Active light shift stabilization in modulated CPT clocks.

V. Shah, P. D. D. Schwindt, V. Gerginov, S. Knappe, L. Hollberg, J. Kitching
National Institute of Standards and Technology
Boulder, Colorado 80305.
Email: vshah@boulder.nist.gov
Telephone: (303) 497 4621
Fax: (303) 497 7845

***Abstract*— We demonstrate a simple technique to significantly improve the long-term frequency stability in atomic clocks based on coherent population trapping (CPT). In this technique, a servo is used to control the local oscillator power level in such a way that the optical spectrum generates no net light shift. This ensures that the clock frequency is always given by the atomic resonance frequency that is not perturbed by the incident light fields.**

I. Introduction

Recently, remarkable progress has been made in the field of atomic clocks based on coherent population trapping or *CPT* (see for example [1],[2] and references therein). Some of the key advantages obtained by using CPT to probe the atomic resonance frequency are lower light-shifts, no requirement for a microwave cavity, and that the physics package of the atomic clock can be implemented in a relatively small device [3]. Even though the light-shifts in CPT atomic clocks are smaller than in conventional optically pumped atomic clocks they can still affect the long term frequency stability.

Figure 1(a) shows a simple schematic of a modulated CPT atomic clock. A local oscillator (LO) is used to modulate the laser to produce optical sidebands. When the frequency difference between the optical sidebands used to excite a CPT resonance is equal to the ground state hyperfine splitting in the alkali atoms, the amount of light transmitted through the atomic sample increases due to the phenomenon of CPT [4][5]. This increase in the light transmitted though the vapor cell is monitored using a photo detector and the information is used to lock the LO-frequency to the ground state hyperfine frequency of alkali atoms.

Recently a prototype physics package of a CPT atomic clock was demonstrated in volume roughly equal to 9.5 mm^3 with a relatively low power consumption. Similar devices have demonstrated a short term stability at about 5×10^{-11} at an integration time of one second [6][7]. These properties make CPT clocks ideally suited for many applications, especially in portable battery operated instruments. However, in order for this technology to really prove effective, the long term frequency stability (over one day, for example) should be correspondingly good as well.

In order to achieve a good long term frequency stability, there are at least two basic issues which need to be addressed. The first issue is the vapor cell temperature stability. Typically the vapor cell contains alkali atoms, such as rubidium or cesium, along with appropriate buffer gases. The role of the buffer gases is to reduce collisions between the alkali atoms and the vapor cell walls, which is important in order to observe narrow resonance line widths. However, collisions between the buffer gas and the alkali atoms induce temperature dependent shifts in the ground state resonance frequency of the alkali atoms. This can put stringent requirements on the temperature stability of the vapor cell. Fortunately, a solution to this problem is well known and has been implemented in optically pumped atomic vapor cell clocks for several decades (see for example [8]). Instead of using a single species of the buffer gas atoms, two or more species of buffer gas atoms are used such that each species produces frequency shifts in opposite directions for a given change in vapor cell temperature. This can sufficiently reduce the magnitude of shifts related to the changing temprature of the vapor cell.

A second issue that needs to be addressed is that of the light-shifts (see for example [9] and references therein). The interaction between the incident light fields and the alkali atoms also produces shifts in the alkali ground state resonance frequency. These light shifts depend on the laser properties and therefore small changes in the laser properties can produce frequency shifts that are difficult to control[10]. To briefly understand the origin of the light-shifts in CPT clocks, consider first the role of the laser. The laser is modulated using a local oscillator to produce optical sidebands. Usually, the two first-order sidebands are used to excite a CPT resonance. However, all the sidebands generated by laser modulation interact with the atoms and contribute to the light shifts. This makes the atomic resonance frequency shift sensitive to changes in the laser properties such as changes in the central frequency of the laser, its total intensity or the amount of optical power distributed among its various sidebands. These changes can be introduced for example by effects related to laser-aging or by changes in the laser operating conditions such as laser junction temperature or the LO-power. Figure (2) shows how the observed atomic resonance frequency can change with changes in the laser temperature for different LO-power levels. From the figure it is evident that light-shifts produce significant changes in the clock frequency.

The fundamental problem with the light shifts arises from

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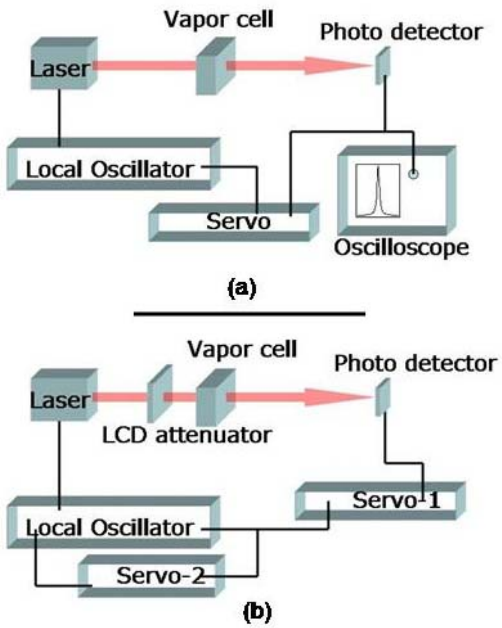

Fig. 1. (a) Schematic of a modulated CPT clock. (b) Schematic of a modulated CPT clock with an additional servo to lock the atomic resonance frequency to the unperturbed atomic resonance frequency.

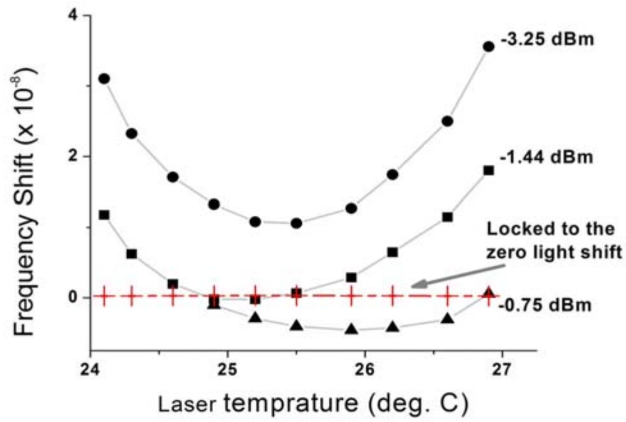

Fig. 2. A plot of clock frequency vs the laser temperature for the conventional case (dots) and when LO-power level is locked to the zero light shifted atomic resonance frequency (+) for different values of LO-power level.

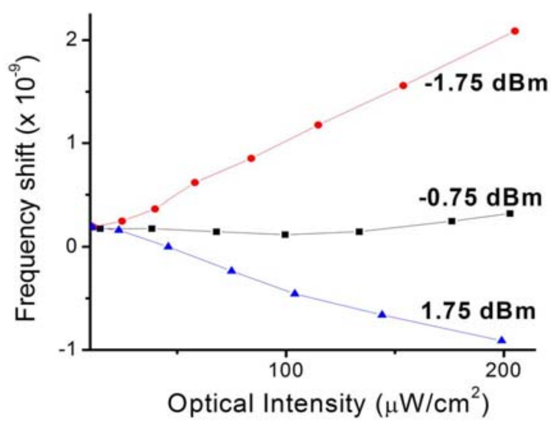

Fig. 3. Frequency shift vs optical intensity for different values of LO-power level

the fact that, instead of locking to the real atomic resonance frequency, the LO is locked to the atomic resonance frequency which is perturbed by the incident light fields. These frequency perturbations can be somewhat arbitrary and time dependent and can therefore adversely affect the long term stability of the atomic clock. In order to reduce the long term instability related to the light shifts, we propose a novel way to ensure that the LO frequency is locked at all times to the unique unperturbed atomic resonance frequency.

One way to determine the unperturbed atomic resonance frequency is by extrapolating the atomic resonance frequency to zero light intensity. However, it is difficult to do this without interrupting the normal clock operation. Another way to identify the unperturbed atomic resonance frequency was proposed earlier by Zhu et al. [11] and Vanier et al. [12]. It was shown that at a given laser temperature, by choosing an appropriate LO-power used to modulate the laser, the various contributions to the light shifts from the resonant and off-resonant optical sidebands can mutually cancel. At this particular LO-power, because there are no light shifts, the atomic resonance frequency is given by the unperturbed atomic resonance frequency. Also, for the same reason, the atomic resonance frequency becomes largely independent of the total incident light intensity (see Figure (3)). This property can be then employed to identify the unperturbed atomic resonance frequency and implement a servo that ensures that the LO remains locked to this frequency.

II. Experimental Setup

In the experiment, a servo is implemented that locks the LO to the unperturbed resonance frequency using an LCD attenuator. The role of the LCD attenuator is to slowly modulate the total intensity of the incident light fields (by about 15 % at 13 Hz). When the LO power is not correct, the oscillations in the incident light intensity produced oscillations in the atomic resonance frequency due to the light shifts. The oscillations in the atomic resonance frequency were then monitored as 13 Hz oscillation in the error signal which was used to lock the LO frequency (from servo-1 in Figure 1(b)). At the LO-power level at which the total light-shift is zero, the laser intensity modulation has no effect on the atomic resonance frequency and therefore the oscillations induced in the error signal by the LCD attenuator vanish. In this way, one can determine the unperturbed resonance frequency. An additional servo (servo-2) was then implemented to ensure that the LO remains locked

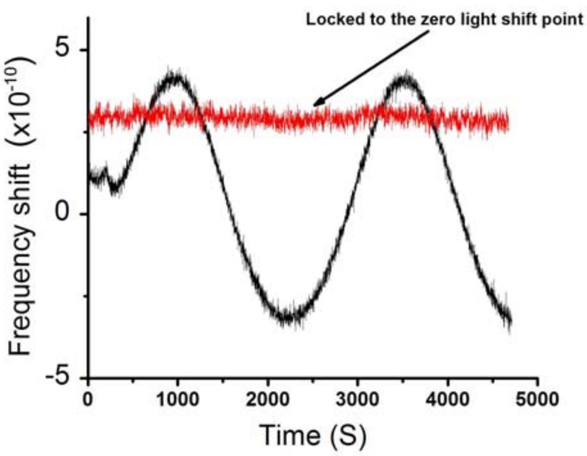

Fig. 4. Clock frequency vs time. The laser temperature was sinusoidally varied with a time period of roughly 2500 s.

to the unperturbed atomic resonance frequency by controlling its output power.

It can be seen from Figure (2) that in order to achieve a good long-term stability in a clock without using this additional lock, both the laser junction temperature and the LO-power level must be well stabilized simultaneously. When the clock is locked to the unperturbed atomic resonance frequency, however, considerably more variation in those parameters is allowed. In this case, the clock frequency is observed to be largely insensitive (at the level 10^{-10}) to simultaneous changes in laser temperature and LO-output power of up to $\sim$ 3°C degrees and $\sim$2 dBm respectively.

Figure (4) compares the atomic clock frequency when operated with or without the additional servo. Here, the laser temperature was deliberately modulated with a time period of roughly 2500 s in order to ensure that clock frequency stability was largely limited by light shifts only. From the results shown in Figure (4) it can be clearly seen that the frequency of the clock, even under conditions where the laser temperature is continuously changing, remains stable when the LO-power level is locked to the unperturbed atomic resonance frequency. The residual oscillations are mainly due to inaccuracies in determining the zero light-shift frequency. We believe that these small inaccuracies arise mainly from the intensity dependent optical pumping effects which induce asymmetries in the CPT resonance line shape.

III. Conclusion

In conclusion, we have demonstrated a new technique that largely eliminates light-shift induced frequency drifts in modulated CPT atomic clocks. By using this technique it is possible to substantially reduce the frequency shifts related to the LO-power and laser temperature instability. This can enhance the technical and commercial feasibility of modulated CPT clocks, especially in portable devices. The technique may also prove useful in improving the reliability of modulated CPT atomic clocks by eliminating laser-aging-related clock frequency drifts. The simplicity of the proposed technique and its variants (such as modulating the optical frequency detuning instead of the light intensity) potentially allows their implementation even in miniature atomic devices.

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