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Reduction of optical field noise by differential detection in atomic clocks based on coherent population trapping

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ABSTRACT

We present preliminary results showing that some noise sources in vapor cell atomic clocks based on coherent population trapping (CPT) can be suppressed with differential detection. The scheme we propose differs from more conventional differential detection in that both optical fields pass through the alkali vapor cell but have different polarizations, one circular and one linear. Because CPT resonances are only excited by the circularly polarized beam, the linearly polarized beam can be used to reduce several important sources of noise. With this technique, we demonstrate reduction of the short-term frequency instability of a CPT atomic frequency reference by a factor of about 1.5.

Keywords: atomic clocks, chip-scale atomic devices, coherent population trapping, noise reduction.

1. INTRODUCTION

Differential detection is a widely used experimental technique for reducing measurement noise[1]. In a generic differential spectroscopy experiment, a probe beam is split into two independent beams with a beam splitter. One beam is sent through the atomic sample to be measured and the other is diverted around the sample. The two beams are then detected on independent photodetectors and the signals are subtracted. Since the signal from the atomic sample is present only on the beam that passed through the atoms, subtracting the photodetector signals does not affect the signal. However, since some noise sources (intensity fluctuations of the laser, for example) are common to both beams, these can be largely suppressed by the subtraction process. In principle, a noise level close to the photon shot noise level can be achieved.

In some spectroscopic measurements, the presence atomic sample itself generates noise on the light field. For example, if FM noise is present on the light, this can be converted into AM noise by the frequency-dependent absorption profile of the atoms[2]. This AM-FM conversion noise can be orders of magnitude larger than the intrinsic laser AM noise if the absorption profile is narrow enough and the laser FM noise is large enough. This noise process is particularly important in vapor cell atomic frequency references. These instruments rely on optical detection of a microwave atomic resonance excited in the atoms either by a microwave field or by coherent population trapping. Since the optical field is generally tuned to be resonant with an optical transition in the atoms, FM noise on this field generates AM noise on the output field. This FM-AM noise cannot be eliminated by the simplest differential detection scheme outlined above, because the reference field has not passed through the atomic sample and therefore does not contain a copy of the FM-AM converted noise.

A nice technique was developed by Mileti, et al[3,4] to address this issue. In their experiment, the reference light beam was passed through a vapor cell identical to the main vapor cell but located outside the microwave cavity. A detector placed after this cell therefore recorded not only the original intensity fluctuations of the optical field but also the FM-AM fluctuation. The signal, however, was unaffected by the presence of this second cell, since the microwave field was only applied to the main cell. A corresponding improvement in the short-term frequency stability of the frequency reference was achieved. One difficulty with this technique, at least with regard to miniaturization, is that two cells are required, and one must be located outside the microwave cavity. As we will see, this type of differential

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detection can be accomplished in CPT atomic clock with two beams propagating very close to each other in the same vapor cell. This allows considerable simplification of the experimental setup and therefore the prospects for miniaturization.

CPT resonances[5] are excited by tuning two phase-locked optical fields to two different atomic transitions, such that the frequency difference of the optical fields corresponds to the energy difference of the two lower atomic levels. If a DC magnetic field is oriented along the direction of the light propagation vector, and if, further, the light polarization is circular, then a reduction in the atomic absorption can be seen when the laser fields are tuned to be in Raman resonance. This reduction in absorption can be used, for example, to stabilize the frequency of a local oscillator to the atomic transition and create a passive atomic frequency reference. If the light field is linearly polarized, however, the CPT signal is absent, because of the complete destructive interference of two indistinguishable excitation paths[6]. This difference in the atomic response to the different polarizations can be used to excite a CPT resonance and generate a reference been with very similar noise signature in the same vapor cell. We demonstrate below that this technique can be implemented experimentally in a CPT atomic clock based on a micromachined alkali vapor cell[7].

2. EXPERIMENTAL SETUP

The experimental setup is shown in Figure 1.

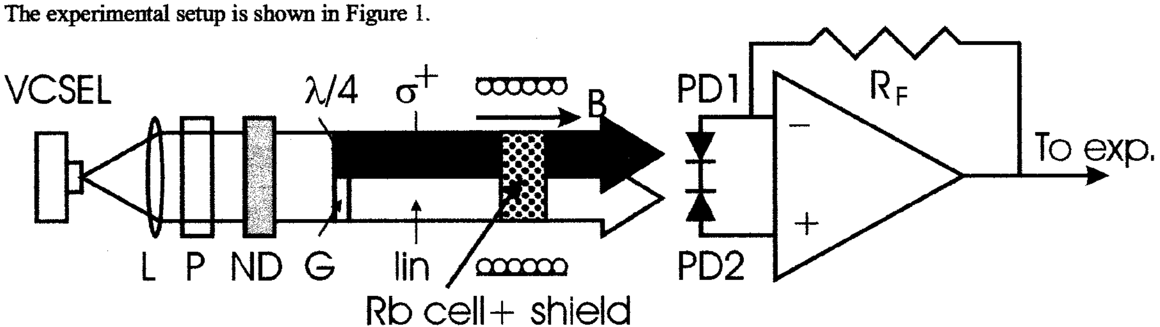

Fig. 1 Experimental setup. VCSEL – vertical cavity surface emitting laser; L – lens; P – polarizer, ND – neutral density filter, l/4 – quarter wave plate; G- glass plate, σ+, lin – circularly and linearly polarized beams, PD – photo diode; LO – local oscillator.

The light from a VCSEL emitting 0.5 mW at 795 nm is linearly polarized, collimated to a 3 mm diameter beam, and attenuated to 2 mW/cm^2. The frequency of the VCSEL is tuned to the vicinity of the D_1 transition in ^{87}Rb. The 2 mm diameter laser beam passes through a quarter wave plate and a glass plate that make the upper semi-circular part of the beam circularly polarized, while leaving the lower semicircular part linearly polarized. The two beams propagate through a microfabricated vapor cell with a rectangular cross-section (1 mm×2 mm). The cell is filled with a buffer gas mixture of Ar and Ne at 26.1 kPa total pressure, and contains isotopically enriched ^{87}Rb[8]. It is placed inside a cylindrical magnetic shield, and a longitudinal DC magnetic field of 50 μT is applied along the laser's direction of propagation. After the cell, each beam is detected by a separate photodiode. The signals from both diodes are subtracted by a high-gain (feedback resistor R_F equal to 2 MΩ) transimpedance amplifier.

3. NOISE CANCELLATION

In order to observe a CPT signal, the laser current is modulated at half of the ground state splitting of ^{87}Rb (6.8 GHz). At a certain modulation index, the current modulation produces first-order sidebands in the optical spectrum that contain ~60 % of the total laser intensity. The laser frequency is tuned such that the two first-order sidebands are resonant with transitions between the two ground-state components and the excited state, forming a Λ-system. The excited state components are broadened to 2 GHz by the presence of the buffer gas and are unresolved. When the second harmonic of the modulation frequency matches exactly the ground state splitting, the atoms are pumped into a superposition state that is uncoupled from the light field, and the transmission through the cell increases. The longitudinal magnetic field isolates the $F_g=1$, $m_g=0$ – $F_g=2$, $m_g=0$ resonance from the magnetically sensitive ones. This 0-0 resonance is used to stabilize the RF frequency to the 3.4 GHz atomic microwave transition.

To excite the $m_g=0 - m_g=0$ resonance, either linear or circular light polarization can be used if the magnetic field is oriented along the laser's direction of propagation. With linearly polarized light, the optical fields form two Λ-systems are formed, corresponding to $\Delta m_g=0$, $\Delta m_e = \pm1$. Because of the sign of the Clebsch-Gordan coefficients, the transition amplitudes of each Λ-system interfere destructively, and no CPT is observed[6]. In cells with low pressure of the buffer gas, two additional Λ-systems form with $m_e=0$, $\Delta m_g = \pm2$ with the linearly polarized laser tuned to $F_g=1,2 - F_e=1$; and a CPT signal is observed when the light fields forming the two Λ-systems are split (to a good approximation) by the $m_g=0$-$m_g=0$ resonance frequency[9]. When the homogeneous broadening of the excited state becomes comparable to the hyperfine splitting of the excited state, however, these resonances are suppressed. Buffer gas pressures around 10 kPa or larger 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. In the case of circularly polarized light, a dark state exists even when the excited states are not resolved, and a CPT signal is always observed.

The sensitivity of the CPT signal to laser polarization can be used to cancel the noise originating in the laser, and to allow the implementation of a CPT clock very nearly limited by photon shot-noise. The system shown in Fig. 1 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, present only in the absorption of the circularly polarized light, is largely unaffected. The intensity noise of the laser, and the FM to AM conversion due to the frequency-dependent absorption, are largely reduced. Results on noise reduction are shown in Figure 2.

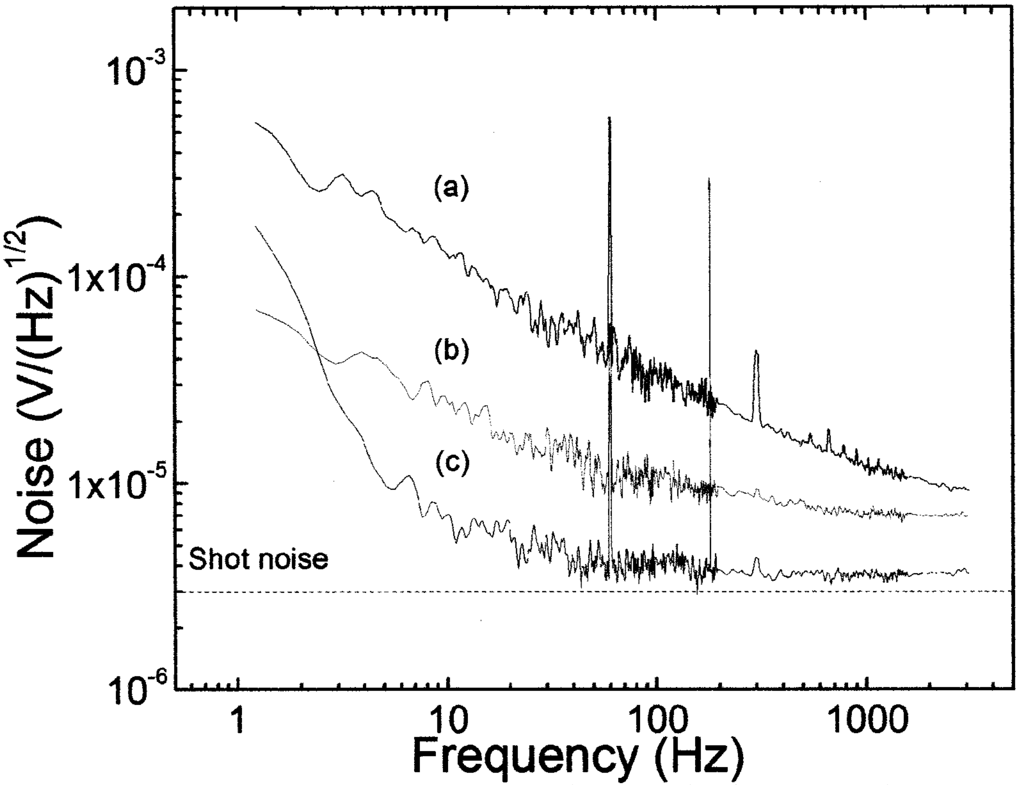

Fig. 2 Noise measurements. (a) Single photodiode, laser tuned on half-maximum of the optical resonance (maximum FM to AM conversion). (b) Single photodiode, laser on optical resonance; (c) Two photodiodes, laser on optical resonance. The shot noise level, corresponding to the measured DC photocurrent on both photodiodes, is shown with a dashed line.

In order to study the noise cancellation, experiments were performed with the subtraction scheme from Figure 1. These results were compared with the spectra from a single photodiode when the linearly polarized light was blocked after passing through the cell. Two experimental regimes were studied. First, the laser frequency was detuned from the maximum of the optical absorption, realizing a maximum FM to AM conversion. Second, the laser was tuned to the maximum of the optical resonance. Based on the diode photocurrents, a shot noise level was calculated and independently measured using a white light source, and is presented on Figure 2 with a dashed line.

As expected, the laser FM to AM conversion due to the frequency-dependent optical absorption with the laser detuned from resonance causes a noise almost an order of magnitude larger than the shot noise of a single photodiode (Figure 2 (a)). This noise is reduced when the laser is tuned on resonance (Figure 2 (b)), but it is still above the shot noise limit. On the other hand, if two photodiodes are used with their signals subtracted, the noise when the laser is detuned from the optical resonance is similar to the noise when the laser is on resonance (Figure 2 (b)). Also, the residual laser noise is similar to the shot noise value estimated from the DC photocurrents.

It should be noted that at high frequencies, the laser noise measured with the two photodiodes becomes significantly larger than the noise of the incoherent light source. By FM modulation of the laser frequency (using laser current modulation) it was found that the noise cancellation depends on the frequency of the modulation. Such behavior is expected due to the process of optical pumping of the atoms, which is different for linear and circular light polarizations. It was found that a cancellation by factor of 100 of the noise at any given frequency can be achieved by changing the intensity of light illuminating the two photodiodes. If the photocurrent of each photodiode is amplified separately and the gain and phase are tailored accordingly, cancellation could be achieved in a wider frequency range. Also, separate amplification of the signals of the two photodiodes allows the laser to be locked to the maximum of the optical absorption by the use of frequency modulation. With the setup from Figure 1, any FM modulation of the laser frequency is highly suppressed if noise cancellation is used.

The laser intensity noise is cancelled after the light interacts with the atoms. This noise can still reduce the short-term stability of the clock, since it affects the CPT clock frequency through the AC Stark shift. The configuration from Figure 1 reduces only the background noise on the photodiodes.

4. CPT CLOCK USING NOISE CANCELLATION

In order to show the improvement in a CPT clock based on the noise cancellation technique, the RF synthesizer, used to modulate the laser injection current at 3.4 GHz, was locked to the maximum of the CPT resonance, and its frequency was measured against a maser-referenced frequency counter. To perform the locking, the RF frequency was modulated at 3 kHz, and an error signal was generated by phase-sensitive detection. The laser frequency was loosely locked to a second absorption cell, because the detection scheme shown in Figure 1 does not allow a simple detection of the total laser power transmitted through the cell. The use of a second cell is not necessary when the two photocurrents are amplified individually before being subtracted, allowing the detection of the laser detuning from resonance. A fractional frequency instability plot is shown in Figure 3.

From Figure 3, the noise cancellation improves the short-term stability of the clock by a factor of 1.5. This number is in good agreement with the noise suppression inferred from Figure 2 at frequencies on the order of 3 kHz used for lock-in stabilization of the clock frequency. Such modest improvement is largely because of the ~2 GHz broad optical transition, which results in suppression of the laser FM-AM conversion noise because of the reduced frequency dependence of the atomic absorption. Even with one photodiode, the system is only a factor of two above the shot-noise limit. It is expected that in cells with lower pressure of the buffer gas or cells with anti-relaxation wall coatings for which the laser FM noise is more pronounced, the cancellation will result in bigger improvement.

5. CONCLUSIONS

We have developed a novel laser noise cancellation technique suitable for CPT clocks that doesn't require an additional vapor cell. The two parts of the same laser beam used for noise cancellation propagate through the same cell, which reduces the common mode noise, and allow miniaturization. Experiments performed with chip-scale components result in a near shot-noise limited system. The technique largely reduces the FM to AM converted noise as well as intensity noise.

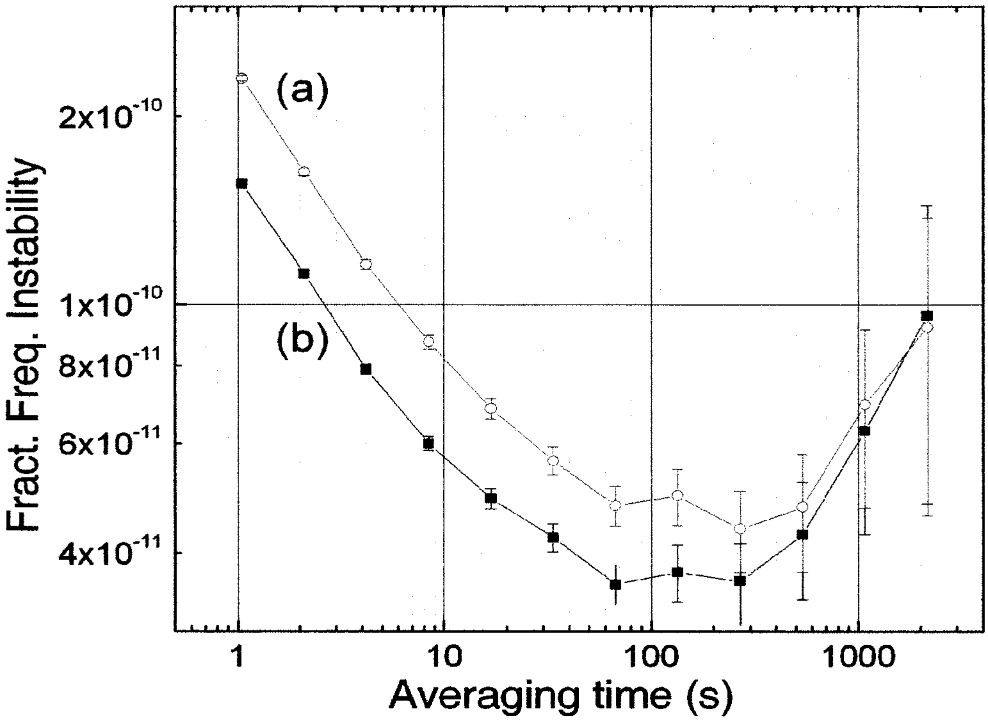

Fig. 3 Fractional frequency instability plot of the CPT clock using (a) a single photodiode and (b) two photodiodes.

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