LIGHT STORAGE IN A DIFFERENTIAL LIGHT-SHIFT COMPENSATED OPTICAL LATTICE

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Abstract

Lifetimes of a fraction of a second are reported for hyperfine coherences of optically trapped rubidium-87 atoms. Decoherence due to differential ac-Stark shift arising from trapping potentials is suppressed using laser-induced two-photon and "magic" magnetic field techniques. These results have implications for quantum information science and precision measurements.

INTRODUCTION

Achieving long lifetimes for atomic coherence is of major importance for precision measurements and quantum information tasks. These often require elimination of decoherence arising from inhomogeneous external fields and trapping potentials. In atomic fountains, long coherence times have been observed using clock transitions, which are first-order insensitive to magnetic fields **[1]**. However, for quantum information processing, it is important to control the positions of atoms. Also, cold atom clocks may benefit from the more compact size of the apparatus needed to work with localized samples in contrast to atomic fountains. A common strategy involves the use of optical traps **[2]**. Ground-level coherences, for atoms at different positions in the trap, will accumulate different phases due to the differential ac-Stark shift caused by the trapping field. This results in dephasing, typically on millisecond time scales, for protocols in which cold but nondegenerate atoms are distributed across the lattice **[3]**. Spin-wave (collective) qubits have also been stored in a one-dimensional (1D) optical lattice with a lifetime of 7 ms, limited by ac-Stark decoherence **[4,5]**. The differential light shifts for degenerate atomic gases can be decreased by employing lower trap depths **[6]**. But that approach suffers from lower atom numbers, additional cooling steps required, and longer sample preparation.

For optical transitions in alkaline-earth atoms, there exist special wavelengths of the lattice light at which the ac-Stark shifts for ground and excited states are identical. This is used in high-accuracy optical clocks **[7]**. In contrast, complete elimination of the ac-Stark shift for the microwave ground level coherences of alkali atoms in optical lattices had been an outstanding challenge.

Here we describe two different techniques that we used to suppress differential light shift experienced by ^{87}Rb atoms trapped in 1064 nm optical lattice.

LASER INDUCED TWO-PHOTON COMPENSATION

Figure 1(a) illustrates differential light shift experienced by ground state ^{87}Rb atoms in a far-off-resonance 1064 nm trap: $\Delta_{diff}(\mathbf{r}) = (\Delta_{hfs}/\Delta_1)(U(\mathbf{r})/\hbar)$, where Δ_{hfs} = 6.8 GHz is the ground state hyperfine splitting, Δ_1 is the detuning from 5P level, $U(\mathbf{r}) = \hbar\Omega^2_t(\mathbf{r})/4\Delta_1$ is the depth of the trapping potential, and $\Omega_t(\mathbf{r})$ is the

Rabi frequency of the trapping field. Let us consider influence of a compensation laser field which, together with the trapping field, is coupled to the transition $|5S_{1/2}, F=1\rangle \leftrightarrow |6S_{1/2}, F=1\rangle$, as shown in Figure 1(b). For our 1064 nm lattice, the wavelength of the compensation field is 931 nm. We consider a compensation field with a flat intensity profile, so that it does not introduce extra dephasing because of inhomogeneous light shift. The total differential light shift is $\Delta'_{diff}(\mathbf{r}) = \Delta_{diff}(\mathbf{r}) + \delta_c(\mathbf{r}) = (U(\mathbf{r})/\hbar\Delta_1)(\Delta_{hfs} + \Omega^2_c/4\Delta_2)$, where the first term is due to the light shift from the trapping field, while the second term arises from the two-photon transition (Ω_c is the Rabi frequency of the compensation field and Δ_2 is two-photon detuning). For a given compensation field intensity, there is a detuning that eliminates the inhomogeneous differential light shift. In practice, Ω_c is not perfectly homogeneous, leaving an average differential light shift $\Delta''_{diff} = 1/(2\tau)(w_a/w_c)^2/(1 + (w_a/w_t)^2)$, where w_a is the radius of the atomic sample, and w_c and w_t are the waists of the Gaussian compensation and trapping fields, respectively. As the lifetime enhancement scales as $(w_c/w_a)^2$, compensation can be obtained with reasonable beam waists. The compensation comes at the expense of two-photon scattering, which limits the lifetime. The rate of scattering $R \sim \Delta'_{diff}(\Gamma_e/\Delta_2)$ provided $\Delta_2 \leq (\Delta_{hfs} - \Delta_{hfs}^e)/2$. Hence, the maximum value of the lifetime enhancement is of the order $(\Delta_{hfs} - \Delta_{hfs}^e) = (2\Gamma_e)$; here Γ_e is the natural linewidth of the level $|e\rangle$. For our case of $|e\rangle = |6S_{1/2}, F=1\rangle$, the maximum enhancement is $\sim 10^3$.

The enhancement factor can in principle be increased by choosing a smaller Γ_e (for example, by employing a Rydberg level). Alternatively, for a circularly polarized optical lattice, the two-photon transition could begin and terminate on the ground clock states (Figure 1(c)). In this case the compensation field would be a frequency-shifted (by $\Delta_{hfs} \pm \Delta_{2ph} \approx 2\pi \cdot 6.8$ GHz) component of the trapping laser field. As $|e\rangle$ is a ground clock state, $\Gamma_e = 0$ and the lifetime enhancement is expected to be limited by inhomogeneity of the compensating field across the atomic cloud. Population transfer between the clock states is negligible when $(\Omega_{2ph}/\Delta_2)^2 \ll 1$, where Ω_{2ph} is the effective two-photon Rabi frequency.

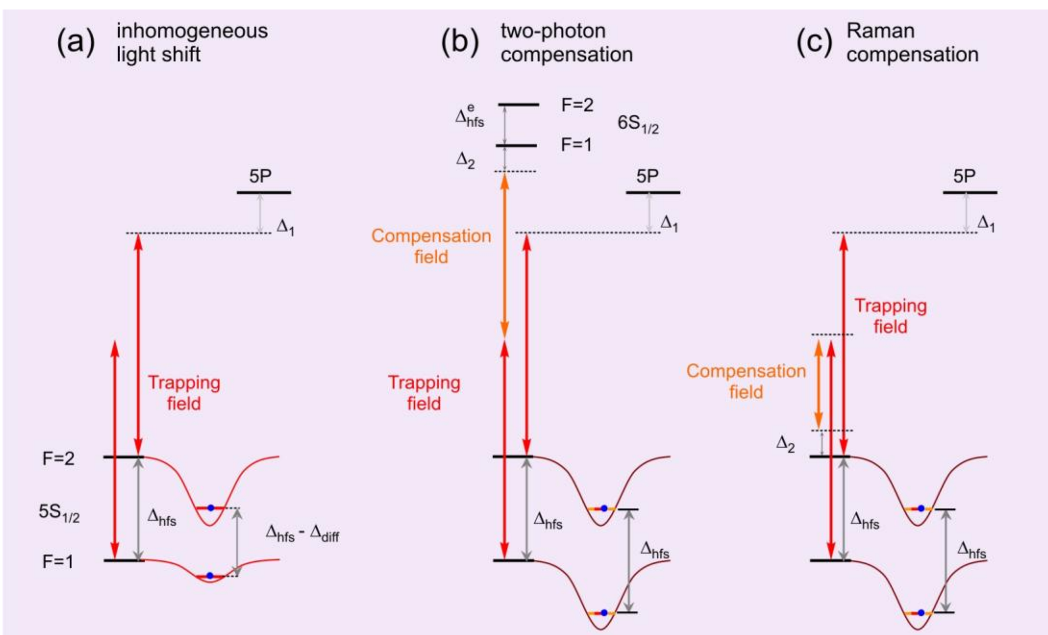

Figure 1. (a) Illustration of inhomogeneous light shift experienced by optically trapped atoms. (b) Two-photon compensation with $6S_{1/2}$ level. (c) Two-photon compensation with Raman configuration of light fields.

To measure ground state coherence times we perform a light storage experiment **[8]**. The experimental setup is shown in Figure 2. We load ^{87}Rb atoms into a magneto-optical trap from background vapor. After compression and post-cooling, the sample is transferred to a 1D optical lattice, resulting in an approximately cigar-shaped cloud of $\sim 10^7$ atoms with $1/e^2$ waists of 130 and 840 μm, respectively. The lattice is formed by interfering two, circularly polarized, 1064-nm (in vacuum) beams intersecting at an angle of 9.6 deg in the horizontal plane. The beams have waists of ~200 μm, and their total power is varied between 8 and 14.6 W.

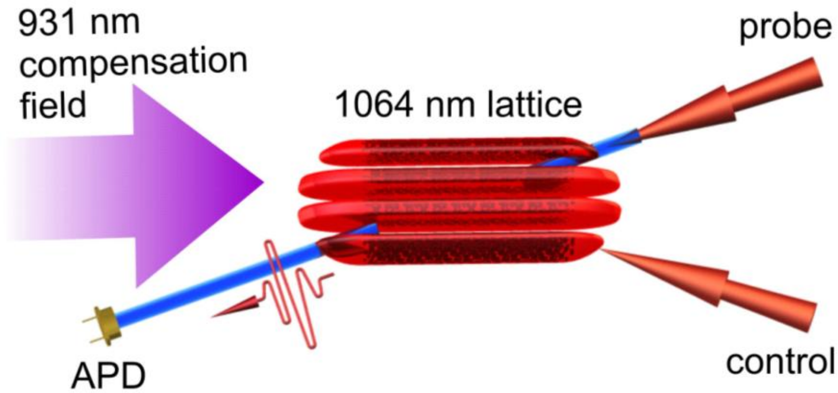

Figure 2. The experimental setup showing a cold sample of ^{87}Rb atoms in an optical lattice formed by interfering two 1064 nm beams. Probe and control fields are derived from single mode fibers. Retrieved field is coupled to a single mode fiber followed by an avalanche photodiode detector (APD).

After loading, a bias magnetic field is applied along the major axis of the trap and atoms are prepared in the $|5S_{1/2}, F=2, m=0\rangle$ state by means of optical pumping. The probe and control fields are tuned to corresponding D1-resonance lines $|a\rangle \leftrightarrow |c\rangle$ and $|b\rangle \leftrightarrow |c\rangle$, respectively, where $\{|a,b\rangle\}$ corresponds to $\{5S_{1/2}, F = 2,1\}$ and $\{|c\rangle\}$ represents $\{5P_{1/2}, F = 2\}$. The compensating beam has wavelength 931 nm and a Gaussian beam profile with waist size 0.46 mm and power 498(15) mW, stabilized by current feedback to the tapered laser amplifier. The two-photon detuning is stabilized to the value $\Delta_2/(2\pi) = -235$MHz from the $|a\rangle \rightarrow |e\rangle$ transition by the frequency locking to a Doppler-free atomic fluorescence signal from a heated vapor cell.

Figure 3 shows the measured efficiency of the retrieved signal as a function of storage time. By comparing the measured lifetime in traps of various depths we observe a factor of approximately 10 lifetime enhancement (see the comparison data for a 48 μK trap in Figure 3a). The maximum memory lifetime of 165 ms is observed for the shallowest, 33 μK, trap (Figure 3b). Longer lifetimes could be readily observed using shallower traps at the cost of reduced retrieval efficiency associated with fewer trapped atoms. The enhancement factor is limited by spontaneous emission from level $|e\rangle$ and alignment and inhomogeneity of the compensation field across the atomic sample. These contributions are largely determined by the power of the compensation laser-diode amplifier system, so that the storage time could be further increased with a more intense source.

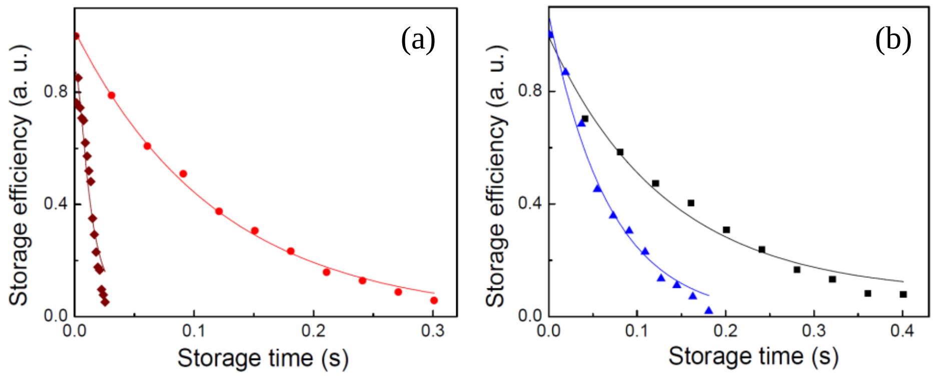

Figure 3. Storage efficiency as a function of storage time. Solid lines are fits of the form $e^{-T/Tc}$ for lattice with compensation, and $(1+(T/T_c)^2)^{-3/2}$ without one. (a) Circles: 48 μK lattice with compensation (T_c = 120 ms, efficiency 3.8%); diamonds: 48 μK lattice without compensation (T_c = 12 ms, efficiency 3.1%). (b) Triangles: 33 μK lattice with compensation (T_c = 165 ms, efficiency 1.6%); diamonds: 62 μK lattice with compensation (T_c = 68 ms, efficiency 3.7%).

"MAGIC" MAGNETIC FIELD COMPENSATION

Recently, Lundblad *et al.* proposed and demonstrated spectroscopically that by mixing the two ground hyperfine levels with a dc magnetic field, it is possible to eliminate ac-Stark shift on the clock transition in an elliptically polarized lattice at a particular (magic) magnetic field value **[9]**. While the clock coherence becomes first-order sensitive to the magnetic field, it is weakly so, and this is promising for greatly increased coherence times. The idea is based on the fact that for an atom in a circularly polarized light field and a dc magnetic field, the clock transition is shifted by $\alpha^1_{12} I \cdot B_0$, where α^1_{12} is the differential vector polarizability, I is the light field intensity, and B_0 stands for the magnetic field. The value of the magnetic field for which this shift cancels the differential scalar light shift is called "magic". Magic magnetic fields values also exist for |F=1, m=∓1> ↔ |F=2, m=±1>. Further details may be found in **[9, 10]**.

We report measurements of increased clock coherence times using this technique. The experimental arrangement is similar to the one described above with the exception of the lattice beams being circularly polarized. Three different polarization configurations of the probe and control fields are employed, each exciting a different long-lived hyperfine coherence: lin ⊥ lin configuration for the clock coherence and σ±/σ∓ configuration for the ∓1/±1 coherences. Atoms are either prepared in the $|5^2S_{1/2}, F = 1, m = 0\rangle$ state by means of optical pumping when clock coherence is addressed or left unpolarized when ∓1/±1 coherences are used.

In order to determine magic magnetic field values for the clock coherence ($B_0^{(0)}$) and for the ∓1/±1 coherences ($B_0^{(\pm)}$), we maximize the retrieved pulse energy while tuning the magnetic field strength, as shown in Figure 4(a). The data are fitted with the function $\exp[-\gamma(B - B_0)^2]$, γ being an adjustable parameter, resulting in $B_0^{(0)}$ = 4.24(1) G, $B_0^{(+)}$ = 5.42(1) G, and $B_0^{(-)}$ = 5.99(2) G, respectively, where the 0.01 G uncertainty is the combined statistical and field calibration error.

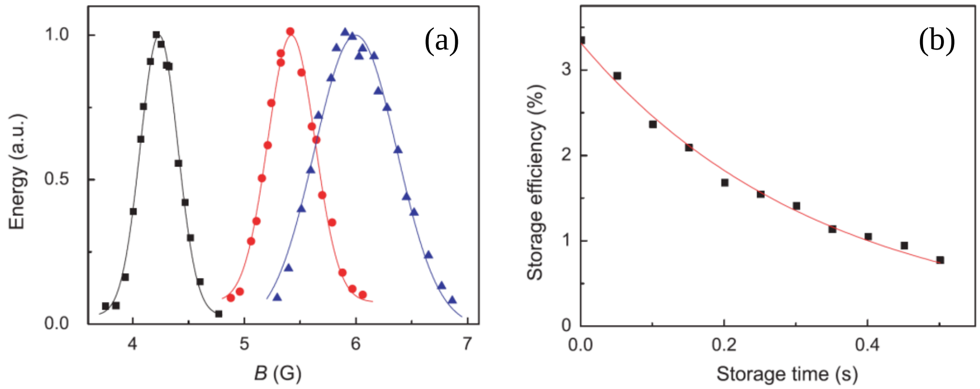

Figure 4. (a) Retrieved pulse energy as a function of magnetic field for three long-lived coherences: squares for clock coherence, circles and triangles for -1/1 and 1/-1 coherences respectively. (b) Efficiency of the retrieved signal as a function of the storage time at $B_0^{(0)} = 4.2$ G for 0-0 coherence in a 48-μK-deep lattice.

The decay of the retrieved signal is well described by an exponential function of storage time (Figure 4(b)). The 1/*e* storage lifetimes τ for clock coherence are shown in Figure 5(a) as a function of applied magnetic field. We observed no significant change in lifetime for trap depths between 34 and 64 μK. The lifetimes for ∓1/±1 coherences are $\tau_- = 0.43(2)$ s and $\tau_+ = 0.10(1)$ s. These can be explained by a combination of the 1-s lifetime of the atoms in the lattice and of the concomitant effective magnetic moments μ´ of the coherences, $\mu' \equiv dE/dB$. The lifetime of a coherence τ in a gradient of the ambient magnetic field *B* is expected to be inversely proportional to μ: $\tau^{-1} = 2\pi\mu' B' l$, where *l* is the length of the atomic sample. After excluding the atomic loss contribution to the measured storage lifetime via $1/\tau_{c,\pm} = 1/\tau^{m}_{c,\pm} + 1/T$, the residual lifetime $\tau^{m}_{c,\pm} \equiv T\,\tau_{c,\pm}/(T - \tau_{c,\pm})$is displayed in Figure 5(b).

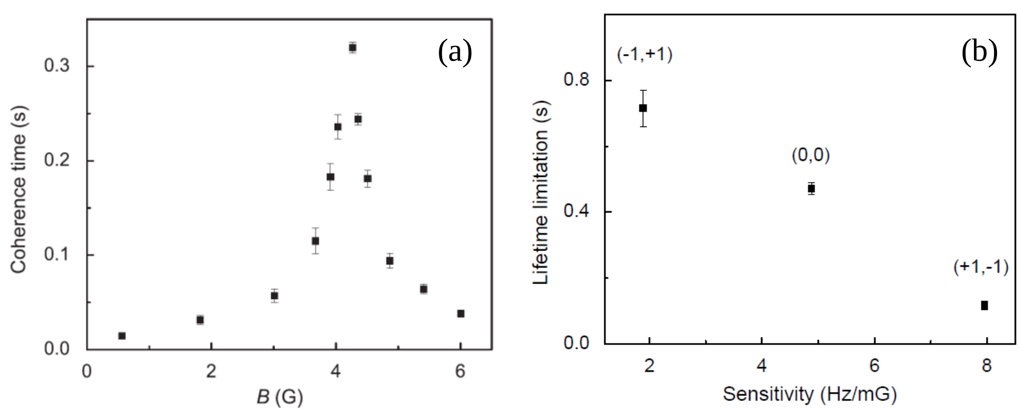

Figure 5. (a) The 1/*e* lifetime as a function of the magnetic field in a 64-μK-deep lattice. (b) The residual lifetime $\tau^{m}_{c,\pm}$ as a function of the effective magnetic field moment $\mu' \equiv dE/dB$, for the three long-lived coherences, each at its respective magic field value, in a 64-μK-deep lattice.

In conclusion, we have achieved a combination of high efficiency and exceptionally long storage time for coherent light pulses in an ac-Stark compensated optical lattice. Laser-induced and magic magnetic field compensation techniques have been demonstrated. These results allowed for demonstration of long-lived quantum memories **[8, 11]** and may be useful for future implementations of a lattice-based cold alkali atom clock.

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