# MITIGATION OF THE LIGHT SHIFT IN LASER COOLED CLOCKS WITHOUT MECHANICAL SHUTTERS

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*Abstract* - **We propose an approach for keeping the light shift in laser cooled frequency standards down to the $10^{-17}$ level without the use of mechanical shutters. For laser systems using a master-slave laser configuration, cutting the injection power to a slave causes it to lase at its free-running wavelength, often two or more nanometers off from the atomic resonance. This approach does not apply to laser systems using power amplifiers.**
***Keywords* - Light shift, frequency standard, cesium**

## I. INTRODUCTION

We will discuss an approach for keeping the light shift in laser cooled frequency standards down to the $10^{-17}$ level in pulsed or quasi-pulsed standards such as atomic fountain standards or PARCS, the cesium clock planned to fly on the International Space Station in 2005. AC Stark shifts are potentially the largest shifts in such standards by far. This shift is most often eliminated by using mechanical shutters in the laser system to prevent light from entering the interrogation region during the Ramsey cycle. While effective and nominally simple, mechanical shutters are prone to failure in a time scale of months, with either complete failure (closed or open), or failing to close fully. For clocks on the ground this can be handled by replacing the shutter, but for space applications this is clearly not an option. The mechanical perturbations caused by shutters also create operational difficulties in such devices.

For laser systems using a master laser-slave laser configuration, cutting the injection power to a slave causes it to lase at its free-running wavelength, often two or more nanometers off from the atomic resonance primarily responsible for the shift. In a sense this mimics the effect of cutting the slave laser current without causing instabilities and damage to the diode from rapid changes in current. Keeping the optical power nearly constant while changing the frequency has additional benefits for fluorescence detection not discussed further in the paper.

In the PARCS laser system, an acousto-optic modulator (AOM) is used between the master and slave to adjust the slave frequency without varying its output amplitude. The slave is then followed by another aom for amplitude control as shown in Fig. 1. As the light shift is proportional to the light intensity and inversely proportional to the detuning, estimates shown in this paper suggest that 150 mW of nominal power in the trapping region will result in a shift below 2 x $10^{-17}$ by both cutting the power to the frequency control aom as well as the intensity control aom.

This scheme is being considered as a backup in case of shutter failure in PARCS. Small gain of near-resonant or

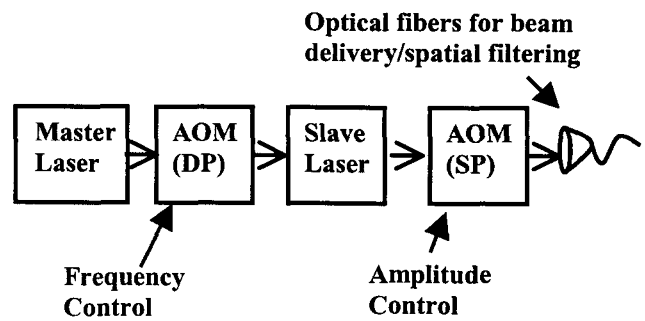


**Fig. 1** PARCS laser scheme, showing a master laser, Double Pass (DP) AOM for frequency control, Slave laser, and Single Pass (SP) AOM for amplitude control. Cutting the RF power to the DP AOM causes the slave to lase at its free running wavelength.

scattered light may limit the effectiveness of the technique as our estimates here assume that the laser output becomes a delta function in frequency far from resonance. Experimental verification of this scheme will be carried out on a cesium fountain in the near future. In this paper we will present calculations of the shift along with data supporting the assumptions in the calculation.

## II. MOTIVATION

In laser-cooled cesium and rubidium clocks, lasers are used to collect, manipulate and detect the state of atoms. Significant optical power is used in close proximity to the microwave interrogation region, and this laser light can cause shifts of the microwave clock frequency that are easily the largest in the standards. Optically pumped standards [2-5] suffer such light shifts and must operate with the laser light continuously present. Laser-cooled standards are usually although not always [6] operated in a pulsed mode, with the option of shuttering the laser light during microwave interrogation.

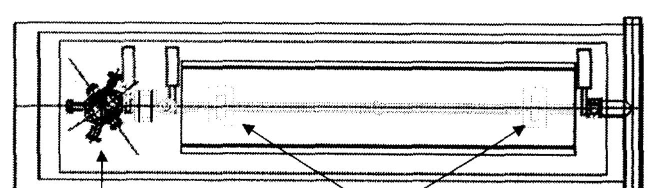


**Figure 2** Sketch of PARCS cesium standard, showing atom collection chamber with fiber-coupled laser ports and microwave interrogation region.

The relatively high optical power, large solid angle for scattered light, and high performance goals make light shifts potentially ruinous to such standards. The PARCS flight cesium standard, shown in Fig. 2, intends to use shutters for the atom beam and numerous shutters in the laser system to prevent light shifts, but as shutter failure would threaten mission failure, a backup operational scheme naturally occurring in our laser system is quite attractive.

The scale of the light shift for laser intensity near saturation and frequency close to resonance is the optical linewidth, approximately 5 MHz in cesium at 852 nanometers. The raw light shift on the 9.2 GHz clock transition in cesium is then of the order $5 \times 10^{-4}$ on a frequency standard being designed to reach an absolute accuracy of $5 \times 10^{-17}$. To be at the $2 \times 10^{-17}$ level therefore requires suppression by over 13 orders of magnitude. We achieve this with a numbers budget including scattered light fraction, attenuation with the single pass AOM, and large detuning for the slave lasers off resonance.

## III. Approach to Light Shift

It is our intention to estimate the light shift and to illuminate scalings, with the understanding that performance in a real system must be verified. The estimates here assume a delta function output of the laser frequency, while unsaturated gain near resonance would render the estimates invalid.

The general approach to the light shift here is to start with a value of the shift approximately equal to the optical linewidth for saturation intensity. The light shift then scales as the intensity and inversely with the detuning. For detunings large compared to the hyperfine splitting there is a further suppression factor for the differential shift between the two clock levels that scales as the hyperfine splitting divided by the detuning. This general scaling can be written out as

$$\text{Light Shift} \sim \text{Linewidth}\ \frac{\text{Intensity}}{\text{Detuning}}\ \frac{\text{Hyperfine}}{\text{Detuning}}\ . \qquad (1)$$

The intensity is a combination of the incident laser power, $P$, the fraction of light scattered into the solid angle of the interrogation zone, $S$, the attenuation effected by cutting the RF power to the single pass AOM used for amplitude control, $AOA$, and the effective cross section of the atom drift tube, $r_{eff}$. For a laser linewidth $\gamma/2\pi$ and detuning $\Delta\nu$, the light shift, $\delta\nu_{LS}$, is

$$\frac{\delta\nu_{LS}}{\nu_{Cs}} = \frac{\gamma/2\pi}{\nu_{Cs}}\ \frac{\dfrac{(P \bullet S \bullet AOA)}{\pi r_{eff}^2}}{C_t\, I_{sat}}\ \frac{\frac{1}{2}\gamma/2\pi}{\Delta\nu}\ \frac{\nu_{Cs}}{\Delta\nu}\ , \qquad (2)$$

where $\Delta\nu_{Cs} = 9.2$ GHz is the ground state hyperfine splitting corresponding to the clock transition and $C_t$, which is taken to be 2, scales the saturation intensity averaged over various

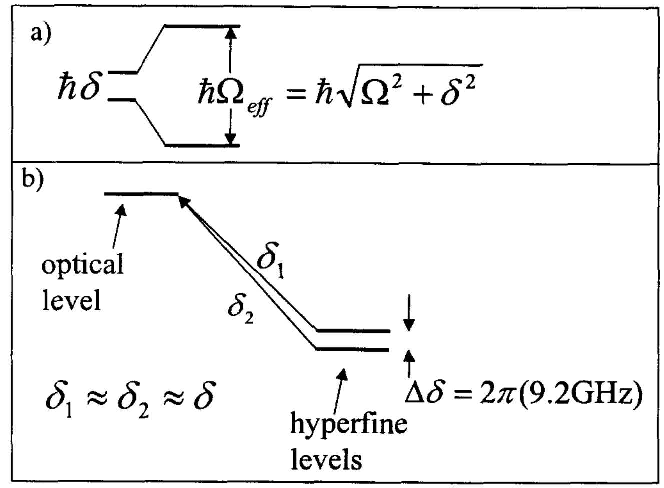


**Figure 3** a) The light shift is described as the effective Rabi splitting between the optical ground and excited states. B) The shift in the clock frequency is the difference between the light shifts of the two hyperfine levels.

transitions. Putting in the values from Table 1, the fractional light shift is below $1 \times 10^{-17}$.

We also considered a more formal approach using the dressed state picture of each ground state coupled to the optical excited state through the light [7]. This picture is shown conceptually in Fig. 3. Here $\delta/2\pi = \Delta\nu$ is the detuning

$$\Omega^2 = \frac{I}{2I_{sat}}\ \frac{\gamma^2}{2} \qquad (3)$$

and $\Omega$ is the applied Rabi frequency, where

and the 2 in front of $I_{sat}$ is again from the average Clebsch-Gordan coefficient. The light shift of a single ground state is

$$|\Delta E_{gs}| = \frac{1}{2}\hbar(\Omega_{eff} - |\delta|), \qquad (4)$$

then given by

and for $\delta >> \Omega$ the differential shift between the two hyperfine states is

$$\Delta(\Delta E_{gs}) = \frac{\hbar}{16}\frac{I}{I_{sat}}\frac{\gamma^2}{\delta^2}\Delta\delta. \qquad (5)$$

$$\frac{\delta\nu_{ls}}{\nu_{Cs}} = \frac{1}{16}\frac{I}{I_{sat}}\frac{\gamma^2}{\delta^2} \qquad (6)$$

From this we deduce that the fractional light shift is which is within a factor of four of our previous estimate.

**Table 1** Values used in estimation of the light shift.

| | |
|---|---|
| Shift (~linewidth, $\gamma/2\pi$) | 5 MHz |
| Input Optical Power, $P$ | 150 mW |
| SP AOM Attenuation, $AOA$ | -40 dB |
| Light Scattered to Atoms, $S$ | -40 dB |
| "Beam" radius, $r_{eff}$ | 0.75 cm |
| Detuning, $\Delta\nu$ | 827 GHz (2 nm) |
| Saturation Intensity, $I_{sat}$ | 1.1 mW/cm$^2$ |
| Saturation scaling factor, $C_t$ | 2 |

## IV. Supporting Measurements

We made a series of measurements in order to provide inputs into our model and to estimate the shift in a real device. These include measuring the spectrum of light emerging from a single pass AOM through an optical fiber; attenuation for several AOM configurations; a free running slave laser's spectrum; and the fraction of light scattered into the clock zone.

The fraction of scattered light, *S*, was measured to be below –40 dB using the atom-collection chamber prototype for PARCS. Two opposing collimators were attached to the collection cube, and the power coming out of the atom extraction port was measured on a photodiode and assumed to be transmitted without loss to the microwave interrogation region. The chamber is shown in Fig. 4 with only a single collimator attached. The chamber is made of uncoated titanium and the windows are synthetic quartz with a 0.15% per surface anti-reflection coating. The collimators are slightly overfilled with light, which likely increases the amount of scattered light.

The various test configurations for AOM performance are shown in Fig 5. The results for overall optical throughput efficiency and attenuation achieved by cutting the RF power to the AOMs are shown in Table 2. We find that a single pass AOM plus optical fiber arrangement can provide ~50 dB of attenuation, two single passes in series provide 100 dB of attenuation despite the fact that we only benefit from spatial filtering of the optical fiber once at the end of the optical chain. Other options for obtaining more than 50 dB of attenuation (2$^{nd}$ order single pass and double pass) were investigated but less effective either in terms of loss efficiency or attenuation or both. The single pass second order efficiency seems anomalously low and may result from lack of optimization of the RF power and beam shape.

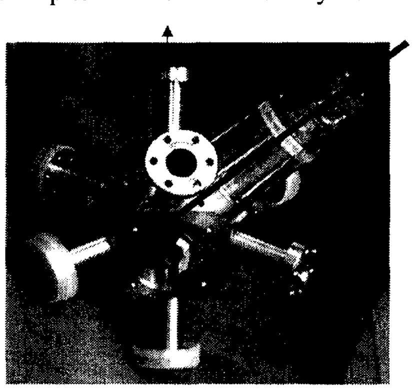

**Figure 4** The fraction of light scattered along the atomic trajectory was measured on the PARCS prototype atom-collection chamber to be less than 7 x 10$^{-5}$.

**Table 2** AOM configuration efficiencies. The 2$^{nd}$ order single pass configuration was likely not optimized.

| AOM Configuration | Total Light Attenuation | Total Efficiency |
|---|---|---|
| Single Pass (1$^{st}$ order) | 47-56 dB | 60-80% |
| Single Pass (2$^{nd}$ order) | 53 dB | 4% |
| Double Pass | 72 dB | 36-64% |
| 2 Single Passes in Series | 100 dB | 36-64% |

The optical spectrum for the light launched into the fibers with and without RF power to the AOMS was verified by beating the output light against a separately injected slave laser and viewing the beat note on a spectrum analyzer. Leakage was dominated by 0$^{th}$ order light scattered into the fiber and was roughly 50 dB below the 1$^{st}$ order carrier. The magnitude of the 0$^{th}$ order scattered light was largely independent of RF power applied to the AOM.

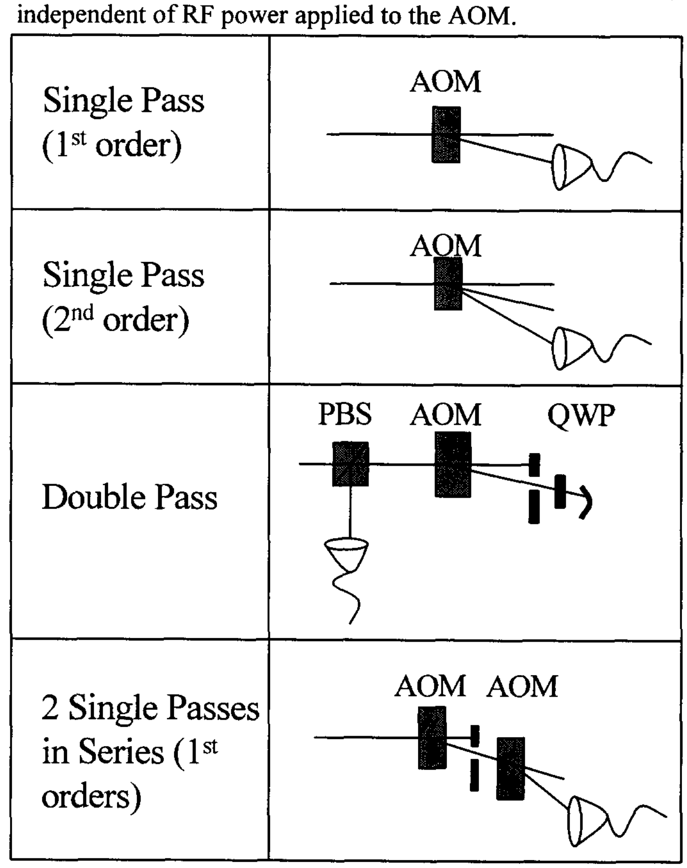


**Figure 5** AOM test configurations.

We also performed this type of heterodyne test for the output of a free running slave laser beat against a separately injection locked slave to test for spurious power close to resonance. The free running slave was first injection locked to be certain it would support light close to resonance, and then had the optical injection signal cut. We saw no evidence of coherence between the two lasers at the limit of our measurement resolution (80 dB below the carrier out to 6 GHz), except for an intermittent broad peak, 10-100 MHz wide near 1.5 GHz, 40-60 dB below the carrier level. Spurious peaks coming from a single laser after going through its single pass AOM and optical fiber originate from the $0^{th}$ order light mentioned above at -50 dBc as well as from sidebands of the RF synthesizer 7-10 MHz off the carrier, at -70 dBc.

## V. CONCLUSION

We have discussed an approach to operating a periodically interrogated laser-cooled cesium frequency standard with fractional light shift below the $10^{-17}$ level along with measurements to support the assumptions in the model. Such low light shifts without the use of mechanical shutters is attractive operationally and is carried as a defense against shutter failure in the PARCS space clock. The use of an uninjected slave laser differs fundamentally from an optical amplifier in that the slave actually commits its gain to lasing far from resonance, while an unseeded amplifier has a large amount of unsaturated gain to amplify any residual light seeding it. Confirmation of the technique including verification of spectral purity of the slaves will be forthcoming.


## ACKNOWLEDGMENT

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