New Method For Light-Shift Elimination

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***Abstract*— We present a new method to eliminate the light shift in atomic frequency standards and other optical pumping systems. This method uses only frequency modulation of a radio frequency or microwave source in order to simultaneously lock the source frequency to an atomic resonance and lock the pumping light to eliminate the light shift. In contrast, conventional stabilization of both sources requires two individual modulation schemes and feedback loops, adding complexity. Our method kills two birds with one stone. The method uses fewer additional components and offers improved performance, reduced cost, and easier miniaturization than previous methods. In particular, few modifications are required for implementation in conventional vapor-cell atomic clocks. We believe this technique will be useful for atomic frequency standards and other optical pumping systems that experience the light shift.**

I. Introduction

The light shift refers to the frequency shift of an atomic resonance due to the dynamic (or AC) Stark effect from optical pumping light [1]. The shift depends on both the frequency and intensity of the light. The light shift is an important source of error in many optical pumping systems. In particular, it is one of the main performance limitations in atomic frequency standards (or clocks), since it turns the fluctuations of the pumping light frequency and intensity into drift and noise in the clock output. This is one reason it is difficult to implement atomic frequency standards with diode lasers. Accordingly, understanding and reducing the light shift in optical pumping systems remains an active area of research [2]–[5].

There are various ways to suppress or eliminate light shifts. One simple technique for monochromatic pumping sources, such as diode lasers, is to tune them to a zero-shift optical frequency or "magic wavelength" that produces no light shift [1]. The zero-shift frequencies are very close to the peaks of the optical absorption lines. The conventional method to eliminate light shifts in laser-pumped frequency standards uses an additional feedback loop to lock the laser to a zero-shift frequency [6]–[8]. In the method we describe here, we use the same feedback loop that locks the local oscillator to the microwave resonance frequency of the atoms to simultaneously adjust the laser frequency to eliminate the light shift.

II. New Method

Conventional atomic frequency standards use a frequency-modulated (FM) microwave field to lock the microwave carrier frequency (the local oscillator) to an atomic resonance (the clock frequency). This is depicted in Fig. 1. When the carrier frequency is off-resonance, the pumping light emerging from the vapor will be modulated at the 1st harmonic of the FM rate. This 1st harmonic component (the signal) is normally detected with a lock-in amplifier and used as an error signal to lock the carrier to the atomic resonance.

We were surprised to find that there were often different microwave zero-crossing frequencies for the in-phase and out-of-phase (quadrature) channels of the lock-in amplifier. We found that if the pumping laser was tuned to a zero-shift frequency, then the microwave zero-crossing frequency was insensitive to the lock-in amplifier phase.

Due to absorption and the beam profile, the pumping light intensity is not uniform throughout a vapor cell. Light-intensity gradients lead to regions in the cell with different light shifts and different light-induced broadening, as shown in Fig. 2. For stronger light intensities than typical in clocks, this leads to the inhomogeneous light shift [9]. These different regions have different resonance frequencies due to the light shift, and experience different effective FM rates due to linewidth broadening.

Usually the FM rate is comparable to the atomic linewidth, leading to significant phase distortion in the signal that depends on the linewidth, the carrier detuning and the FM parameters. As a result, when there is a light shift, the signal amplitude will not vanish for any carrier frequency, or in other words, there will be no choice of carrier frequency for which both lock-in channels vanish. When the in-phase channel is used to lock the local oscillator, the quadrature channel output

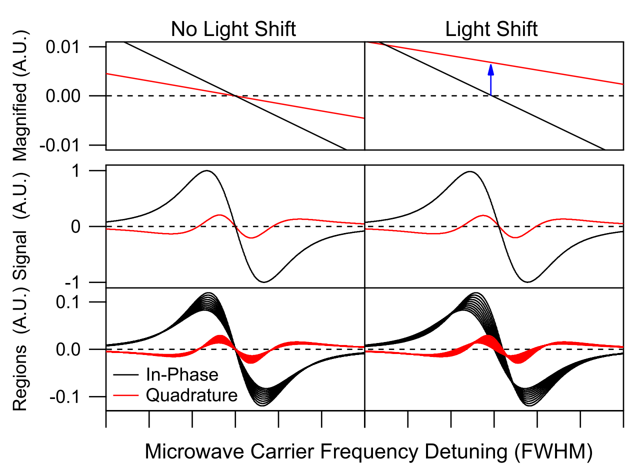
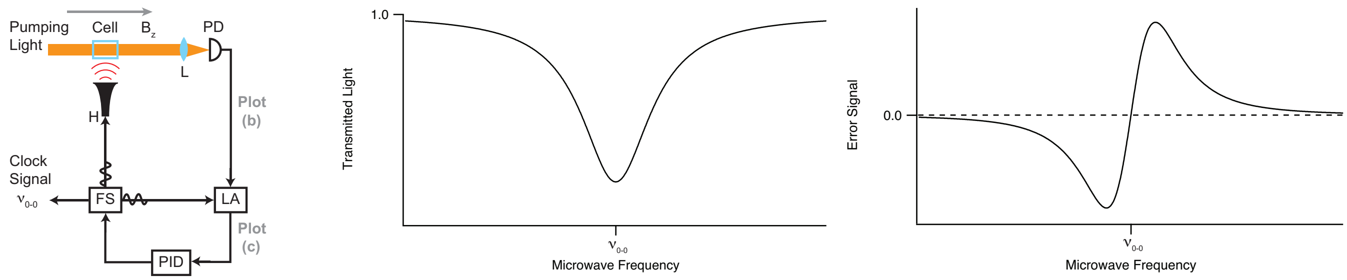


Fig. 2. Modeling of lock-in channel outputs versus microwave carrier frequency, where the in-phase channel is optimized as the microwave error signal. An array representing the different regions in a cell with a light-intensity gradient is combined to obtain the total signal. The top panel shows the zero-crossing region of the middle row, with both axes magnified. The blue arrow indicates the quadrature channel output at the in-phase channel zero-crossing for the case with a light shift.



(a) Vapor-Cell Clock (b) Pumping Light Transmission (c) Microwave Error Signal

Fig. 1. Conventional vapor-cell atomic clock using frequency modulation to lock the microwave carrier frequency to the atomic resonance frequency $\nu_{0\text{-}0}$. B_z, applied magnetic field; L, lens; PD, photodetector; LA, lock-in amplifier; PID, PID controller; FS, frequency synthesizer; H, horn.

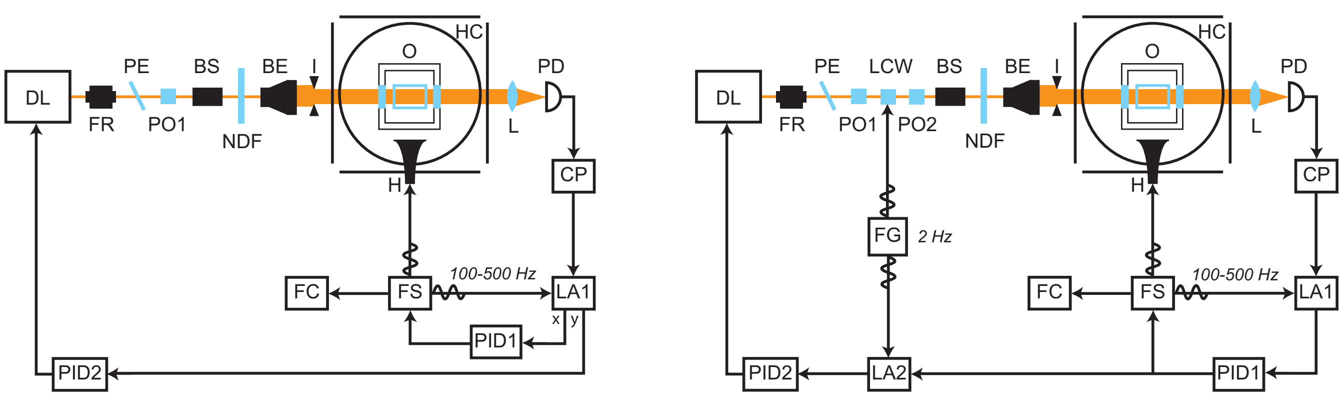
is proportional to the light shift near a zero-shift frequency. Therefore the quadrature channel may be used as an error signal to lock the pumping light to a zero-shift frequency.

III. Experiment

A comparison of the new method with the conventional, intensity-modulation method to eliminate the light shift in a laser-pumped, vapor-cell atomic clock is sketched in Fig. 3. Both methods use two different error signals to lock the local oscillator and to tune the laser to the zero-shift frequency. Both measure the light-field-independent ground-state hyperfine resonance frequency of ^{87}Rb atoms to about 1 Hz.

Alternating between the two configurations allowed direct comparison between both methods in the same setup. The experimental setup closely follows the description in Ref. [8]. The vapor cell is a cylindrical Pyrex cell, 17 mm in diameter and 25 mm long, filled with a small amount of ^{87}Rb metal. An external buffer-gas reservoir, pressure gauge, and vacuum port permit convenient changes of the buffer-gas species and pressure. An air-heated, non-magnetic oven (O) holds the cell at constant temperature between 35–65°C. Helmholtz coils (HC) cancel ambient fields and provide a static longitudinal field of about 0.2 G. A Toptica DL100 diode laser (DL) provides 795 nm D1 optical pumping light for ^{87}Rb. A Faraday rotator (FR) isolates the laser from back-reflected light. A pellicle (PE) skims off light for analysis with a wavemeter and a Fabry-Perot interferometer (not shown). Polarizers (PO) ensure that the pumping light is linearly polarized. When included, a liquid crystal wave plate (LCW) driven by a function generator (FG) provides about 30% intensity modulation of the pumping light at a rate of 2 Hz. A beam shaper (BS), a beam expander (BE), and an iris (I) ensure that the pumping light fills the cell uniformly. A rotatable neutral density filter (NDF) adjusts the pumping beam intensity. A lens (L) collects the transmitted pumping light onto a photodetector (PD). Microwaves from a frequency synthesizer (FS) are transmitted towards the cell by a horn (H) roughly 10 cm away to drive magnetic resonances. A frequency counter (FC) referenced to a rubidium frequency standard (not shown) measures the microwave frequency. The microwaves are frequency modulated at a rate of roughly 100–500 Hz with a modulation index of about 1. A lock-in amplifier (LA1) with a 10–300 ms time constant provides an error signal for a PID controller (PID1) to lock the microwave carrier frequency to the atomic resonance.

For implementation of the new method (Fig. 3(a)), the quadrature channel of LA1 provides an error signal for a PID



(a) New Method (b) Conventional Method

Fig. 3. Experimental setups with different light-shift elimination methods. DL, diode laser; FR, Faraday rotator; PE, pellicle; PO, polarizer; LCW, liquid crystal wave plate; BS, beam shaper; NDF, neutral density filter; BE, beam expander; I, iris; O, oven; H, horn; HC, Helmholtz coils; L, lens; PD, photodetector; CP, current preamplifier; LA, lock-in amplifier; PID, PID controller; FS, frequency synthesizer; FC, frequency counter; FG, function generator.

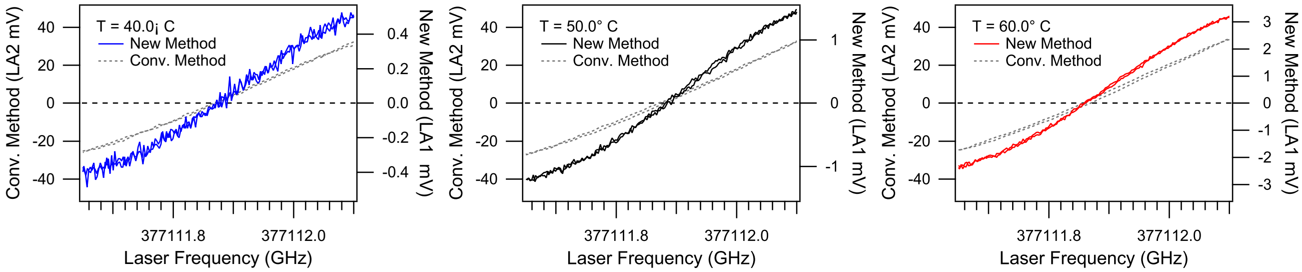


Fig. 4. Comparison of laser frequency error signals illustrating that the new method locks to the same frequency as the conventional method, which is a zero-shift frequency. The signal-to-noise ratio of the new method improved at higher temperatures due to increased cell optical thickness.

controller (PID2) to lock the laser to a zero-shift frequency. For implementation of the conventional method (Fig. 3(b)), a second lock-in amplifier (LA2) provides the error signal for PID2 by detecting modulation in the first feedback loop error signal due to intensity modulation from the LCW. Feedback adjusts the laser frequency through a piezoactuator. As a quick test for light-shift elimination, we used the NDF filter to temporarily adjust the laser intensity by a factor of 2–4 to verify intensity independence of the clock output.

To verify that the new method locks the laser to a zero-shift frequency, we measured the error signals from both the new and conventional methods as a function of laser frequency. Here, the cell was filled with 30.0 torr of N_2 (at 50.0°C). The error signals for each method were recorded separately with laser frequency sweeps in both directions, using a wavemeter to record the laser frequency to a precision of 0.01 GHz. Fig. 4 shows the results at 40.0°C, 50.0°C, and 60.0°C, which demonstrate that the error signals of both methods share the same zero-crossing frequency to within experimental error. Therefore both methods lock to the same zero-shift frequency. The data also illustrate how higher temperatures improve the signal-to-noise ratio for the new method, which results from increased cell optical thickness.

To compare the clock frequencies of the two methods, we measured the clock frequency as a function of N_2 buffer-gas pressure from 2.0 to 31.0 torr at 50.0°C. We first measured with the new method over the pressure range, and then with the conventional method after resetting the cell pressure. The pressure gauge recorded the cell pressure to an accuracy of about 0.01 torr below 4 torr and 0.25% above 4 torr. Table I lists the linear fit coefficients to the data. The results for both methods agree to within experimental error. Therefore, the clock frequencies of both methods agrees over a wide range of buffer gas pressure.

TABLE I
CLOCK FREQUENCY VERSUS N_2 BUFFER-GAS PRESSURE

	Intercept (Hz)	Slope (Hz/Torr)
New Method:	6,834,682,623.4 ± 4.5	506.14 ± 0.50
Conventional Method:	6,834,682,617.3 ± 4.1	507.34 ± 0.48

We measured the clock performance both with and without the new method engaged. For these tests we used a 27.1 torr buffer-gas mixture of N_2 and Ar at 52.6°C, optimized for zero-pressure shift since we were able to control temperature much better than pressure. Fig. 5 shows the Allan deviation for the data. The clock stability is significantly improved with the new method compared to a free-run system without laser feedback and light-shift elimination.

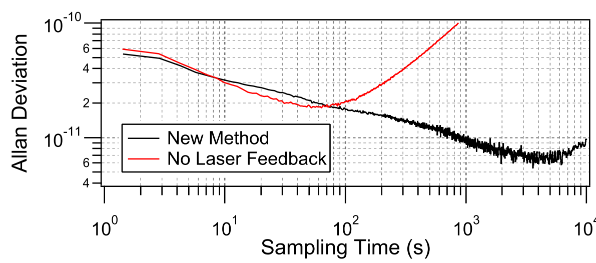


Fig. 5. Comparison of clock frequency stability with and without the new method of light-shift elimination.

IV. MODELING

We modeled this phenomenon in two numerical simulations: an approximate two-level system and an analogous damped simple harmonic oscillator. Both simulations combined an array of signals representative of regions in a cell with different light shifts and inhomogeneous broadening due to a light-intensity gradient. This is shown with the two-level model in Fig. 2. Both simulations agree qualitatively with experimental tests.

In particular, both experiment and modeling show that the selection of lock-in phase is not critical for the quadrature error signal, as shown in Fig. 6, where the different curves represent different laser frequency detuning from the zero-shift frequency. Here, the experimental values are for 30.0 torr of N_2 at 50.0°C, and the simulation values are for the two-level model. Additionally, both experiment and modeling reveal that the quadrature error signal changes sign with increased FM amplitude.

V. CONCLUSION AND FUTURE WORK

We have demonstrated a new method to eliminate the light shift in optical pumping systems, which can be readily applied

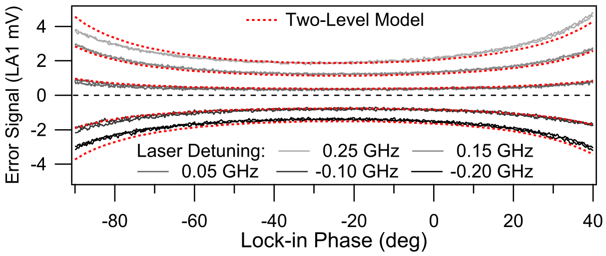


Fig. 6. Quadrature channel error signals for experiment and modeling versus lock-in phase, with the local oscillator locked. The different curves denote different fixed laser frequency detuning from the zero-shift frequency.

to existing atomic clocks with few additional components. The method uses only frequency modulation of an RF or microwave source in order to simultaneously lock the source to an atomic resonance and lock the pumping light to eliminate the light shift. In principle, this new technique can also work for CPT-interrogated clocks and other optical pumping systems that experience light shifts.

We have observed a small difference in clock frequencies between the new and conventional methods at low buffer-gas pressures, that is sensitive to the buffer-gas pressure, the microwave power, the choice of zero-shift frequency, and the cell temperature. We hope to further investigate this discrepancy in future work.

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