Performance of a prototype atomic clock based on lin||lin coherent population trapping resonances in Rb atomic vapor

Eugeniy E. Mikhailov, Travis Horrom, Nathan Belcher, Irina Novikova*  
The College of William & Mary, Williamsburg, VA, 23187, USA  
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We report on the performance of the first table-top prototype atomic clock based on coherent population trapping (CPT) resonances with parallel linearly polarized optical fields (lin||lin configuration). Our apparatus uses a vertical cavity surface emitting laser (VCSEL) tuned to the D1 line of \(^{87}\)Rb with current modulation at the \(^{87}\)Rb hyperfine frequency. We demonstrate cancellation of the first-order light shift by proper choice of rf modulation power, and further improve our prototype clock stability by optimizing the parameters of the microwave lock loop. Operating in these optimal conditions, we measured a short-term fractional frequency stability (Allan deviation) \(2 \times 10^{-11} \tau^{-1/2}\) for observation times \(1 \text{s} \leq \tau \leq 20 \text{s}\). This value is limited by large VCSEL phase noise and environmental temperature fluctuation. Further improvements in frequency stability should be possible with an apparatus designed as a dedicated lin||lin CPT resonance clock with environmental impacts minimized.

In the recent decades impressive progress has been made in development of miniature precision measurement devices (clocks, magnetometers, gyroscopes, etc.) that use atomic energy levels as a reference. A promising scheme for all-optical interrogation of a microwave clock transition in chip-scale atomic devices is based on the modification of optical properties of an atomic medium under the combined action of multiple resonant optical fields. For example, under the conditions of coherent population trapping (CPT) simultaneous action of two optical fields [as shown in Fig. 1(a)] allows “trapping” atoms in a non-interacting coherent superposition of two long-lived hyperfine sublevels of the ground energy state \(|g_1, 2\rangle\) that, under idealized conditions (isolated three-level scheme, no ground-state decoherence), is completely decoupled from the excited state \(|e\rangle\). Such non-interacting state (usually called “dark state”) exists only when the differential frequency of two optical fields (two-photon detuning) matches the energy splitting of the hyperfine states, and leads to a narrow peak in optical transmission - the effect known as electromagnetically induced transparency, or EIT [11]. The linewidth of a CPT resonance depends on the intensities of the optical fields, but it is ultimately limited by the finite interaction time of atoms with light. Since it is possible to obtain CPT resonances as narrow as a few tens to hundreds of Hz [12, 13], one can lock a microwave oscillator controlling the frequency difference between two optical fields such that its output frequency is stabilized at the atomic transition frequency \(|g_1\rangle - |g_2\rangle\) \[14\]. Frequency stability of such atomic clocks improves for a high-contrast narrow CPT resonance. Also, minimal sensitivity of the CPT resonance frequency to the experiment environmental fluctuations (such as temperature, laser frequency and power) is required to ensure long-term stable operation of the clock.

![Fig. 1](image-url)  

FIG. 1: (a) Idealized three-level \(\Lambda\) system that allows for coherent population trapping. (b) Optical transitions excited during the interaction of two linearly-polarized optical fields at the carrier frequency \(E^{(0)}\) and the first modulation sideband \(E^{(+1)}\) for the D1 line of \(^{87}\)Rb atoms. In the presence of a longitudinal magnetic field each light field is decomposed into \(\sigma_+\) and \(\sigma_-\) circular components of equal amplitude. Solid arrows indicate the two \(\Lambda\) systems responsible for magnetic-field insensitive CPT resonances at the hyperfine frequency \(\text{lin||lin CPT resonances}\). One-photon detuning \(\Delta\) is the frequency difference between the \(F=2 \rightarrow F'=1\) transition and the unmodulated laser frequency.

Alkali metal atoms (Cs, Rb, etc.) are well-suited for practical realization of CPT-based atomic clocks, since their ground electronic state consists of two long-lived hyperfine states. Also, their optical transitions are easily addressable with diode lasers, allowing potential miniaturization of such clock devices. However, the complex Zeeman structure of these atoms poses several challenges. Only the frequency between magnetic field-insensitive Zeeman sublevels \(m_F = 0\) (“clock transition”) of each ground state should be measured to avoid the detrimental effects of ambient magnetic fields, since good magnetic shielding is not likely possible in a chip-scale atomic clock. At the same time, for a traditional CPT configuration using two circularly polarized optical fields, most atoms are concentrated at the magnetic sublevels with the highest angular momentum \(m_F = \pm 1\) (“pocket”

*Corresponding author: inovikova@physics.wm.edu
states). As a result only a small fraction of atoms contribute to enhancing transmission at the clock transition, leading to very low CPT contrast, and consequently to a limited clock stability. Various groups proposed a number of techniques to improve the CPT resonance characteristics [16, 17, 18, 19], although many of them add to the complexity of the experimental setup by requiring, for example, two optical fields of different polarizations.

Recently, a promising approach to produce high-contrast CPT resonances with a single phase-modulated laser was proposed [20], taking advantage of a unique level combination of the alkali atoms with nuclear spin $I=3/2$. In general, two optical fields of the same linear polarization (lin/lin configuration) do not create a dark state required for a CPT resonance between the $m_F=0$ sublevels due to destructive interference of the involved $\Lambda$ systems. However, when two ground states with total angular momenta $F=1,2$ are coupled only with an excited state with total angular momentum $F'=1$, a high-contrast magneto-insensitive CPT resonance can be formed using $m_F = \pm 1$ Zeeman sublevels [21, 22, 23, 24]. In a vapor cell this situation is realized only for the D$_1$ line of $^{87}$Rb, when the exited-state hyperfine levels are spectrally resolved. The relevant $\Lambda$ systems formed by the circularly polarized components of two linearly polarized optical fields are shown in Fig. 1(b). In the linear Zeeman effect approximation, shifts of $|F=1, m_F=\pm 1\rangle$ and $|F=2, m_F=\mp 1\rangle$ are almost identical. The two-photon CPT resonance for a $\Lambda$ system formed by the $\sigma_+$ component of one optical field (e.g., $E^{(0)}_+$) applied to the $|F=2, m_F=-1\rangle \rightarrow |F'=1, m_{F'}=0\rangle$ transition and the $\sigma_-$ component of the other optical field ($E^{(+)}_-\rangle$ applied to the $|F=2, m_F=-1\rangle \rightarrow |F'=1, m_{F'}=0\rangle$ occurs at the unshifted clock frequency (i.e., at the hyperfine splitting $\Delta_{\text{hf}}$). The same is true for a symmetric $\Lambda$ system formed by the opposite circular components. The advantage of the lin/lin scheme over a traditional circ/lin is the absence of any “pocket” states, and hence higher contrast of a CPT resonance [21, 24].

In this manuscript we report the first experimental realization of a table-top atomic clock prototype based on a lin/lin CPT resonance in $^{87}$Rb using a VCSEL laser with direct current modulation. Our system is potentially scalable to miniature applications. We demonstrate the cancellation of the first-order light shift of a CPT resonance, confirming the previous results, obtained with an externally phase-modulated narrow-band diode laser [24]. Operating at such light-shift cancellation conditions, we observed promising short-term frequency stability ($\approx 2 \times 10^{-11} \tau^{-1/2}$). The long-term stability is limited by insufficient temperature control of the environment. We expect superior frequency stability will be possible in a small lin/lin CPT clock designed for good thermal control, low phase noise, etc.

A schematic of the experimental apparatus is shown in Fig. 2. We used a temperature-stabilized vertical cavity surface-emitting diode laser (VCSEL), operating at 794.7 nm (Rb D$_1$ line). The laser wavelength was locked to the desired atomic transition using a dichroic-atomic-vapor laser lock (DAVLL) [25]. The details of the apparatus design and construction are described in [26]. To produce the two optical fields required for CPT, we combined the direct laser current with a 6.8347 GHz modulation signal produced by the home-made tunable microwave source described below. For most of the data described below, the unmodulated laser frequency (carrier) was tuned at or near $5S_{1/2} F = 2 \rightarrow 5P_{1/2} F=1$ transition, while the +1 modulation sideband frequency was correspondingly tuned to $5S_{1/2} F = 1 \rightarrow 5P_{1/2} F=1$ transition. We monitored the intensity ratio between the sideband and the carrier using a high-finesse Fabry-Perot cavity with free spectral range of approximately 40 GHz (not shown in the diagram), and we were able to adjust it in a wide range (from zero to more than 100%) by changing the rf power sent to the VCSEL.

The laser beam with maximum total power 120 $\mu$W and a slightly elliptical Gaussian profile (1.8 mm and 1.4 mm full width half maximum (FWHM)), was linearly polarized by a polarizing beam splitter (PBS) and then directed into the cylindrical Pyrex cell (length 75 mm; diameter 22 mm) containing isotopically enriched $^{87}$Rb vapor and 15 Torr of Ne buffer gas. The cell was mounted inside a three-layer magnetic shielding to reduce stray magnetic fields, and its temperature was actively stabilized at 47.5°C. To lift the degeneracy of the Zeeman sublevels we applied a weak homogeneous longitudinal magnetic field $B \approx 12$ mG produced by a solenoid mounted inside the innermost magnetic shield. A photodiode (PD) placed after the cell detected the total transmitted intensity.

The detailed schematic of the home-made microwave source operating at 6.835 GHz is shown in Fig. 3. It consists of a Zcomm CRO6835z voltage control oscillator (VCO), for generation of a microwave field, which is in a phase locked loop (PLL) with a Wenzel 501-04609 voltage controlled oven stabilized 10 MHz crystal oscillator (VCOCXO). A National Semiconductor PLL chip (LMX2487) with a computer controlled fractional divider.
allows rough tuning of the microwave frequency with sub
Hertz steps in several hundreds mega-Hertz range, while
fine tuning is done via variable voltage of the VCOCXO.

To lock the frequency of the microwave source (and
hence the two-photon detuning of the two laser fields)
to the maximum transmission, a slow frequency modula-
tion at \( f_m = 3 \text{ kHz} \) was superimposed on the 6.835 GHz
microwave modulation signal. Then the photodetector
signal was demodulated at \( f_m \) using a lock-in amplifier.
The resulting error signal was fed back to lock the fre-
cquency of the 10 MHz VCOCXO and consequently, the
frequency of the 6.835 GHz signal was phase-locked to
the VCOCXO. The frequency of the locked VCOCXO
was measured by beating it with a reference 10 MHz sig-
nal derived from a commercial atomic frequency standard
(SRS FS725).

To determine the optimal parameters for the mi-
crowave lock operation, we measured the error signal as a
function of lock-in frequency and amplitude. The result-
ing dependence is shown in Fig. 4 Similar to previous
studies \cite{27} we found that there is a particular combina-
tion of the lock-in parameters that result in the highest
slope of the error signal as function of the two-photon de-
tuning: the lock-in frequency \( f_m = 3 \text{ kHz} \) and the modu-
lation depth is 4 kHz. We experimentally confirmed that
under these conditions the microwave lock loop is the
most sensitive, and results in the best frequency stability
measurements.

To ensure stable operation of a CPT-based atomic
clock, the frequency of a CPT resonance must be maxi-
mally decoupled from any fluctuations of the experimen-
tal parameters. For example, any variations in the light
intensity change the measured clock frequency because of
the resonance light shift due to interaction of various
VCSEL modulation components with optical transitions.
Since the overall CPT resonance shift combines the con-
tributions of all optical fields on each ground state, it
has been previously shown \cite{24} that careful adjustment
of the intensity ratio of two CPT optical fields allows
cancellation of the first-order light shift. Our current
measurements confirm that the same cancellation hap-
pens for a current-modulated VCSEL output by adjusting
the microwave modulation strength (and hence the
sideband/cARRIER intensity ratio), even though the VC-

\[ \Delta = 0 \]

\[ \Delta = -200 \text{ MHz} \]

FIG. 3: Schematic of the 6.835 GHz microwave source.

FIG. 4: Dependence of the clock sensitivity in arbitrary uni-
ts on the lock-in modulation frequency and modulation depth.
Crosses mark measured data location with the rest of the map
recreated via interpolation routine.

FIG. 5: Dependence of the clock sensitivity in arbitrary uni-
ts on the lock-in modulation frequency and modulation depth.
Crosses mark measured data location with the rest of the map
recreated via interpolation routine.
nal magnetic field. Three distinct resonances correspond to a magneto-insensitive $|\text{lin}|\text{lin}$ CPT resonance [central peak, created by the fields depicted by solid arrows in Fig. 1(b)], and two additional Zeeman-shifted CPT resonance shifts [two side peaks, caused by the $\Lambda$ configurations shown in dashed arrows in Fig. 1(b)]. As expected from the theory, the central peak has the highest contrast and the narrowest linewidth: two conditions required for optimal microwave oscillator locking.

Fig. 1(b) zooms in on the central $|\text{lin}|\text{lin}$ CPT resonance to analyze its lineshape. The resonance was slightly asymmetric due to non-zero one-photon laser detuning $\delta$. In this case CPT resonance lineshape should be described by a generalized Lorentzian function [32]:

$$ T(\delta) = 1 + \gamma \frac{A\gamma + B(\delta - \delta_0)}{(\gamma)^2 + (\delta - \delta_0)^2}, \quad (1) $$

where $T(\delta)$ is the total laser transmission through the cell normalized to the background $I_{bg}$ (i.e., the transmitted power at large two-photon detuning away from CPT resonance), $\delta_0$ is a resonance shift, $\gamma$ is a CPT resonance linewidth measured at half maximum, and $A$ and $B$ are amplitudes of the symmetric and anti-symmetric Lorentzian components respectively. All of the above parameters are weakly dependent on one-photon detuning $\Delta$.

Under the conditions of the first-order light shift cancellation that we used in our atomic clock, the CPT resonance had the following parameters: resonance width $\gamma = 700 \text{ Hz}$, resonance contrast $C = 6.1 \%$ (where the contrast is defined as a ratio between resonance amplitude and background), and the resonance asymmetry $B/A = 0.29$. Fig. 1(b) shows that Eq. (1) provides excellent fit to the experimental lineshape everywhere except for the peak of the resonance, where we observed higher and sharper transmission than predicted by the fit. This occurs as a result of diffusion of atoms and their repeated interaction with the laser field [32, 34], and it can improve atomic clock frequency stability by further increasing the overall resonance contrast [31]. For example, the measured CPT contrast exceeded 7% compared to the 6% given by the Lorentzian fit. Also, it is important to note that the resonant asymmetry is quite small, and may lead to only a very weak effect of the resonance position on the lock-in slow modulation parameters [32].

The estimated fractional stability of the microwave oscillator locked to the CPT resonance is proportional to the quality figure $Q = C/2\gamma$ – the ratio between the resonance contrast and its full width at half maximum. The measured resonance parameters ($C = 0.07$ and $\gamma = 700 \text{ Hz}$) provide the quality factor $Q \approx 5 \cdot 10^{-5}$/Hz. This value implies the fractional frequency stability (Al- lan variance) at the level of $\sigma(\tau) \sim 2 \cdot 10^{-14} \tau^{1/2}$ if limited
only by the photon shot noise \[36]:

\[
\sigma(\tau) = \frac{1}{4} \sqrt{\frac{\eta e}{I_{bg} q\nu_0}} \tau^{-1/2}.
\]

Here \(\nu_0 = \Delta_h f_s = 6.834 \text{ GHz}\) is the clock reference frequency, \(e\) is the electron charge, \(\eta = 1.8 \text{ W/A}\) is the photodetector sensitivity (measured optical energy per photoelectron), \(I_{bg}\) is the background intensity, and \(\tau\) is the integration time. However, a broad spectral width of VCSEL results in large residual intensity noise at the output of the cell and therefore significantly degrades realistically achievable frequency stability.

Fig. 5 shows the measured fractional Allan deviation of the clock frequency when our prototype CPT clock setup operated at optimal light shift cancellation conditions: we detune our carrier by 200 MHz to decrease sensitivity of the CPT position on the laser detuning (see Fig. 4), and maintain 60% laser field ratio to eliminate light shift dependence (see Fig. 5). The short-term stability was \(\simeq 2 \times 10^{-11} \tau^{-1/2}\) for observation times \(1 \text{ s} \leq \tau \leq 20 \text{ s}\). This value was most likely limited by the large VCSEL phase noise (\(\approx 100 \text{ MHz}\)) as well as by the stability of our commercial reference clock SRS FS725 with manufacturer fractional stability \(< 2 \times 10^{-11}\) at 1 second. At longer integration times the stability degraded due to uncontrolled temperature variations in our tabletop apparatus and their effect on the laser wavelength drift that caused the CPT resonance shift (see Fig. 5). Despite this non-optimal clock apparatus, the measured short-term frequency stability is already comparable or better than the values reported for many recently-demonstrated atomic clocks \[1, 2, 3, 23, 37\]. Our experimental results also match the theoretically predicted stability limited by broad spectral width of a VCSEL \[23\]. We expect that both the short- and long-term frequency stability can be further improved with better temperature stabilization of the experimental apparatus, better laser control, and possibly using a VCSEL diode with reduced linewidth.

In summary, we systematically studied a magnetoinsensitive CPT resonance in the \(\text{lin}||\text{lin}\) configuration using a current-modulated VCSEL on the \(D_1\) line of \(^{87}\text{Rb}\), and identified the optimal parameters for atomic clock operation that cancel the effect of the first-order light shift. Employing this light-shift cancellation in a tabletop apparatus (not engineered for stable clock performance), we nonetheless observed short-term frequency stability of \(\simeq 2 \times 10^{-11} \tau^{-1/2}\) that is comparable to or better than existing CPT clocks. Significant improvements in such clock frequency stability should be possible in a small scale device with standard techniques minimizing the impact of the environment.

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\[\text{References}\]

[1] J. Vanier, Appl. Phys. B 81, 421 (2005).
[2] M. Merimaa, T. Lindwall, I. Tittonen, and E. Ikonen, J. Opt. Soc. Am. B 20, 273 (2003).
[3] S. Knappe, L. Liew, V. Shah, P. Schwindt, J. Moreland, L. Hollberg and J. Kitching, Appl. Phys. Lett. 85, 1460 (2004).
[4] S. Knappe, P. D. D. Schwindt, V. Shah, L. Hollberg, J. Kitching, L. Liew, and J. Moreland, Opt. Express 13, 1249 (2005).
[5] R. Lutwak, J. Deng, W. Riley, M. Varghese, J. Leblanc, G. Tepolt, M. Mescher, D. K. Serkland, K. M. Geib, and G. M. Peake, Proc. 36th Ann. FTTI Meeting, 339 (2004).
[6] J. K. Kominis, T. W. Kornack, J. C. Allred, and M. V. Romalis, Nature 422, 596 (2003).
[7] T. W. Kornack, R. K. Ghosh and M. V. Romalis, Phys. Rev. Lett. 95, 230801 (2005).
[8] V. Shah, S. Knappe, P. D. D. Schwindt, and J. Kitching, Nature Photonics 1, 649 (2007).
[9] M. P. Ledbetter, I. M. Savukov, D. Budker, V. Shah, S. Knappe, J. Kitching, D. J. Michalak, S. Xu, and A. Pines, Proc. Nat. Acad. Sci. 105, 2286 (2008).
[10] W. C. Griffith, R. Jimenez-Martinez, V. Shah, S. Knappe, and J. Kitching, Appl. Phys. Lett. 94, 023502 (2009).
[11] M. Fleischhauer, A. Imamoglu, and J. P. Marangos, Rev. Mod. Phys. 77, 633 (2005).
[12] M. Erhard and H. Helm, Phys. Rev. A 63, 043813 (2001).
[13] S. Knappe, L. Hollberg, and J. Kitching, Opt. Lett. 29, 388 (2004).
[14] N. Cyr, M. Tétu, and M. Breton, IEEE Trans. Instrum. Meas. 42, 640 (1993).
[15] Y. Y. Jau, A. B. Post, N. N. Kuzma, A. M. Braun, M. V. Romalis, and W. Happer, Phys. Rev. Lett. 92, 110801 (2004).
[16] A. V. Taichenachev, V. I. Yudin, V. L. Velichansky, S. V. Kargapol'tsev, R. Wynands, J. Kitching, L. Hollberg,
[17] Y.-Y. Jau, E. Miron, A.B. Post, N. N. Kuzma, and W. Happer, Phys. Rev. Lett. 93, 160802 (2004).
[18] T. Zanon, S. Guerandel, E. de Clercq, D. Holleville, N. Dimarco, and A. Clarion, Phys. Rev. Lett. 94, 193002 (2005).
[19] V. Shah, S. Knappe, L. Hollberg, and J. Kitching, Opt. Lett. textbf{32}, 1244 (2007).
[20] A. V. Taichenachev, V. I. Yudin, V. L. Velichansky, and S. A. Zibrov, JETP Lett. 82, 398 (2005).
[21] G. Kazakov, B. Matisov, I. Mazets, G. Miletli, and J. Delporte, Phys. Rev. A 72, 063408 (2005).
[22] S. A. Zibrov, V. L. Velichansky, A. S. Zibrov, A. V. Taichenachev, and V. I. Yudin, JETP Lett. 82, 477 (2005).
[23] E. Breschi, G. Kazakov, R. Lammegger, G. Miletli, B. Matisov, and L. Windholz, Phys. Rev. A 79, 063837 (2009).
[24] S. A. Zibrov, I. Novikova, D. F. Phillips, R. L. Walsworth, A. S. Zibrov, V. L. Velichansky, A. V. Taichenachev, and V. I. Yudin, arXiv:0910.4703 (2009).
[25] V. V. Yashchuk, D. Budker, and J. R. Davis, Rev. Sci. Instr. 71, 341 (2000).
[26] N. Belcher, E. E. Mikhailov, and I. Novikova, Am. J. Phys., Issue 11, 77, 988-998 (2009).
[27] I. Ben-Aroya, M. Kahnov, and G. Eisenstein, Opt. Express, 15, 15060 (2007).
[28] A. V. Taichenachev, V. I. Yudin, R. Wynands, M. Stahler, J. Kitching, and L. Hollberg, Phys. Rev. A 67, 033810 (2003).
[29] E. E. Mikhailov, I. Novikova, Y. V. Rostovtsev, and G. R. Welch, Phys. Rev. A 70, 033806 (2004).
[30] S. Knappe, M. Stahler, C. Affolderbach, A. V. Taichenachev, V. I. Yudin, and R. Wynands, Appl. Phys. B 76, 57 (2003).
[31] I. Novikova, Y. Xiao, D. F. Phillips, and R. L. Walsworth, J. Mod. Opt. 52, 2381 (2005).
[32] I. Novikova, D. F. Phillips, A. S. Zibrov, R. L. Walsworth, A. V. Taichenachev, and V. I. Yudin, Opt. Lett. 31, Issue 5, pp.622-624 (2006).
[33] Y. Xiao, I. Novikova, D. F. Phillips, and R. L. Walsworth, Phys. Rev. Lett. 96, 043601 (2006).
[34] Y. Xiao, I. Novikova, D. Phillips, and R. L. Walsworth, Opt. Express 16, 14128 (2008).
[35] D. F. Phillips, I. Novikova, C. Y.-T. Wang, M. Crescimanno and R. L. Walsworth, J. Opt. Soc. Am. B 22, 305 (2005).
[36] J. Vanier, M. W. Levine, D. Janssen, M. J. Delaney, IEEE Trans. Instrum. Meas. 52, 822 (2003).
[37] http://www.kernco.com/pdfs/CPT-C01DataSheet060704D.pdf.