EFFECTS OF POLARIZATION FLUCTUATIONS IN CPT-BASED ATOMIC CLOCKS

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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 also 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.

INTRODUCTION

In the CPT clock, the microwave atomic signal is generated in an all optical fashion **[1]**. Briefly, sidebands are placed on the optical carrier at one-half the frequency corresponding to the ground state hyperfine splitting. When the separation between the two sidebands matches the ground state hyperfine splitting, both levels are simultaneously coupled to the same excited state. It is a feature of the atom's quantum nature that excitation pathways interfere, and when the two hyperfine states are coupled to the same excited state in this fashion, the pathways interfere destructively (i.e., the atoms cannot absorb photons). If the atoms cannot be excited, there is no scattering of the laser light, and consequently the intensity of light transmitted by the vapor increases. The transmitted light thereby acts as a monitor of the atoms' interaction with a microwave frequency (i.e., the laser sideband separation), and can be used to lock the frequency of a quartz crystal oscillator to the atom's ground state hyperfine splitting.

The obvious advantage to this design is that the microwave cavity is eliminated. In addition to allowing for "chip-scale" atomic clocks **[2]**, elimination of the microwave cavity removes a number of microwave power shifts that can give rise to frequency instability **[3,4]**. 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 in general translates into greater device reliability. Though the CPT clock has real advantages over the conventional laser-pumped atomic clock, its novel nature suggests that it may be subject to new processes that play little, if any, role in the conventional laser-pumped clock. One of these is the effect of laser polarization fluctuations on the CPT clock signal, which the present work was initiated to investigate **[6]**.

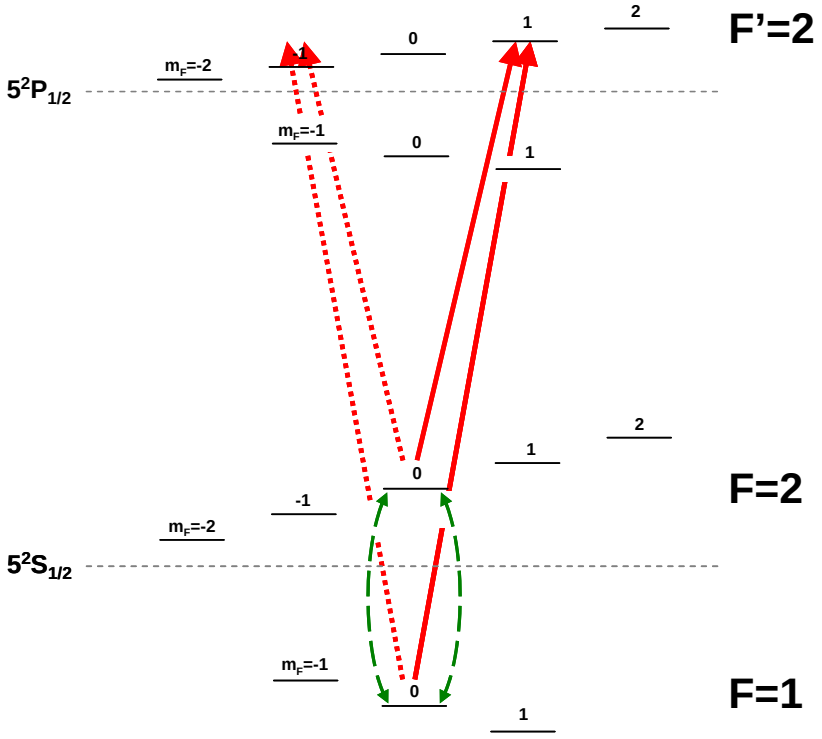

Figure 1. In an illustrative realization of the CPT clock signal process, the two $m_F = 0$ Zeeman sublevels of the ground state are connected to the $m_F = +1$ Zeeman sublevel of the excited state. A sudden variation in laser polarization will change the common excited state from $m_F = +1$ to $m_F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

In the most 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 is known as the 0-0 transition.) As is well-known, this "lambda-system" coupling creates a coherence between the $m_F = 0$ ground state sublevels, which is at the heart of the CPT signal. If the circular polarization switches from right-circularly polarized light to left-circularly polarized and back again, a transient will be introduced into the CPT signal, which will appear as CPT atomic signal noise.

The question, of course, is why we would expect the polarization of the laser field to switch. In the simplest CPT atomic clock design, a vertical cavity surface emitting laser (VCSEL) is employed. The emission of the laser light is linearly polarized and passes through a quarter-wave plate, creating (for example) left-circularly polarized light, which in turn generates the CPT signal. VCSELs are the laser of choice, given their very low threshold currents; this has advantage for chip-scale atomic clocks. The problem, however, is that VCSELs are subject to polarization noise: the laser can change its linear

polarization abruptly by ninety degrees **[7]**. The change in linear polarization will change left-circularly polarized light to right-circularly polarized light; and as mentioned in regard to Fig. 1, this sudden change in polarization results in CPT signal transients. The real question, of course, is whether these transients are truly problematic for clock operation. The specific purpose of our recent work has been to try to understand the seriousness of this potential problem, and (if necessary) to devise mitigation strategies.

EXPERIMENT AND RESULTS

As illustrated in Fig. 2, our experiment is fairly straightforward. We start with a cleaved-facet Fabry-Perot diode laser, which does not suffer from intrinsic polarization fluctuations. Though not shown in the figure, the laser light passes through an electro-optic modulator (EOM). The EOM places sidebands on the laser field at 3.4 GHz. The modulated and linearly polarized field then passes through a ferroelectric liquid crystal polarization rotator that has a bandwidth of 10 kHz. This polarization rotator changes the field's polarization 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 is tuned to the CPT resonance, and we monitor the change in transmitted light intensity with a photodiode, averaging the system's transient response to a polarization change using an averaging oscilloscope.

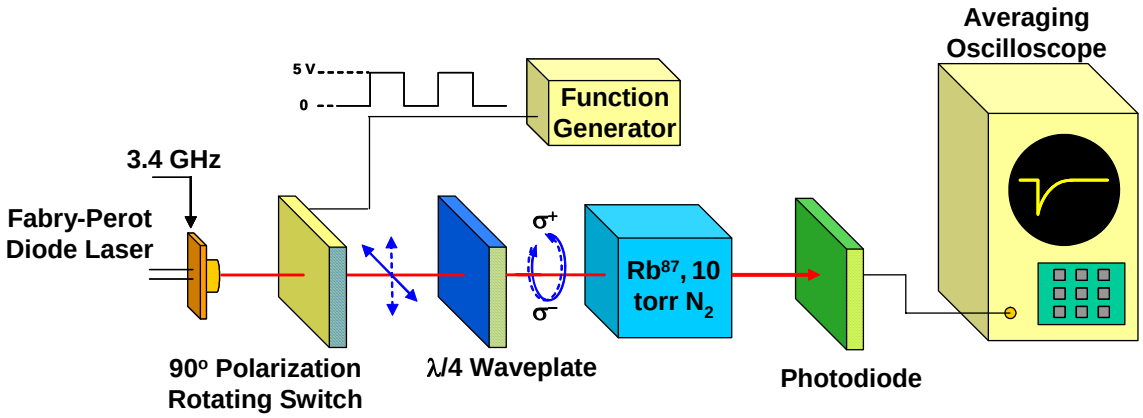

Figure 2. Experimental arrangement. Though not shown, we phase-modulate the field at 3.4 GHz by passing the diode laser output through an electro-optic modulator. The resonance cell contains 10 torr of N_2 as a buffer gas, and sits in a static magnetic field of 0.9 G supplied by Helmholtz coils. The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

The real difficulty in the experiment is the data manipulation. We first transform the data using the law of exponential attenuation (i.e., the Beer-Lambert law) in order to obtain information on the exponential attenuation coefficient, $N\sigma L$. (N is the number density of absorbing Rb^{87} 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 exponential terms. Theoretically, there may be up to eight terms describing the transient in the case of rubidium. To determine the number of terms that actually make the dominant contribution to the transient, we perform a nonlinear least-squares fit to 99.5% of the transient change. Additionally, we require that any exponential term contribute ten or more percent to the transient. Our purpose with this last restriction is to keep spurious terms that might arise in the nonlinear fitting procedure from too greatly influencing our

results. In no cases have we needed more than two exponential terms to describe the transient signal.

As discussed previously **[6]**, we measure the transient change with the sidebands tuned "off-resonance" (~ 1 MHz) and the sidebands tuned "on-resonance." In the off-resonance case, we can understand the major portion of the transient change as due to the generation of electronic and nuclear spin polarization, $\langle S_z \rangle$ and $\langle I_z \rangle$, within the vapor. Briefly, the angular momentum carried by the laser light is transferred to the atom through the photon absorption process, and this creates a macroscopic magnetic dipole moment in the vapor that is associated with a nonuniform population distribution among the atoms' Zeeman sublevels. When the laser polarization changes, the angular momentum transferred to the atom changes and as a result the macroscopic magnetic dipole moment changes its orientation by 180 degrees.

In contrast to the off-resonance case, where a single exponential decay term often provides the best fit to the transient response of the vapor, the *on-resonance* transient requires two exponential terms to describe its behavior in all cases that we have examined. The decay rates of the two transients are quite different, with one of the rates typically about five times greater than the other. At the present time, we are trying to understand the origin of the "fast" exponential term. The slower exponential term is most likely associated with the same reorientation of $\langle F_z \rangle$ that we observe in the off-resonance case.

Figure 3 shows the "slow" rate for the polarization transient, γ_a, as a function of light intensity. Consistent with expectations, if we associate γ_a with $\langle F_z \rangle$ reorientation, in the off-resonance case γ_a is a linear function of light intensity. Moreover, at low light intensity levels, γ_a is the same for the on-resonance and off-resonance cases. At high light intensity, γ_a appears to saturate in the on-resonance case. The inset shows the relative amplitude of the CPT atomic clock signal as a function of laser intensity, indicating that the peak signal corresponds to a light intensity where γ_a for the sidebands tuned off-resonance and γ_a for the sidebands tuned on-resonance just begin to differ. (The dashed lines are simply meant as aids to guide the eye.)

Figure 4 shows the "fast" rate, γ_b, for the polarization transient as a function of light intensity (i.e., blue and brown data), along with the linewidth of the CPT resonance (i.e., yellow data), which corresponds to the 0-0 transition dephasing rate. Note that we see a fast transient even with the laser tuned off-resonance. This observation, together with the fact that the on-resonance fast rate does not scale with light intensity like $\Delta\nu_{1/2}$, suggests that γ_b may not be equivalent to the 0-0 dephasing rate. Our working hypothesis is that γ_b corresponds to the reorientation of a high-order state-multipole of the Rb^{87} atom's ground state population distribution **[8]**. Similar to Fig. 3, the inset shows the relative amplitude of the CPT resonance as a function of laser intensity, indicating that the peak signal corresponds to a light intensity where γ_b off-resonance is no longer present and γ_b on-resonance and $\Delta\nu_{1/2}$ are very nearly equal. (Dashed lines are simply meant as aids to guide the eye.)

SUMMARY

We have investigated the change in a CPT atomic clock signal when the laser polarization changes abruptly. For the case of the laser sidebands tuned on resonance, the transient is best described by two exponential terms in all cases with two very different decay rates. Though not discussed here, but noted elsewhere **[6]**, the amplitude of the transient is significantly larger than the CPT signal itself. Based on these results, we can say that laser polarization noise is of significance for chip-scale atomic clocks and that laser polarization noise will affect a CPT clock's signal-to-noise ratio up to Fourier frequencies of ~ 10^3 Hz. Our plans are to continue this work in order to gain a better understanding of the mechanisms associated with γ_a and γ_b.

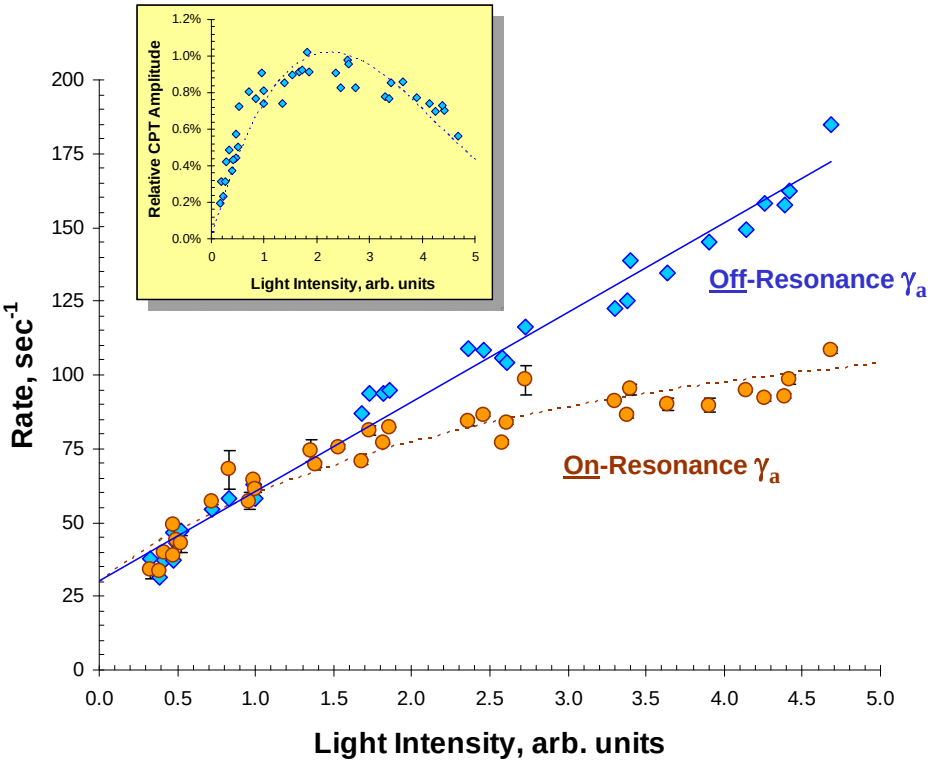

Figure 3. The "slow" decay rate, γ_a, for the cases of the sidebands tuned off-resonance and on-resonance as a function of relative light intensity. The inset shows the amplitude of the CPT signal as a function of relative light intensity. The dashed line is simply an aid to guide the eye.

ACKNOWLEDGMENT

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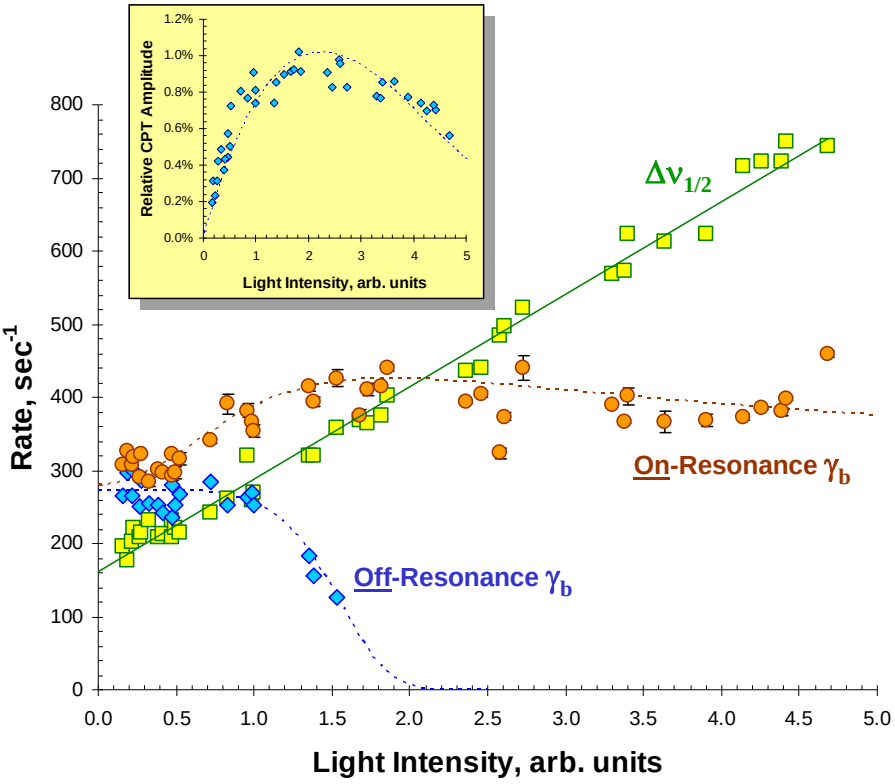

Figure 4. The "fast" decay rate, γ_b, for the cases of the sidebands tuned off-resonance and on-resonance as a function of relative light intensity. The inset shows the amplitude of the CPT signal as a function of relative light intensity. The dashed lines are simply aids to guide the eye.

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