Optical lattice on an atom chip

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Optical dipole traps and atom chips are two very powerful tools for the quantum manipulation of neutral atoms. We demonstrate that both methods can be combined by creating an optical lattice potential on an atom chip. A red-detuned laser beam is retroreflected using the atom chip surface as a high-quality mirror, generating a vertical array of purely optical oblate traps. We transfer thermal atoms from the chip into the lattice and observe cooling into the two-dimensional regime. Using a chip-generated Bose–Einstein condensate, we demonstrate coherent Bloch oscillations in the lattice. © 2009 Optical Society of America

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The engineering quantum states on a microscale has been a long standing goal in atomic physics and quantum optics. Atom chips [1,2] provide a robust technological basis for the manipulation of neutral atoms, e.g., coherent manipulation of internal (spin) [3] and external (motional) [4] states has been demonstrated. So far, atom chip traps mainly rely on the interaction of neutral atoms with static (or slowly varying) magnetic [1,2] or electric [5] fields. This imposes a restriction to magnetically trappable weak-field seeking atomic states, which represents a severe limitation. For example, using Feshbach resonances [6] to modify the atom–atom interactions becomes very difficult.

This limitation can be overcome by employing rapidly time-varying fields. The interaction with oscillating fields can be strongly enhanced when coupling to internal states of the trapped atoms. Prime examples are optical dipole potentials [7] and rf-induced dressed state potentials [8]. Whereas rf-induced potentials allow very versatile atom manipulation, they are still linked to magnetically trappable states. The optical dipole potential in contrast gives complete freedom in choosing the trapped state.

In this Letter we present experiments combining standard atom chip technology with optical dipole trapping. To demonstrate the feasibility of such a concept, we implement an optical lattice potential, combining strong atomic confinement and high flexibility with respect to manipulating *all* internal atomic states with precise local manipulation and single-site addressability. The approach of a hybrid magnetic-optical atom chip significantly enhances the experimental tools available. An integrated optical dipole trap allows one to trap any magnetic substate on the atom chip and opens the path toward the manipulation of atomic scattering properties by Feshbach resonances and the creation of molecules. An optical lattice can conveniently be implemented on atom chips if the chip surface serves as a mirror to create a standing light wave. Our atom chip easily sustains high laser intensities (up to 100 mW/μm^2) without significant heating and allows for far-detuned dipole trapping. Structuring the atom chip surface (e.g., by height variations or patterning reflecting and absorbing elements) allows one to design intrinsically stable and versatile optical potentials. These can range from designed circuits to high resolution random potentials. Multiple laser beams enable more sophisticated standing-wave configurations creating 2D or 3D lattice potentials; the lattice spacing can be adjusted by changing the angle of incidence.

In the experiments discussed in this Letter we use a very simple implementation of an optical lattice potential on an atom chip: a single red-detuned laser beam impinges on the chip surface at almost normal incidence. Interference with the reflected beam creates a vertical lattice of oblate ("pancake"-shaped) traps, all parallel to the chip surface (Fig. 1). In these potentials, atoms can be confined to two dimensions, analogous to electrons in a quantum well [9].

To demonstrate the feasibility of combining optical trapping with an atom chip we performed two proof-of-principle experiments. In the first experiment we transfer atoms from the chip trap into the optical lat-

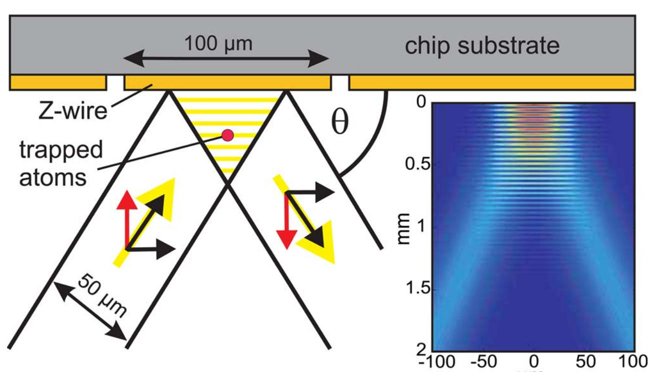

Fig. 1. (Color online) Setup to create an optical lattice on an atom chip (not to scale, $\theta \sim 87°$). A focused laser beam (50 μm) is reflected from the central part of a 100 μm wide Z-shaped trapping wire and forms a standing light wave (inset, λ multiplied by 100 for visualization).

tice and cool them into the 2D regime. In the second experiment we show that atoms can undergo coherent Bloch oscillations in the lattice close to the atom chip surface.

Our experimental apparatus is based on a hybrid macroscopic–microscopic atom chip assembly [10]. It holds the macroscopic wire structures used to capture and precool the atoms in the primary phase of the experiment as well as the microstructures needed for trapping and cooling the sample to quantum degeneracy. The microstructures on the atom chip are fabricated from a thermally evaporated high-quality (rms surface corrugation of <10 nm) gold layer (thickness of 3.1 μm) deposited on a 700-μm-thick silicon substrate and patterned using UV-light lithography [11]. Away from wire edges, the resulting mirror has a reflectivity of $>95\%$ so that an optical lattice can conveniently be formed by shining a focused laser beam ($w\sim 50$ μm) onto a broad (100 μm) wire that is also used in the magnetic trapping and cooling procedure (Fig. 1). The laser light (up to 8 mW) is derived from a laser diode, tuned to 782 nm, 2 nm above the $D2$ transition in ^{87}Rb. The beam is reflected under an angle of $\theta\sim 87°$ to the chip surface. The vertical distance between the trapping layers is $d=\lambda/2\sin\theta=392$ nm. The transverse size of the trap is given by the overlap of the laser beam with its reflection.

A cold sample of typically 10^5 ^{87}Rb atoms in the $F=m_F=2$ state just above or within the quantum degenerate regime is prepared in a magnetic microtrap at a distance of 210 μm from the atom chip surface (trap parameters are $\omega_\perp=2\pi\times 1.34$ kHz and $\omega_\parallel=2\pi\times 57.8$ Hz) following the procedure described in [10]. All information about the ultracold atomic sample is extracted from resonant absorption imaging, performed on the $F=2\rightarrow F'=3$ transition.

In the first demonstration experiment we load a cloud of thermal atoms ($T\sim 5$ μK) into the planes of the optical lattice, realizing purely optical trapping. This is accomplished by first adiabatically switching on the lattice and then adiabatically switching off the magnetic atom chip trap holding the atoms. Typically ten lattice sites are then populated; a slight mismatch in the longitudinal extension of the atom cloud trapped in the magnetic and the optical traps reduces the transfer efficiency to 88%. After an adjustable holding time, the trapped atoms are released from the lattice and observed in free expansion. Experiments are performed with different lattice depths ranging from 32 μK and $\omega_{tr}=2\pi\times 100$ kHz transverse confinement to a shallow lattice of only 4 μK depth with $\omega_{tr}=2\pi\times 35$ kHz transverse confinement (see Table 1).

After loading, we observe a fast initial loss of atoms on the time scale of about 40 ms. Together with this initial decay we observe significant cooling of the atoms (see Table 1). We hence attribute this fast loss to plain evaporation owing to the limited depth of the optical trap; the high ratio of the trap depth to the final temperature indicates very efficient cooling. Beyond the initial decay we find a slower loss process (decay constant $\tau\sim 100-200$ ms, depending on the laser intensity) at approximately constant temperature. The cooling appears to be compensated by heating processes induced, for example, by spontaneous photon scattering in the lattice with small detuning (calculated rates in Table 1). The heating in turn translates into loss, again owing to the finite trap depth.

For the shallow (low intensity) optical trap we clearly observe an anisotropic momentum distribution in the time of flight (TOF) at the end of the first plain evaporation process. The expansion in the transverse strongly confining direction is significantly larger than in the 2D plane ($T_{tr}=0.6$ μK compared with $T_{2D}=0.35$ μK). This behavior indicates that the zero point motion of the trap ground state starts to dominate the momentum distribution. The measured transverse momentum spread is consistent with what is expected from the transverse ground-state energy. The anisotropy is hence a clear sign that we cool the atoms into a 2D gas, with the transverse degree of freedom frozen out. The in-plane width of the expanded cloud remains a good measure of temperature as the zero point motion is negligible in these dimensions. However, we detect no signs of Bose condensation in the 2D traps; neither a bimodal distribution [12] nor an interference between the layers [13] is observed. We therefore conclude that we create a set of thermal, rather than (quasi-)condensed, 2D gases in the optical lattice on the atom chip. For the trap containing the maximal atom number ($N\sim 10^4$), an ideal gas would form a Bose–Einstein condensate (BEC) [$N_c^{id}=(\pi^2/6)(k_BT/\hbar\omega_{2D})^2=5600$ [14]], but in the presence of interactions a Berezinskii–Kosterlitz–Thouless (BKT) type transition occurs at higher critical atom numbers. For the case of our layered traps, the dimensionless 2D coupling constant $\tilde{g}=0.46$ leads to a threefold increase in the BKT critical atom number with respect to the ideal gas BEC transition. The absence of signs of quantum degeneracy in our experiment confirms previous observations of BKT transitions in less strongly ($\tilde{g}=0.13$) interacting 2D gases [15].

In the second experiment we demonstrate a coherent manipulation of atoms in the optical lattice by studying Bloch oscillations [16,17]. We start with a

Table 1. Parameters for the 2D Traps in the Optical Lattice

U_{dip} (μK)	$\omega_{2D}/2\pi$ (Hz)	$\omega_{tr}/2\pi$ (kHz)	Heating (μK/s)	T_{load} (μK)	$T_{2D,final}$ (μK)	$T_{tr,final}$ (μK)
35	350	100	14	5	2.4	2.4
20	280	80	10	5	1.7	1.8
4	125	36	2	5	0.35	0.6

BEC created on the atom chip. We then rapidly switch off the wire trap and, 500 μs later, switch on a weak optical lattice (potential depth of $\approx 2E_{\text{recoil}} = 1.4\ \mu$K) adiabatically with respect to the vertical trapping frequency ω_{2D} of the lattice. After an adjustable interaction time, during which the Bloch oscillations occur, we switch off the optical lattice and observe the atoms after a fixed total expansion time of 15 ms.

For the data displayed in Fig. 2 the time before switching on the lattice was set such that a small fraction of the atoms was already too fast to fulfill the Bragg condition $\hbar k = mv$ and continues to fall in gravity. Their position after 15 ms TOF corresponds to the one of free-falling atoms without any lattice potential. Slower atoms ($v < \hbar k/m = 5.9\ \mu$m/ms, where $k = 4\pi/\lambda$ is the grating vector of the lattice) get accelerated until they fulfill the Bragg condition and are "caught" in the optical lattice, continuously performing Bloch oscillations with a period of 0.6 ms. The first three successive Bloch oscillations can clearly be seen in Fig. 2.

The observation of Bloch oscillations close to a surface opens up new possibilities for precision atom–surface interaction measurements such as probing the Casimir–Polder potential. Atom chip based microtraps allow one to accurately control the starting position of the atoms. To suppress dispersion effects owing to interactions, fermions [18] or noninteracting bosons [19] can be used.

In conclusion we have demonstrated that an optical lattice can be integrated on an atom chip for both trapping and coherent manipulation of ultracold atomic ensembles. This combination of two powerful tools in atom optics paves the path for many new possibilities ranging from studies of low-dimensional quantum systems to single-site addressability in a quantum register to precision measurements of atom–surface interactions and other short-range forces.

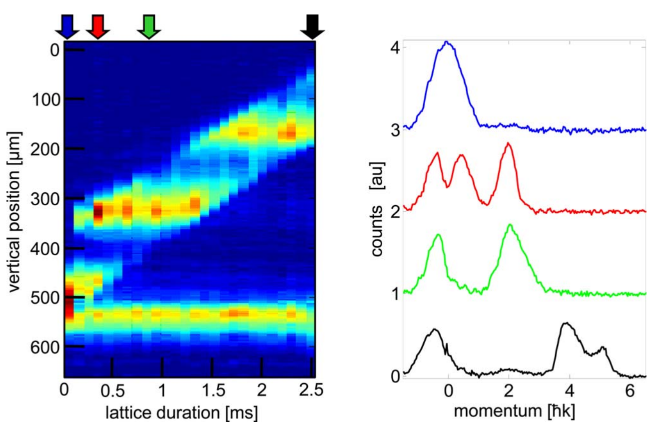

Fig. 2. (Color online) Observation of Bloch oscillations of a BEC accelerated by gravity. (Left) Series of TOF images with increasing interaction time with the optical lattice. Each vertical line corresponds to a single absorption image, integrated along the horizontal direction. (Right) Momentum distribution at specific times, indicated by arrows of corresponding color (left-most arrow corresponds to the uppermost curve) in the left graph.

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