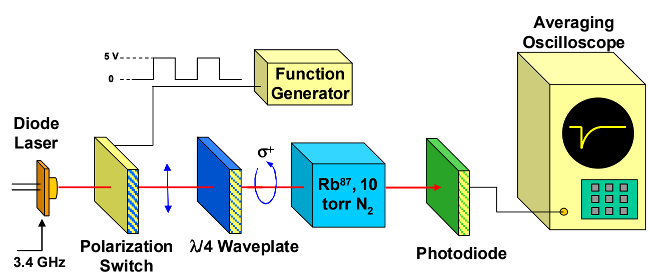

Figure 2. Experimental arrangment as described in the text. Though not shown, we phase modulate the field at 3.4 GHz by passing the diode laser output through an electro-optic modulator. The resonance cell contains 10 torr of N_2 as a buffer gas, and sits in a static magnetic field of 0.9 G supplied by Helmholtz coils. The cylindrical resonance cell is 3.9 cm long and is maintained at 46 °C.

III. Results

Figure 3 shows a typical transient with the sidebands tuned away from the CPT resonance. For the data shown in the figure, the laser intensity was chosen so as to maximize the relative CPT amplitude (i.e., $\Delta I/I_o$). The time constant for this decay was 11 msec (i.e., $\gamma = 94$ sec^{-1}), and as the data clearly show this transient is well described by a single exponential out to $t = 4/\gamma$. As shown in Fig. 4, a very different situation occurs when the sidebands are tuned onto the CPT resonance. In this case, at the exact same laser intensity, the non-linear least-squares fit indicates that two exponentials contribute to the transient: a "slow" exponential term with $\gamma_s = 77\ sec^{-1}$, and a "fast" exponential term with $\gamma_f = 414\ sec^{-1}$. In all cases of laser intensity that we have examined, we obtain a two-exponential fit when the sidebands are tuned to the CPT resonance.

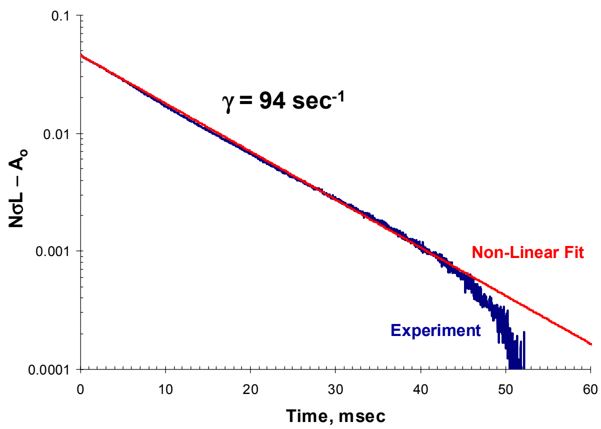

Figure 3. Transient change of the vapor's attenuation coefficient when the laser sidebands were tuned *1 MHz away* from the CPT resonance condition. The laser intensity was chosen to maximize the relative CPT amplitude.

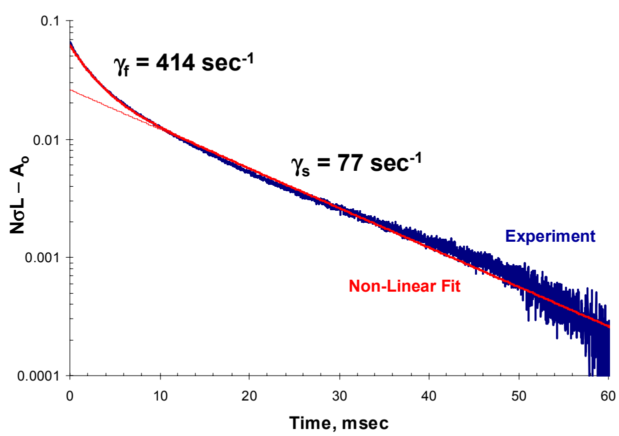

Figure 4. Transient change of the vapor's attenuation coefficient when the laser sidebands were tuned *onto* the CPT resonance condition. As with Fig. 3, the laser intensity was chosen to maximize the relative CPT amplitude.

IV. Discussion

The γ_s-process (sidebands tuned onto resonance) is likely associated with the same process that drives the transient in the off-resonance case. Though the rates are numerically different in the examples of Figs. 3 and 4, they are nonetheless similar, and preliminary results show that at low laser intensity γ_s and the off-resonance decay rate converge to the same numerical value.

Since circularly polarized photons carry one unit of angular momentum, the absorption of circularly polarized light creates an electronic spin polarization in the vapor, $\langle S_z \rangle$, which leads to the necessity of including a trapping state in the analysis of CPT atomic clock signals [12]. If the state of circular polarization changes, then $\langle S_z \rangle \rightarrow -\langle S_z \rangle$ and there is an increase in photon absorption by the vapor until the new equilibrium in spin polarization is achieved. Consequently, in order to understand CPT noise that is associated with laser polarization fluctuations, we must recognize that there are actually *two* trapping states (i.e., the analysis of CPT clock signals requires a five-state model). As the laser polarization fluctuates, atomic population transitions between these two distinct trap states and this gives rise to transmitted intensity noise.

With regard to the γ_f-process, we are less sure of its physical origin. Though one might argue that this must be associated with the 0-0 hyperfine coherence, we doubt that this is the case. Preliminary results indicate that while the linewidth of our CPT resonances increases linearly with laser intensity, we find that γ_f saturates at high laser intensities. Further, at low laser intensities it does not appear that our linewidths and γ_f converge to the same value. Like the γ_s-process, we believe that the γ_f-process is associated with an atomic population realignment following a laser polarization change. Unfortunately, more cannot be said without further study.

The final question to be addressed here concerns the magnitude of the transients. Specifically, what is the magnitude of the transmitted light intensity relative to the amplitude of the CPT signal when the laser polarization changes? If the amplitude of the transient were some very small fraction of the CPT amplitude, then the transient's presence would likely have little effect on the signal-to-noise ratio of a chip-scale atomic clock.

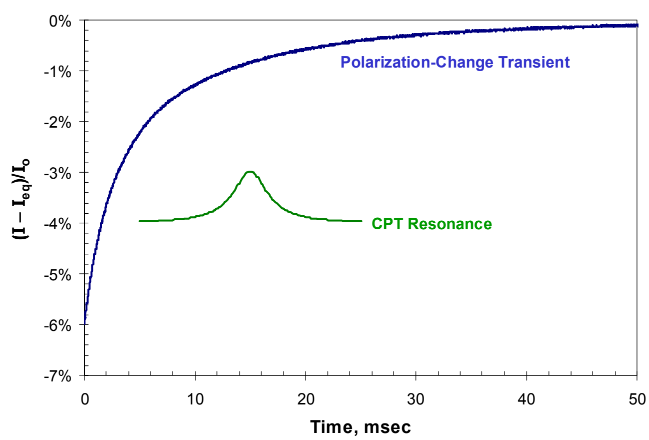

Figure 5. Transient change of the light intensity transmitted by the vapor for the laser intensity that maximized the relative CPT amplitude. For comparision, the CPT resonance under these conditions is also shown.

Figure 5 shows the change in transmitted light intensity following a polarization change for the laser intensity that maximized the relative CPT amplitude. Also shown on the same scale is the CPT resonance. As is easily discerned, the transient's amplitude is about six times larger than the CPT resonance's amplitude. At all laser intensities that we investigated, the transient amplitude was several times larger than the CPT resonance. Thus, even very short-lived changes in the laser polarization could have very serious consequences for a CPT clock's signal-to-noise ratio.

V. Summary

In this work, we have examined the transient response of Rb^{87}, under lambda-type excitation, to a laser polarization change. With the sidebands tuned to the CPT resonance, we find that the transient is described by two processes, a slow γ_s-process and a fast γ_f-process. While the γ_s-process is likely associated with population transfer between trapping states, we have yet to identify the physical mechanism associated with the γ_f-process. We also examined the magnitude of the transient change in transmitted laser intensity relative to the CPT resonance amplitude, and in all cases the transient change was several times larger than the CPT resonance. We therefore believe that a VCSEL's polarization fluctuations could be an important process influencing chip-scale atomic clock stability.

Acknowledgement

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