Resonator-Enhanced Optical Dipole Trap for Fermionic Lithium Atoms

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We demonstrate a novel optical dipole trap which is based on the enhancement of the optical power density of a Nd:YAG laser beam in a resonator. The trap is particularly suited for experiments with ultracold gases, as it combines a potential depth of order 1 mK with storage times of several tens of seconds. We study the interactions in a gas of fermionic lithium atoms in our trap and observe the influence of spin-changing collisions and off-resonant photon scattering. A key element in reaching long storage times is an ultra-low noise laser. The dependence of the storage time on laser noise is investigated.

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Far-detuned optical dipole traps are rapidly becoming standard tools for atomic physics at ultralow temperatures [1]. They allow trapping of practically any atomic species, and even molecules. In the field of quantum gases they allow trapping of mixed-state and mixed-species ensembles. The coupling of the atoms to the light field, which is small for far detuned traps, can be strongly enhanced by means of an optical resonator. Indeed, in cavity quantum electrodynamics experiments, single atoms have been trapped by a light field that corresponds to a single photon [2]. Optical resonators have also been used to sensitively detect optical fields in a quantum non-demolition way using cold atoms [3], and even open up new possibilities for optical cooling of atoms and molecules [4].

We take advantage of the resonant enhancement of the optical power required to create such a trap without resonant enhancement exceeds 100 W. Our REDT only requires a 1.2 W Nd:YAG laser (λ = 1064 nm), the power density of which is resonantly enhanced 130-fold in a 15 cm near-confocal resonator (See Fig. 1). The resonator mirrors are placed outside the vacuum, which facilitates adjustment of the resonator and at the same time avoids many of the problems associated with optics in ultra-high vacuum (UHV). The MOT overlaps with approximately 1000 antinodes of the standing wave, which act as separate microtraps, with an axial separation of λ/2 = 532 μm and a radial extension given by the beam waist, w₀ = 160 μm. The resonator length is increased by ∼ 3 mm from the confocal condition to lift the degeneracy of the higher order modes. The optical losses at the vacuum windows are minimized by using a high purity fused-silica UHV cell and by traversing all intracavity glass surfaces at Brewster’s angle. The small residual round trip loss L permits a maximal resonant enhancement A = 1/L, where the resonant enhancement factor A is defined as the increase of the intracavity intensity compared to a retroflected beam standing wave.

In this letter we demonstrate a resonator-enhanced dipole trap (REDT) for experiments with ultracold gases. We take advantage of the resonant enhancement of the optical power density and the corresponding trap depth. To suppress photon scattering and reach storage times of several tens of seconds, the detuning of the trap light from the atomic resonances is large. At the same time the trap volume and potential depth are large to transfer many atoms into the trap. We expect the high optical power density reached in the REDT will be useful in many contexts, for instance for trapping earth-alkali atoms, buffer-gas cooled atoms or cold molecules.

Our primary interest is in spin mixtures of fermionic ⁶Li, as a promising candidate system for the formation of Cooper pairs in an atomic gas [5]. In particular, we aim to study Feshbach scattering resonances which have been predicted at experimentally accessible magnetic fields, which may provide a binding mechanism for the Cooper pairs [6].

To sufficiently suppress photon scattering, the trap light must be detuned from the 670-nm D lines of Li by few hundred nm. In addition, to capture atoms from a magneto-optical trap (MOT), the optical trap must have a depth of the order of the temperature of Li in a MOT (∼ 1 mK), and a similar spatial extension. The optical power required to create such a trap without resonant enhancement exceeds 100 W. Our REDT only requires a 1.2 W Nd:YAG laser (λ = 1064 nm), the power density of which is resonantly enhanced 130-fold in a 15 cm near-confocal resonator (See Fig. 1). The resonator mirrors are placed outside the vacuum, which facilitates adjustment of the resonator and at the same time avoids many of the problems associated with optics in ultra-high vacuum (UHV). The MOT overlaps with approximately 1000 antinodes of the standing wave, which act as separate microtraps, with an axial separation of λ/2 = 532 μm and a radial extension given by the beam waist, w₀ = 160 μm. The resonator length is increased by ∼ 3 mm from the confocal condition to lift the degeneracy of the higher order modes. The optical losses at the vacuum windows are minimized by using a high purity fused-silica UHV cell and by traversing all intracavity glass surfaces at Brewster’s angle. The small residual round trip loss L permits a maximal resonant enhancement A = 1/L, where the resonant enhancement factor A is defined as the increase of the intracavity intensity compared to a retroflected beam standing wave.
trap. To obtain the maximum enhancement, the reflectivity \( R \) of the input coupler must match \( \mathcal{L} \). For our UHV cell we measured \( \mathcal{L} = 0.004(2) \) in a test resonator, and correspondingly we chose \( R = 0.9940(2) \). This theoretically would allow a resonant enhancement factor of 240, at a calculated finesse \( F = 600 \). We typically measure \( A = 130 \pm 15 \), at \( F = 650 \pm 60 \), where the loss is due to incomplete mode matching.

A rigid resonator body, which is acoustically decoupled from mechanical vacuum pumps by flexible bellows, provides passive stability. In addition a piezomechanical actuator compensates for changes in the cavity length caused e.g. by thermal drifts and acoustical noise. This servo loop, with a servo bandwidth of 8 kHz, uses the Hänisch-Couillaud method to derive an error signal \( \tilde{E} \), where the Brewster windows act as the intracavity polarizer. No high-bandwidth stabilization proved to be necessary. The drive laser for the resonator trap is a commercially available ultra-low-noise 1.2 W diode pumped solid state Nd:YAG laser (Innolight “Mephisto”). Two Faraday rotators provide a 70 dB reduction of feedback of the resonator to the laser, and an acousto-optical modulator provides control over the laser power admitted to the cavity. Approximately 20\% of the laser power is lost in these elements.

The energy density inside the cavity is the same as in a retroflected 130 W beam, which leads to a calculated trap depth of 0.8 mK \( k_B T \). The corresponding photon scattering rate in the intensity maximum is calculated to be \( \sim 1 \text{ s}^{-1} \). In the harmonic approximation of the potential near the trap center we calculate the axial and radial trap frequencies \( \omega_{\text{ax}}/2\pi = 1.4 \text{ MHz} \) and \( \omega_{\text{rd}}/2\pi = 2.0 \text{ kHz} \). The trap, however, is very anharmonic and atoms in higher vibrational states oscillate at lower frequencies.

Our source of cold atoms is a MOT based on diode lasers \[^8\text{Li} \] which consists of a “cooler” beam, detuned \(-20 \text{ MHz}\) from the \( ^2S_{1/2} F = 3/2 \rightarrow ^2P_{3/2} F = 5/2 \) transition and a “repumper” at \( \sim 20 \text{ MHz} \) from \( ^2S_{1/2} F = 1/2 \rightarrow ^2P_{3/2} F = 3/2 \). In the MOT we collect approximately \( 2 \times 10^7 \) atoms in 10 seconds from a Zeeman slowed beam. The atoms then are cooled and compressed by reducing the detunings, to a density \( \sim 10^{11} \text{ cm}^{-3} \) at a temperature \( \lesssim 1 \text{ mK} \). The MOT light beams and magnetic fields are turned off after 20 ms of compression. The REDT is kept permanently on during the MOT phase as it does not influence the loading of the MOT. Approximately 0.5\% of the atoms remain in the REDT after the MOT is turned off, the remainder being lost in the first 60 ms. Atoms remaining in the REDT are detected by turning on the MOT fields again and subsequently measuring the fluorescence. The fluorescence is proportional to the number of atoms in an optically thin MOT, with an uncertainty of 50\% in the calibration.

The number of atoms transferred into the REDT can be estimated for a shallow trap (trap depth smaller than MOT temperature) as the phase-space density provided by the MOT multiplied by the number of quantum states in the shallow trap. The latter increases with the trap depth to the power \( 3/2 \). We observe this behavior experimentally up to the maximum available power, even though the condition of a shallow trap is not strictly fulfilled.

\[^8\text{Li} \] strongly depend on the composition of the trapped gas. By choosing the order in which we turn off the MOT light fields we can influence this composition: turning off the repumper several milliseconds before the cooler we obtain atoms in the \( F = 1/2 \) state, by leaving the repumper on longer we obtain atoms in the \( F = 3/2 \) state. Atoms in the \( F = 3/2 \) state are lost from the trap due to spin changing collisions with a second order decay rate \( N/N^2 = 2 \times 10^{-5} \text{ s}^{-1} \) (see curve in Fig. 2). Since the initial density of the trapped atoms is of order \( 10^9 \text{ cm}^{-3} \) this implies a rate constant of order \( 10^{-9} \text{ cm}^3/\text{s} \) in agreement with theoretical predictions \[^5\text{Li} \].

\[^5\text{Li} \]
The atoms in the $F = 1/2$ hyperfine ground state are non-interacting to a very good approximation, since the $s$-wave scattering length between the two Zeeman sublevels is very small in low magnetic field, and $p$-wave scattering is expected to be strongly suppressed at the relevant energies. The data show an initial fast decay on the order of 10 s, followed by a long storage time, the latter being well described by an exponential decay with a time constant of $\sim 50$ s. The initial decay can be explained as follows: Since the density of trapped states in our potential is strongly peaked just below the trap edge, a large fraction of atoms occupy states which are only very weakly bound. A single photon recoil momentum then suffices to transfer such an atom into an untrapped state, therefore the number of weakly bound atoms decays strongly in the first few photon scattering times. We numerically modeled the effect of photon scattering and rest-gas collisions on the distribution of the atoms, starting from a distribution that matches the density of states in the trap. Details of this model will be published elsewhere. The model curve (Dashed line in Fig. 2), which has no adjustable parameters except for the initial number of atoms, fully agrees with our measurements.

Laser intensity noise, especially at twice the axial trap frequency, causes heating of the atomic gas since fluctuations of the trap potential at this frequency exert resonant work on the gas. The resonator has a mode-cleaning effect: the modes have a spatially well defined profile and pointing- and shape fluctuations of the laser beam do not affect the shape of the trap potential. However, these fluctuations are converted to intensity fluctuations. Great care must therefore be taken in choosing the drive laser: the absence of laser noise especially at frequencies around $2\omega_{ax}$ is crucial to obtaining long storage times. An estimate of the relevant loss rate can be found from a harmonic oscillator model [11]:

$$\Gamma = 2\pi\nu^2 S_k(2\nu),$$

where $\nu$ is the relevant oscillation frequency and $S_k$ is the one-sided power spectrum of relative intensity noise (RIN) as defined in [11].

In preliminary experiments with a different single-frequency diode pumped Nd:YAG laser, with a RIN of $S_k(2\omega_{ax}) = 10^{-10}$Hz$^{-1}$, we were able to trap atoms, but storage times were less than one second. The “Mephisto” laser, which has $S_k(2\omega_{ax}) \leq 10^{-14}$Hz$^{-1}$, is much more suitable as drive laser and enables the long storage time shown in Fig. 2. To study the strong dependence of the storage time on laser noise we modulated the laser output power with white noise (bandwidth 5 MHz). The resulting intracavity RIN was measured on an InGaAs photodiode behind the resonator end mirror. Figure 3 shows that the storage time is inversely proportional to the intensity noise level, $\tau^{-1} = (4.5 \times 10^{13}$s$^{-1}) \times S_k(2\omega_{ax}) \times$Hz. The loss rate due to laser noise becomes of the same order as the rest-gas and photon scattering terms at a RIN level of $S_k = 0.5 \times 10^{-15}$Hz$^{-1}$.

The measured storage times are slightly shorter than the characteristic times predicted by the harmonic oscillator model of Ref. [11], which is probably due to the anharmonicity of the trap: Many atoms oscillate at lower frequencies and hence respond to a different part of the noise spectrum.

In conclusion, we have demonstrated a resonator-enhanced dipole trap that traps approximately $10^5$ fermionic lithium atoms. Although this type of trap is sensitive to laser noise, a storage time of several tens of seconds can be reached by using an ultra-low noise laser. On this time scale atoms are lost due to photon scattering and rest-gas collisions.

The storage time in our present system greatly exceeds the expected collision times in the Li gas at fields $\sim 0.08\text{T}$, which are of order one second. Since the thermal energy of the trapped gas is comparable to the trap depth, these collisions will then lead to evaporative cooling of the gas, which can be observed through loss of atoms. Additionally, by lowering the trap potential in a controlled way we can measure the energy distribution of atoms in the trap. Thermalization and loss measurements taken together will characterize the interactions in the vicinity of the Feshbach resonance.

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