Continuous light-shift correction in modulated coherent population trapping clocks

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The authors demonstrate a simple technique to significantly improve the long-term frequency stability of atomic clocks based on coherent population trapping (CPT). In this technique, the CPT fields are created by a modulated diode laser and a slow servo is used to actively tune the laser modulation index to a value where the light shift vanishes. The observed clock frequency at this modulation index is given by the rubidium hyperfine frequency when no light fields are present, and this makes the clock frequency largely insensitive to variations in laser properties. In addition to reducing stringent requirements on the long-term stabilities of laser temperature, laser frequency, and rf modulation power, this technique may also significantly reduce frequency drifts related to laser aging. In the experiment, they demonstrate improvement by over one order of magnitude in the stability of a clock that is limited by light-shift-induced frequency drifts. *© 2006 American Institute of Physics*. [DOI: 10.1063/1.2360921]

All-optical microwave atomic clocks based on coherent population trapping (CPT) (see, for example, Ref. 1 and references therein) have been under development for sometime. One of the key advantages that CPT offers is the possibility to drastically miniaturize the physics package of an atomic clock. This advantage has been realized most effectively in physics packages based on microfabrication processes.[2–4] The devices open up new avenues for applying the atomic clock technology, especially to portable devices.

In one simple implementation of a CPT atomic clock, a modulated semiconductor laser is used to measure the ground-state energy splitting in alkali atoms.[5–7] The semiconductor laser is modulated using a local oscillator (LO) which produces a comb of optical sidebands; usually the two first-order sidebands are used to excite a CPT resonance.[8,9] The CPT resonance is detected as a change in the absorption of the incident light fields by the atoms. This occurs when the frequency difference between the optical sidebands used to excite a CPT resonance is nearly equal to the frequency separation of the hyperfine split ground states of the atoms. In a passive CPT atomic clock, the frequency of the LO used to modulate the laser is stabilized onto the peak of the CPT resonance by a feedback loop. The frequency disciplined local oscillator is then used to provide a stable frequency reference.

Despite its inherent stability, the atomic hyperfine frequency may be shifted in the presence of the interrogating light fields. Such frequency shifts are referred to as light shifts[10] and they depend on the nature of the interrogating light fields. In modulated CPT clocks, both the resonant and the off-resonant optical sidebands contribute to light shifts. In some of the earlier experiments to improve the long-term stability of CPT clocks, it was demonstrated that by choosing an appropriate index of modulation for the laser, the net contribution to the light shifts from the resonant and the off-resonant optical sidebands can be mutually canceled out.[11,12] This modulation index can be experimentally determined by adjusting the LO power level to a value where the clock frequency becomes largely independent of variations in the total intensity of the incident light fields. Stabilizing the LO power level to such a value thus makes the clock frequency stable to changes in the total laser intensity. However, in order to improve the long-term frequency stability of the clock, simply stabilizing the LO power level may not always prove to be sufficient. This is because the LO power level at which the light-shift contributions vanish depends on operating conditions such as the laser junction temperature or the laser impedance, which can change due to laser aging or external environmental fluctuations.[13] Changes in the laser temperature or its input impedance redistributes the optical power among the various optical sidebands, thereby changing its modulation index, which produces light shifts.

Controlling light shifts to within acceptable limits can be a challenge and may put stringent requirements on the stability of the laser properties and the LO output power.[14] This, in addition to increasing engineering-related constraints in the manufacturing of CPT atomic clocks, may also require very good control over the laser aging processes.

In order to significantly reduce the dependence of the atomic clock frequency on properties of the laser, we demonstrate here a simple technique that can largely eliminate light-shift-induced frequency drifts in modulated CPT atomic clocks. The basic idea behind this technique is to use an additional servo to ensure that the clock frequency is given at all times by the unique atomic resonance frequency that is not perturbed by the incident light fields. To do this, the LO power level is continuously tuned to a value where the light-shift contributions to the clock frequency vanish. This ensures that the observed clock frequency is at all times mostly independent of the specific laser operating conditions.

A schematic of the experimental setup used to demonstrate this technique is shown in Fig. 1. In the experiment, light from a vertical-cavity-surface-emitting laser (VCSEL)

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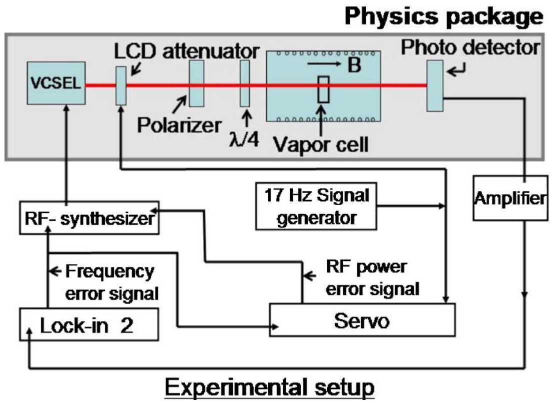

FIG. 1. (Color online) Schematic of the experimental setup. VCSEL: vertical cavity surface emitting laser. LCD: liquid crystal display.

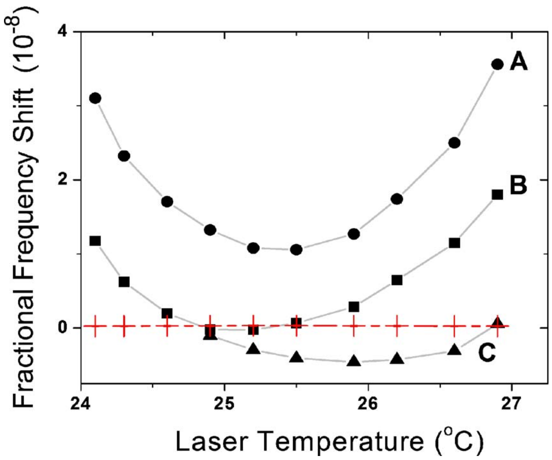

FIG. 2. (Color online) Plot of clock frequency vs the laser temperature for the conventional case (dots) and when rf-power level is locked to the zero light-shifted atomic resonance frequency (+) for different values of LO power level. A: −3.25 dBm, B: −1.44 dBm, and C: −0.75 dBm. The fractional frequency shift refers to the clock frequency shift normalized using the measured ^{87}Rb ground state hyperfine frequency. The zero on the *y* axis corresponds to the atomic resonance frequency extrapolated to zero light intensity.

at 795 nm is incident on a $1\times1\times4.5$ cm^3 ^{87}Rb vapor cell containing 1.3 kPa of N_2 buffer gas. The vapor cell is temperature stabilized at around 20% optical absorption and is enclosed inside a μ-metal shield. A small magnetic field is generated by a solenoid (~40 μT) to lift the degeneracy of the Zeeman levels. The light transmitted through the vapor cell is monitored using a Si-*p*-*i*-*n* photodetector. The intensity of the incident light field is controlled using a liquid crystal display (LCD) attenuator after which it is circularly polarized by a quarter wave plate. In order to produce the optical sidebands required to excite a CPT resonance, the VCSEL current is modulated by a voltage-controlled frequency synthesizer (LO) at 3.417 GHz. The two first-order optical sidebands are used to excite a CPT resonance on the $m_f=0$ Zeeman ground states. The wavelength of the VCSEL is stabilized to the optical resonance with a lock-in amplifier (not shown in the figure) and fed back to the dc-laser current. The frequency of the LO is locked to the peak of the CPT resonance with a second lock-in amplifier. In order to detect the LO power level at which the light-shift contributions to the hyperfine resonance frequency vanish, the total intensity of the incident light field is modulated by ~15% at 17 Hz. The effect of intensity modulation on the CPT resonance frequency is monitored as 17 Hz modulation on the error signal generated by the second lock-in amplifier (used to correct the frequency of the LO). The 17 Hz modulation is observed on the error signal because a change in the total optical intensity produces a corresponding change in the CPT resonance frequency due to light shifts. The LO power level at which the light-shift contributions vanish occurs when the 17 Hz modulation on the error signal generated by the second lock-in amplifier vanishes. This modulation is continuously minimized by use of an additional servo that controls the output LO power level. The time constant for correcting the LO power level is set roughly equal to 10 s. To verify that the clock frequency locked in this way is truly given by the unique zero light-shift frequency, it was compared with the frequency obtained in the conventional case by extrapolating to the zero light intensity.

Two important laser-related factors responsible for inducing light shifts are the laser temperature and the LO power with which the laser is modulated. Figure 2 shows a plot of the clock frequency as a function of the laser temperature for the conventional case and for the case when the LO power level is locked to the zero light-shift frequency. It can be seen from Fig. 2 that in order to achieve a good long-term stability in a clock operating using the conventional technique, both the laser junction temperature and the LO power level must be simultaneously well stabilized. In the conventional case, it can also be seen that there are local mimima in the clock frequency as a function of the laser temperature. These local minima do not necessarily correspond to the zero light-shift frequency and although the clock frequency at these values is largely insensitive to changes in the laser temperature, its sensitivity to changes in the LO power level is not necessarily equally low. These local minima are the result of a number of effects that combine to change the light shift in a complex way. These include changes in the overall optical intensity emitted by the laser, as well as the optical sideband spectrum resulting from altered laser impedance or LO power. Since the light shift depends on the optical spectrum, and hence the rf power coupled into the laser, in a highly nonlinear manner, it is difficult to predict how the clock frequency should depend on the laser temperature. Similar behavior to that shown in Fig. 2 has been observed previously in clocks based on CPT.[13,15] When the clock is locked to the zero light-shift value, however, considerably more variation in these parameters is allowed. In this case, the clock frequency is observed to be largely insensitive (at the level of 10^{-10}) to changes in laser temperature of up to ~3 °C.

Figure 3 shows a comparison between the Allan deviations for a clock operating using the conventional scheme and when the LO power level is locked to the zero light-shift value. The LO power level during measurement in the conventional case was set to a value where the best short-term stability was observed. This was within a factor of 2 of the short-term stability observed when the LO power level was set to a value for which the light shifts were minimized. Here the laser temperature was deliberately modulated with a period of roughly 2500 s in order to ensure that the clock frequency stability at long integration times was limited mostly by light shifts. From the results in Fig. 3 it can be clearly seen that the frequency of the clock, even under conditions in which the laser temperature is continuously changing

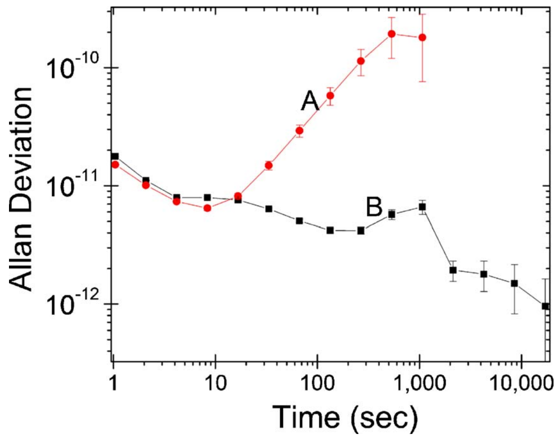

FIG. 3. (Color online) Plot of Allan deviation for the conventional case (A) and when LO-power level is locked to the zero light-shifted atomic resonance frequency (B). The laser temperature was sinusoidally varied with a time period of roughly 2500 s. The average laser temperature during the measurement was set equal to 25.3 °C and the LO power level in the conventional case was set equal to −2 dBm. When locked to the zero light-shifted frequency, the average LO power level was −1.44 dBm.

(which, can be caused by daily ambient temperature variations, for example), remains stable when the LO power level is locked to the zero light-shift value. A slight increase in the Allan deviation around an integration time of 1000 s is mainly due to inaccuracies in the determination of 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.

In conclusion, we have demonstrated a technique that largely eliminates light-shift-induced frequency drifts in modulated CPT atomic clocks. Further extensions of this technique, such as in combination with the technique proposed in Ref. 16 may yield similar results in conventional optically pumped atomic clocks also. It is demonstrated here that this technique makes it possible to substantially reduce stability requirements related to the LO power and laser temperature. This may enhance the technical and commercial feasibility of modulated CPT clocks, especially in portable battery operated devices that may be subject to significant variations in environmental conditions. The technique may also prove useful in improving the reliability of modulated CPT atomic clocks by eliminating clock frequency drifts related to laser aging. The simplicity of the proposed technique potentially allows its implementation (or its variants such as those based on modulation of optical frequency detuning) even in miniature atomic devices.

Note added in proof. A similar scheme has also been described[17] to stabilize the laser frequency to the zero–light-shift point in a conventional laser-pumped atomic clock.

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