Cold atoms in a high-\(Q\) ring cavity

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We report the confinement of large clouds of ultracold \(^{85}\text{Rb}\) atoms in a standing-wave dipole trap formed by the two counterpropagating modes of a high-\(Q\) ring cavity. Studying the properties of this trap, we demonstrate loading of higher-order transverse cavity modes and excite recoil-induced resonances.

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The tremendous progress of ultracold atomic physics in the past decades is mainly due to the invention of powerful techniques for trapping and cooling atoms. Besides magnetic traps, optical forces are used to store atoms in tightly focused red-detuned laser beams, in the antinodes of a standing wave formed by two counterpropagating laser beams or even in three-dimensional optical lattices. Spontaneous scattering processes are avoided by tuning the lasers far from resonance. High light intensities are then needed to keep the atoms from spontaneous Rayleigh scattering of a photon between the counterpropagating laser beams. In multimode configurations to study the atomic motion which do not rely on sudden changes of the intracavity intensity. This is because the long lifetime of a high-\(Q\) cavity inhibits the nonadiabatic switch off of deep cavity dipole traps and thus impedes a straightforward interpretation of time-of-flight (TOF) images to determine the temperature.

In a recent paper [14], we have shown that a far-detuned optical lattice can be formed inside a high-\(Q\) ring cavity and that heating due to intensity fluctuations can be kept at very low levels despite of the need to maintain a sharp resonance condition by a high-bandwidth servo control. Here, we present a setup where we show that the atomic motion can be probed nondestructively and \textit{in situ} by recoil-induced resonances [15]. There is an important reason to look for methods to study the atomic motion which do not rely on sudden changes of the intracavity intensity. This is because the long lifetime of a high-\(Q\) cavity inhibits the nonadiabatic switch off of deep cavity dipole traps and thus impedes a straightforward interpretation of time-of-flight (TOF) images to determine the temperature.

We fill our ring-cavity dipole trap with \(^{85}\text{Rb}\) atoms from a standard magneto-optical trap (MOT) that is loaded from a vapor generated by a rubidium dispenser. Typically, we load \(10^9\) atoms into the MOT at temperatures around 140 \(\mu\)K with a vapor pressure of \(3 \times 10^{-9}\) mbar.

The geometry of the ring cavity is shown in Fig. 1. The transmissions \(T_i\) of the mirrors depend on the (linear) polarization of the light modes. For \(s\) polarization \(T_0 = 27 \times 10^{-6}\), \(T_1 = T_2 = 2 \times 10^{-6}\), while for \(p\) polarization \(T_0 = 2200 \times 10^{-6}\), \(T_1 = T_2 = 9 \times 10^{-6}\). The experiments pro-

![FIG. 1. Geometry of the ring cavity. The atomic cloud is located in the free space waist of the cavity mode. The system is characterized by the pumping parameter \(\eta_1\), the atom-field coupling \(g\), the laser detuning with respect to the cavity \(\Delta_c\), and to the atomic resonance \(\Delta_a\), and the decay rate of the atom \(\Gamma\) and of the cavity field \(\kappa\).]

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sented here are carried out with $p$-polarized light and a measured finesse of $F = 2500$, which corresponds to an intracavity intensity decay rate of $2 \pi \times 1.4$ MHz. However, by simply rotating the polarization of the light injected into the cavity, we can switch to $s$ polarization, where we measure using the ring-down method a much higher finesse of $F = 170,000$ corresponding to $2 \pi \times 21$ kHz. The round-trip length of the ring cavity is $L = 85$ mm, the beam waists in horizontal and in vertical direction at the location of the MOT are $w_c = 129 \mu$m and $w_h = 124 \mu$m, respectively. This yields a cavity mode volume of $V_{mode} = (\pi/2)Lw_cw_h = 2$ mm$^3$. The intracavity power $P$, largely enhanced by the factor $F/\pi$ to values around 10 W, gives rise to an optical potential with a depth of $k_B \times 1.4$ mK at the wavelength 799 nm. The radial and axial secular frequencies in the harmonic region close to the center of the trap are $\omega_{rad}/2\pi = 1$ kHz and $\omega_{ax}/2\pi = 700$ kHz.

The ring cavity is driven by a titanium-sapphire laser delivering up to 2 W output power into three optical modes separated by 1.2 GHz [16]. The central mode is filtered by an external confocal Fabry-Perot etalon. The titanium-sapphire laser is locked to one of the eigenfrequencies of the ring cavity using the Pound-Dreher-Hall locking technique [17,18] (see Fig. 2). A feedback servo drives a piezoelectric transducer mounted in the titanium-sapphire laser cavity, whose frequency response is limited to 10 kHz. Faster fluctuations of the laser frequency are balanced by means of an external double-passed acousto-optic modulator (AOM). The servo bandwidth of 1 MHz is limited by a 100 ns time delay in the response of the AOM. The laser frequency is stable enough to yield intensity fluctuations observed in the cavity transmission signal below 2% even in the high finesse case.

The dipole trap is permanently operated, because keeping the titanium-sapphire laser locked requires a certain amount of light inside the cavity. The standing-wave dipole trap is loaded from a spatially overlapping MOT for a period of 15 s. Before switching off the MOT, we apply a 40-ms-temporal-dark MOT stage [19] by increasing the detuning of the MOT laser beams to $-90$ MHz and reducing the intensity of the repumping beams. For the conditions given above, we typically capture $3 \times 10^7$ atoms distributed over 10,000 antinodes of the standing wave. The temperature of the atomic ensemble is measured using the TOF method. We suddenly switch off the dipole trap and image the shadow that the cloud imprints on a weak probe beam after a period of ballistic expansion. Note that, since we operate in a regime of low cavity finesse, the switch-off time is fast compared to the trap’s secular frequencies. During the expansion, the initial momentum distribution of the cloud evolves into a density distribution, whose radial width yields the temperature of the cloud. Depending on the potential well depth, we obtain temperatures between 70 and 280 $\mu$K, corresponding to roughly $1/5$ of the well depth. The peak density is typically $3 \times 10^{12}$ cm$^{-3}$. The lifetime of the dipole trap measured at 799 nm is 0.5 s. A thorough investigation of trap loss processes in a similar system is presented in Ref. [14].

With a slight misalignment of the incoupled laser beam, the ring cavity can be locked to higher-order transverse modes, into which the atoms can settle. Figure 3 shows absorption pictures of atomic clouds confined in different higher-order transverse modes. Such modes exhibit an enhanced surface-to-volume ratio, which may prove advantageous for forced evaporation.

We perform spectroscopy of recoil-induced resonances (RIR) [15,20,21], i.e., we probe two-photon Raman transitions between two velocity states of the same atom. Two Raman beams $k_1$ and $k_2$ enclosing a small angle $\theta = 13.1^\circ$ are radiated onto the atomic cloud such that the difference vector $q = k_1 - k_2$ is oriented nearly parallel to the dipole trap symmetry axis $\hat{z}$. The two beams, whose frequencies are $\omega_1$ and $\omega_2$, give rise to a standing wave with periodicity $2\pi/q$ slowly moving in $\hat{z}$ direction with velocity $v_z = \Delta \omega/q$, where $q = (k_1 + k_2)\sin(\theta/2)$ and $\Delta \omega = \omega_1 - \omega_2$. The light wave leads to a periodic dipole potential for the atoms, which in our experiment has a well depth of $60 \mu$K in units of $k_B$. Only atoms satisfying the energy and momentum conservation requirement can undergo Raman transitions, i.e., only atoms moving synchronously to the standing wave can scatter light from one beam into the other. This scattering is monitored as an intensity variation in one of the beams. The net rate for scattering from beam 2 into beam 1 may be written as $W(v_z = \Delta \omega/q) = (h/2\pi)\Omega_{k_1}^2N\Xi/v_z$, where $\Pi(v_z)$ denotes the Maxwell-Boltzmann momentum distribution, $N$ the number of atoms, and $\Omega_{k_1} = \Omega_1\Omega_2/2\Delta$ with the

FIG. 2. Experimental setup for pumping both directions of the ring cavity, while locking the laser to a resonator eigenfrequency via the Pound-Dreher-Hall technique. The AOM and the piezo rule out the laser frequency fluctuations. Also shown are the demodulated reflection signal (a) and the transmission signal (b) of the cavity.

FIG. 3. Absorption pictures of atoms stored in higher-order transverse cavity modes.
The dipole trap. Ringing is already very pronounced at this rate. Trace (c) shows a spectrum of RIR resonances recorded on free atoms. The intensity of Raman beam with \( \omega_2 \) is measured, while the frequency of beam with \( \omega_2 \) is scanned. Both beams were detuned by \(-110\) MHz from resonance and their peak intensities were \( 50\) mW/cm\(^2\). The scan rate was \( 2.1\) kHz/\( \mu \)s. Trace (b) shows calculated transition rate for the same parameters assuming a \( 100\)–\( \mu \)K cold cloud. Trace (c): Same conditions but recorded on trapped atoms. The trap had a well-depth of \( U_0 = h \times 30\) MHz = \( k_B \times 1.4\) mK corresponding to secular frequencies \( \omega_c = 2\pi \times 700\) kHz and \( \omega_r = 2\pi \times 1\) kHz. Trace (d) shows a simulation (see text) of the susceptibility of a two-level atom subject to a laser quickly swept over its resonance. The chosen decay rate was \( \Gamma = 2\pi \times 5\) kHz and the Rabi frequency \( \Omega = 0.1\) \( \Gamma \).

Resonant Rabi frequencies \( \Omega_1 \) for each Raman beam. By varying \( \Delta \omega \), the derivative of the Maxwell-Boltzmann momentum distribution is scanned from which the temperature can be derived [21]. Trace (a) of Fig. 4 shows such RIR-scans recorded on a cloud 200 \( \mu \)s after being released from the dipole trap. Trace (b) has been calculated assuming a 100–\( \mu \)K cold cloud.

The scan rate must be judiciously chosen [22]. If the scan rate is too slow, the atoms are notably redistributed between the velocity classes while scanning. The above expression shows that the scattering process preferentially occurs towards higher velocities, so that although the momentum transfer is quite small, the cloud is slightly heated under the influence of the Raman beams. If, on the other hand, the scan rate is too fast the signal can be strongly distorted and a ringing-type oscillation is observed [23]. For an untrapped cloud of atoms first indication of ringing can be observed for scan rates above \( 2.1\) kHz/\( \mu \)s. For trapped atoms, however, ringing is already very pronounced at this rate. Trace (c) shows a spectrum of RIR resonances recorded on a cloud 200 \( \mu \)s after being released from the dipole trap. Trace (b) has been calculated assuming a 100–\( \mu \)K cold cloud.

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induced resonances, we can excite and probe the motion of atoms trapped in the ring-cavity field. In the near future, we plan to look for the expected feedback of the atomic motion on the standing light wave and for interatomic coupling induced by the standing wave. It is also tempting to explore the predicted new types of cavity cooling in view of their aptitude of cooling below the threshold of quantum degeneracy. The Bose-Einstein condensates are very appealing objects in the context of ring-cavity studies. For example, Meystre and co-workers [25] have discussed the use of ring cavities for recycling super-radiant light pulses produced by Rayleigh-scattering off condensates [26] and predict for such systems the possibility of mutual coherent quantum control between optical and matter-wave modes.

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[23] Similar observations have been made in the case of untrapped atoms for a very rapid change of the detuning \( \Delta \omega \) from zero to a nonzero value [24]. In this case, the observed oscillations have been explained with the development of a stationary atomic density grating periodically sensed by the Raman standing wave moving with velocity \( \Delta \omega \).