Laser Noise Cancellation in Single-Cell CPT Clocks

Vladislav Gerginov, Svenja Knappe, Vishal Shah, Leo Hollberg, and John Kitching

***Abstract*—We demonstrate a new technique for the suppression of noise associated with the laser source in atomic clocks based on coherent population trapping (CPT). The technique uses differential detection of the transmission of linearly and circularly polarized beams that propagate through different parts of a single rubidium vapor cell filled with a buffer gas mixture. The common-mode noise associated with the laser frequency and amplitude noise is suppressed by the differential detection of the two laser beams. The CPT signal, which is present only in the circularly polarized laser beam, is unaffected. The implementation of the technique requires only a change of the polarization of part of the laser beam and an additional photodiode. The technique is simple and applicable to CPT frequency references where a major source of noise is the laser, such as compact and chip-scale devices.**

***Index Terms*—Atomic clocks, coherent population trapping (CPT), compact frequency references, diode lasers, noise reduction, vertical-cavity surface-emitting lasers (VCSELs).**

I. Introduction

THE INCREASING demand for precise timing in such areas as communications, network synchronization, and navigation has led to the development of small and robust lamp-pumped atomic clocks. Significant advances in the field of coherent population trapping (CPT) have made it possible to reduce the size of these devices even further [1]–[3]. In such devices, a laser replaces the lamp, and no RF cavity is required, because the atomic microwave transition is excited by light components that are present in the laser spectrum that have a frequency difference equal to the ground state splitting. The use of vertical-cavity surface-emitting lasers (VCSELs) with high microwave modulation efficiencies and low threshold currents, combined with the advantages of small size enabled by CPT, has reduced the power consumed by the physics package [4] to the point where these devices are expected to be powered by batteries.

The properties of the light assembly in any laser-pumped atomic reference are of great importance in determining the frequency stability of the system. Slow changes in the laser intensity, optical frequency, or modulation properties may degrade the performance of the atomic reference over long time scales. AM and FM noise on the laser light largely determines the short-term performance. In particular, the partitioning of the optical power between transverse and polarization modes in VCSELs can lead to intensity noise significantly above the shot noise level on the laser output. Such noise increases if a polarizer is placed in the beam path to purify the polarization state of the light. If the microwave modulation of the laser injection current with a high FM modulation index is used, the intensity noise increases further. The conversion of frequency noise into amplitude noise, due to the frequency-dependent absorption of the atomic media (FM–AM conversion) [5], [6], is another important source of noise. For VCSELs, the FM noise is particularly high because of their relatively large laser linewidth (often around 50 MHz) and the sensitivity of the optical frequency to variations in the injection current (300 GHz/mA) and temperature (30 GHz/K).

In this paper, we present a method for reducing the sensitivity of CPT-based atomic references to laser noise. Similar techniques have been developed for optically pumped microwave clocks [7]–[10]. In contrast with the work in [7], here, a single cell is used to create the CPT signal and cancel the noise, which allows for a smaller overall size and builds on the original advantage of CPT over microwave excitation with respect to miniaturization. In [9], two spatial regions of the same cell were used, and noise cancellation was achieved through the use of different laser and microwave intensities in each region. Although this method eliminates the complexity inherent in using two cells, the size of the device is still set by the wavelength of the microwave radiation. In [10], an optical delay was required, which may limit the size of the device to a centimeter scale. The scheme presented in this paper allows simplification of the physics package miniaturization to a length scale set by the diffusion length of the atoms and is compatible with the chip-scale atomic clock architectures [2]. It is especially valuable in VCSEL-based devices where the noise due to the laser significantly contributes to the overall instability of the instrument.

The basic idea presented in this paper aims at illuminating spatially distinct parts of an alkali vapor cell with the light of two different polarizations: one linear and one circular. If a dc magnetic field is oriented along the direction of propagation of the light field, only the light beam with a circular polarization excites a CPT resonance on the $m_{g1} = 0 \rightarrow m_{g2} = 0$ transition. In the case of the linearly polarized beam, each of the two circularly polarized components forms its own Λ-system, corresponding to $m_{g1} = 0, m_{g2} = 0$ and $m_e = \pm 1$ [see Fig. 1(a)]. Because of the signs of the Clebsh–Gordan coefficients, the transition amplitudes of these Λ-systems interfere destructively [11], and no superposition of the ground state components exists that is uncoupled from all light fields. Therefore, no CPT

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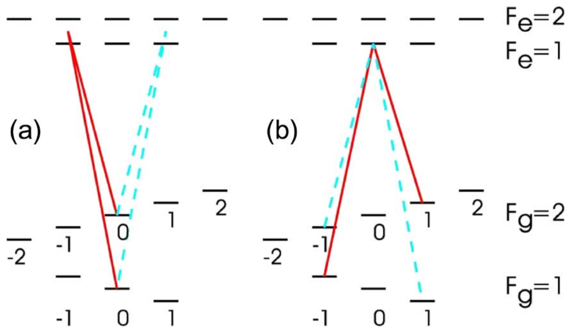

Fig. 1. Λ-systems formed in a ^{87}Rb atomic system that is excited by a linearly polarized light. (a) $\Delta m_g = 0$ and $m_e = \pm 1$. (b) $\Delta m_g = \pm 2$ and $m_e = 0$.

signal associated with the $m_{g1} = 0 \rightarrow m_{g2} = 0$ transition is observed.

In cells with low buffer gas pressure, CPT resonances associated with two additional Λ-systems with $\Delta m_g = \pm 2$ can be observed with linearly polarized light fields tuned to $F_g = 1, 2 \rightarrow F_e = 1$ [12] [see Fig. 1(b)]. These CPT resonances are at approximately the same frequency as the $m_g = 0 \rightarrow m_g = 0$ resonance and are, hence, in principle, simultaneously excited. However, when the homogeneous broadening of the excited states becomes comparable to their hyperfine splitting, these resonances are suppressed. Buffer gas pressures around 10 kPa or higher are used in chip-scale atomic devices to increase the lifetime of ground state coherences that are otherwise limited by wall collisions. When such vapor cells are used, no CPT resonances at all are observed with linearly polarized light.

II. EXPERIMENTAL SETUP

The experiment, which is shown in Fig. 2, demonstrates the implementation of differential noise cancellation with a single optical beam. Light emitted by a vertical-cavity surface-emitting laser is collimated and passes through a polarizer and neutral-density filter, which determine the polarization and intensity of the field entering the vapor cell. The light is then directed toward a micromachined alkali vapor cell [13] that contains isotopically enriched ^{87}Rb at its vapor pressure and a buffer gas of Ar and Ne at a total pressure of 26 kPa. The vapor cell, with interior transverse dimensions of 1 mm × 2 mm and a length of 1 mm, is located inside a magnetic shield, and an axial magnetic field of 50 μT is applied to lift the degeneracy of the ground-state Zeeman manifold. A piece of thin quartz is placed on the front surface of the cell, such that about one-half of the cross-sectional area of the cell interior is covered. This piece of quartz acts as a quarter-wave plate when appropriately oriented with respect to the polarization of the incident light beam and transforms about half the beam from linear to circular polarization. The remainder of the cell surface is covered with a piece of glass, which has no effect on the polarization. Thus, the atoms in one part of the cell see circularly polarized light, while atoms in another part of the cell see linearly polarized light. The intensity of the light before it enters the waveplate–cell assembly is 2 mW/cm^2. The power that is transmitted in each polarization component of the beam is detected with a split photodiode that is placed after the cell. The photocurrents are subtracted, as shown in Fig. 2.

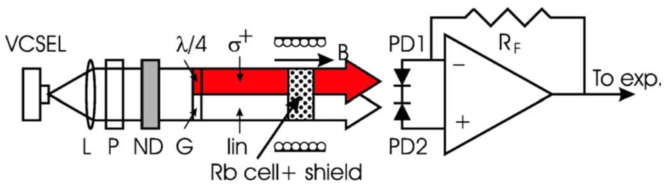

Fig. 2. Experimental setup. VCSEL: L—lens; P—polarizer, ND—neutral-density filter; $\lambda/4$—quarter-wave plate; G—glass plate σ^+, lin—circularly and linearly polarized beams, PD—photodiode.

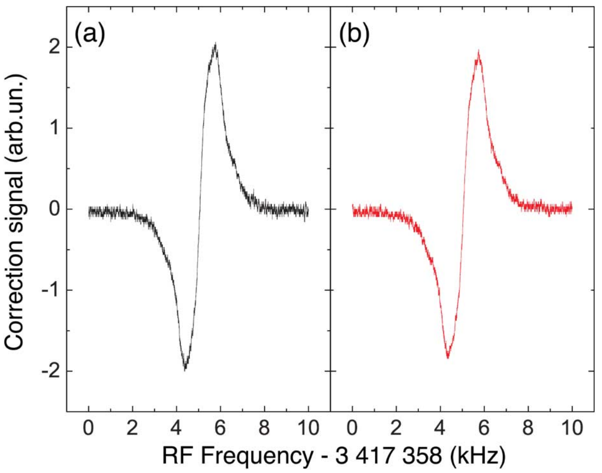

Fig. 3. LO correction signal obtained with the linearly polarized beam (a) blocked and (b) present in the experimental setup in Fig. 1.

The laser wavelength is tuned to be resonant with the $5s_{1/2} - 5p_{1/2}$ (D1) optical transition in ^{87}Rb, and the laser current is modulated near one half the frequency splitting of the hyperfine ground states. As the modulation frequency is scanned, a CPT resonance is excited in the part of the vapor cell that is illuminated by the circularly polarized beam. The decreased absorption, resulting from the CPT effect, is monitored with the photodiode. The sensitivity of the CPT signal to laser polarization can cancel the noise that originates with the laser and allow the implementation of a CPT clock very nearly limited by photon shot noise of the excitation light. The system shown in Fig. 2 rejects the common-mode noise due to the laser by subtracting the photocurrent of the two photodiodes, while, at the same time, the CPT signal, which is present only in the absorption of the circularly polarized light, is largely unaffected. This can be seen in Fig. 3, where the correction signal for the local oscillator (LO) is shown with the linearly polarized beam (a) present and (b) blocked, respectively. The correction signal is generated by applying a slow modulation to the frequency of the LO and detecting the differential photodetector current with phase-sensitive detection.

Since both laser beams pass through a single alkali vapor cell, we may consider the extent to which diffusion of atoms between the two illuminated volumes may affect the measured signals. The results of Fig. 3 indicate that the presence of the linearly polarized beam in one part of the cell does not affect the CPT resonance excited in the other part of the cell. In fact, the buffer gas pressure in the cell (Ar and Ne at ∼20 kPa total pressure)

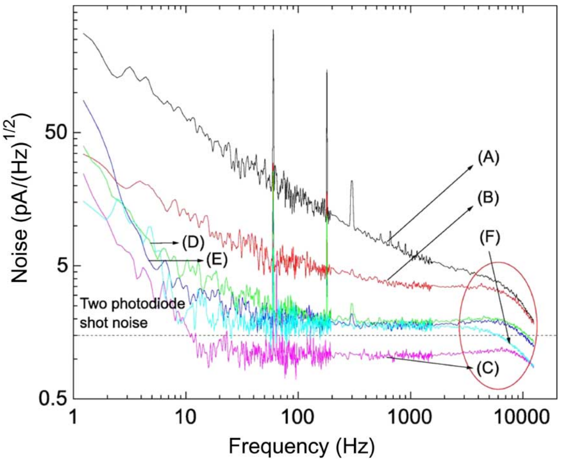

Fig. 4. Amplified photocurrent noise under a variety of experimental conditions. (A) Single photodiode: laser tuned on half-maximum of the optical resonance (maximum FM to AM conversion). (B) Single photodiode: laser on optical resonance. (C) Single photodiode: white light. (D) Two photodiodes: laser tuned on half-maximum of the optical resonance. (E) Two photodiodes: laser on optical resonance. (F) Two photodiodes: white light. The shot noise level, corresponding to the measured dc photocurrent on both photodiodes, is shown with a dashed line.

is chosen such that the polarization relaxation due to diffusion of the atoms to the cell walls is approximately equal to that due to alkali–buffer gas collisions. The presence of the linearly polarized beam in one-half the volume of the cell depolarizes atoms that enter that volume, thereby decreasing somewhat the relaxation time due to diffusion. A shorter total relaxation time is therefore expected. Taken together, the high buffer gas pressure and the use of CPT to excite the resonance allow the circular and linear beams to be separated by a distance that is much smaller than the microwave wavelength (in contrast with [9]) and allow the technique to be applicable to chip-scale device architectures [2].

The noise on the dispersive CPT signal generated by the lock-in amplifier [Fig. 3(b)] was measured with the RF tuned to the center of the resonance. Data under a variety of conditions are shown in Fig. 4. In particular, we demonstrate that both laser AM noise and noise generated through the conversion of laser FM to AM noise by the slope of the atomic absorption profile can be suppressed with this differential detection technique. The suppression of laser noise can be seen by comparing the spectra of traces (B) and (E) in Fig. 4. For both of these traces, the laser was tuned to the peak of the atomic absorption profile, which minimizes the FM–AM conversion noise, at least for low Fourier frequencies. Trace (B) shows the noise on the transmitted circularly polarized beam, which was measured by a single photodiode when the linearly polarized beam was blocked before it entered the cell. This is the usual optical arrangement that is used to excite a CPT resonance. Trace (E) shows the noise with both beams present and with the signals from the two photodiodes subtracted. A reduction of the noise by about a factor of two is observed when differential detection is used.

The suppression of noise generated by FM–AM conversion is also evident by comparing traces (A) and (D) in Fig. 4. These data are taken with the laser tuned to the side of the optical transition, where the noise due to FM–AM conversion is large. A roughly tenfold reduction in the noise at 10 Hz is observed over the single beam conditions [trace (A)] when the differential detection is used [trace (D)].

The noise spectra were referenced to an approximate measure of the photocurrent shot-noise level. The shot-noise level was estimated in two ways. First, the sum of the dc photocurrents from both photodiodes i_0 was recorded, and the shot-noise spectral density was calculated based on the equation $\Delta i_{\mathrm{SN}} = \sqrt{2 i_0 e}$. This value, which was translated into voltage noise by the measured value of the amplifier transimpedance, is shown in Fig. 4 by the dashed line. The shot-noise level was also estimated by illuminating the photodiodes with light from an incandescent white light source (appropriately filtered near 795 nm) such that the dc photocurrents were approximately the same as under laser illumination. The noise spectra shown in traces (C) and (F) are measurements that were taken with a single photodiode and subtracted dual photodiodes, respectively, and correspond roughly to the calculated value of the shot noise level.

It appears that the noise in the frequency region between 10 Hz and 5 kHz can be suppressed to a level that is rather close to that of the shot noise, both when dominated by converted FM noise and when dominated by AM noise. In this experiment, the excess AM noise is generated by the presence of the polarizer, which attenuates noise in the secondary polarization mode that is anticorrelated with that of the main mode. We anticipate, however, that a similar suppression will be obtained if the AM noise is present on the total optical power emitted by the laser.

It should be noted that at high frequencies, the laser noise that is measured with the two photodiodes becomes significantly larger than the noise of the incoherent light source. By measuring FM modulation of the laser frequency (through modulation of the injection current), it was found that the signal cancellation depends on the frequency of the modulation. Such behavior is expected due to optical pumping of the atoms, which is different for linear and circular light polarizations. Since the photodiodes are a matched pair, their bandwidth and efficiency are expected to be similar. It was found that cancellation of the noise by a factor of 100 at any given frequency can be achieved by changing the intensity of light that illuminates the two photodiodes. As seen in Fig. 4, the noise is not suppressed as significantly in some frequency bands (encircled region). Still, if the photocurrent of each photodiode is separately amplified and the gain and phase are tailored accordingly, cancellation could be achieved in a wider frequency range. In addition, separate amplification of the signals of the two photodiodes allows the laser to be locked to the maximum of the optical absorption by frequency modulation. With the setup in Fig. 1, any FM modulation of the laser frequency is highly suppressed if noise cancellation is used.

III. CPT CLOCK BY MEANS OF NOISE CANCELLATION

If the CPT resonance is used to stabilize the frequency of an external oscillator, the reduced noise observed in Fig. 4 directly translates into improved short-term frequency stability. To demonstrate this, a frequency synthesizer was locked to the

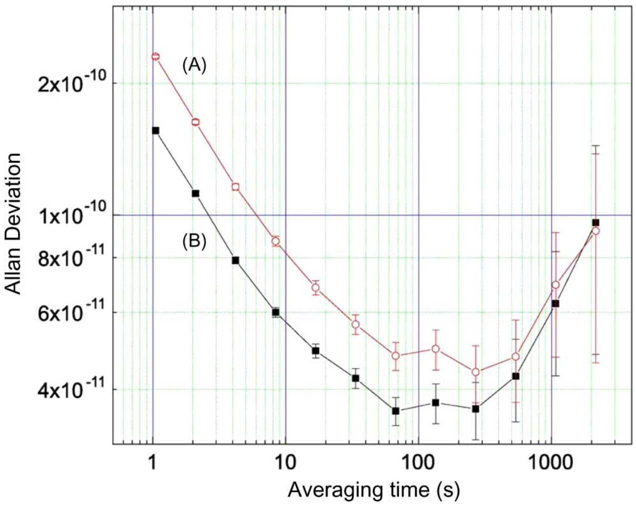

Fig. 5. Allan deviation plot of the CPT clock by the use of (A) a single photodiode and (B) two photodiodes.

atomic resonance by use of the dispersive error signal shown in Fig. 2. The frequency stability of this synthesizer was measured by comparing the locked frequency to a secondary more stable frequency reference. The difference between these two frequencies was measured with an electronic counter and recorded as a function of time with a computer. The corresponding Allan deviation [14] was calculated from the frequency–time set and is shown in Fig. 5. The precision of the measurements was limited by the precision of the reference oscillator and counter timebase, both of which were referenced to a hydrogen maser. The instability is roughly 10^{-13} at one second and 10^{-15} at 10 000 s and, therefore, contributes negligibly to the measurement. The error bars in Fig. 5 are estimates based on the length of the frequency–time data set.

An improvement in the short-term stability by roughly a factor of 1.5 is obtained when differential detection is used. For these measurements, the laser optical frequency was locked to near the top of the atomic absorption spectrum by the use of a secondary vapor cell. This additional cell was needed because the differentially detected signal, as implemented here, did not allow a simple determination of the transmitted power. The use of a second cell is unnecessary when the two photocurrents are individually amplified before being subtracted, allowing the detection of the laser detuning from the optical transition.

In Fig. 5, the noise cancellation improves the short-term stability of the clock by a factor of 1.5. This number agrees well with the noise suppression inferred from Fig. 2 at frequencies on the order of 3 kHz used for lock-in stabilization of the clock frequency. Such modest improvement occurs largely because the system noise when the laser is locked to the peak of the atomic absorption profile is quite close to the shot noise level. In cells with a lower buffer gas pressure or cells with antirelaxation wall coatings, the noise generated by FM–AM conversion will be larger due to the narrower optical transitions in these cells. This improvement in the detection signal to noise translates directly into improved short-term frequency stability of the passive frequency references, as can be seen in our case in Fig. 5. The long-term stability of the frequency references is mainly determined by drifts in the parameters of the vapor cell or the light assembly and, in our case, reaches a value of 3.5×10^{-11} at an integration time of ~100 s.

IV. CONCLUSION

A novel laser-noise cancellation technique has been demonstrated in this paper, where the common-mode noise in the frequency correction signal, which is due to the laser, is largely suppressed by subtracting the signal obtained from a reference laser beam. The implementation of this technique requires only a single vapor cell that can be much smaller than the wavelength of the microwave radiation. Noise generated by the conversion of FM laser noise to AM noise is reduced by a factor of ten, and performance within a factor of two of the shot-noise limit is achieved between 30 Hz and 3 kHz. This improvement in the detection signal to noise translates directly into improved short-term frequency stability of a passive frequency reference. The technique is most suitable for devices where the major source of noise arises from the laser. One example of such a device is a chip-scale atomic frequency reference [2] based on VCSELs.

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