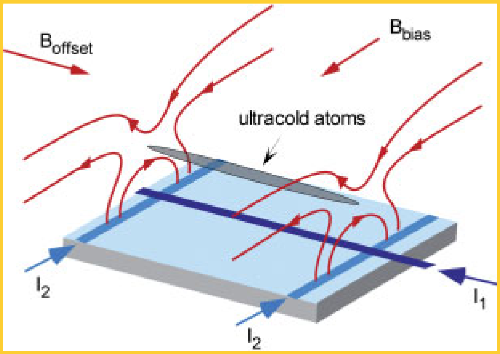
Abstract: We review recent experimental progress towards quantum information processing and precision force sensing using neutral atoms in micro traps. Microscopic potential structures as generated by optical or electronic microstructures (micro traps) allow for a versatile manipulation of quantum states of atoms and of ultracold atomic quantum gases. Most recent experimental results include the implementation of single-qubit-operations in both, optical and magnetic micro traps, as well as in the demonstration of matter-wave interferometer using Bose-Einstein condensates coherently split in micro traps.



Micro traps for quantum information processing and precision force sensing

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1. Introduction

The dramatic advances of quantum- and atom-optics allow at present accurate control over the internal and external degrees of freedoms of atoms. In particular, atoms can be routinely cooled down to temperatures in the nK range, they can be stored in magnetic or optical traps for up to several minutes and a precise control over their quantum state is possible. These achievements motivate several new directions, such as the implementation of quantum information processing using neutral atoms or the construction of matter-wave interferometers. Besides these final goals, experiments investigating the coherent quantum behaviour of neutral atoms provide new insights into quantum physics and into new applications of quantum technology in a rapidly expanding area of science and technology.

Engineering quantum systems with neutral atoms requires means for coherent manipulation and state sensitive detection. A natural way to attempt coherent control over atoms is using potential structures which are comparable in size with the de Broglie wavelength of the atom. Optical standing wave fields, so called optical lattices, generate potential structures on this length scale, typically on the order of the optical wavelength ($\sim \lambda/2$), and are sufficiently strong to confine and structure an ultracold cloud of atoms [17, 19, 32]. Alternatively, optical micro traps using diffractive and refractive elements [2, 10], and magnetic micro traps, based on micro-fabricated magnets [14, 16, 27, 54], have been introduced. In micro traps, the potential is defined by the geometry of the microstructure and almost arbitrary spatial and temporal potential shaping is possible. The implementation of optical, electrostatic, electrodynamic and magnetic micro potentials on a single chip not only promises a versatile control over atomic quantum states but also makes widespread applications possible. Matter wave interferometers using micro traps have recently been realized [21, 22, 33, 58–60, 63]. Interfer-

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ence fringes related to the quantum mechanical phase of atomic Bose-Einstein condensates were thereby detected by standard absorption imaging. This is possible due to the large number of atoms involved in the interference. However, quantum information processing or interferometry with single atoms require the development of detectors, sensitive to the signal of single atoms [5,45,47,50,61]. At present, research is focussed on both coherent manipulation techniques and state selective single atom detection. Some aspects of the recent progress on coherent manipulation using micro traps based on micro-fabricated current-carrying and optical structures are reviewed in this article. The selection is far from being complete. The tremendous growth of the field during the last years does not allow us to present a comprehensive overview and we are forced to restrict ourselves to describe an admittedly biased selection. For a more complete description we refer to [2,16].

2. Quantum information processing with neutral atoms

Quantum information processing with neutral atoms offers a set of advantages over other approaches:
(1) Flexible implementation of qubits: atoms and molecules as carriers of quantum information represent intrinsically identical systems of qubits which can be decoupled from their environment to a high degree. In addition, there exist a range of possibilities to encode quantum information in quasi spin-1/2 systems. For atoms in micro traps quantum information can be encoded in the internal (e.g. hyperfine ground states) as well as external degrees of freedom (e.g. vibrational modes of the trapping potential).
(2) Scalability: trapping geometries based on magnetic and optical micro traps (Fig. 1) allow for the implementation of hundreds or even thousands of identical atomic qubits in parallel. Based on optical lattices the number of qubits can be increased to about 10^5. This gives the unique possibility to develop and experimentally test schemes for quantum information processing on large scales.
(3) Flexible quantum gates: in recent years, several promising candidates for the implementation of 2-qubit quantum gates for neutral atoms have been developed. Examples include gates based on the phase shift during ultra-cold collisions [30], on tunnelling processes depending on the motional states of atoms [6,11], on dipole-dipole interactions between atoms in high-lying Rydberg states [31], and on the coupling of atoms via the radiation field of optical or microwave resonators [53,55]. Common to all these schemes is that the interaction process is acting only during the gate operation and typically is independent of the mechanism for atom trapping. A large number of research groups are currently working on the first demonstration of a full 2-qubit quantum gate for a functional quantum processor with neutral atoms (See for example [56]).

Atomic quantum systems offer the important advantage, that they can be decoupled from their environment to a high degree in modern quantum optics experiments. For neutral atoms this is achieved through atom trapping in inhomogeneous magnetic or optical fields. Here, the short range character of the trapping force additionally facilitates the decoupling. In this detail, neutral atoms differ from charged ions. Due to the long-range character of the Coulomb interaction, charged ions are more sensitive to external electrostatic and electrodynamic perturbations. On the other hand, this long-range character of the ion-ion coupling is responsible for the exciting advances in the implementation of quantum algorithms in ion trap experiments.

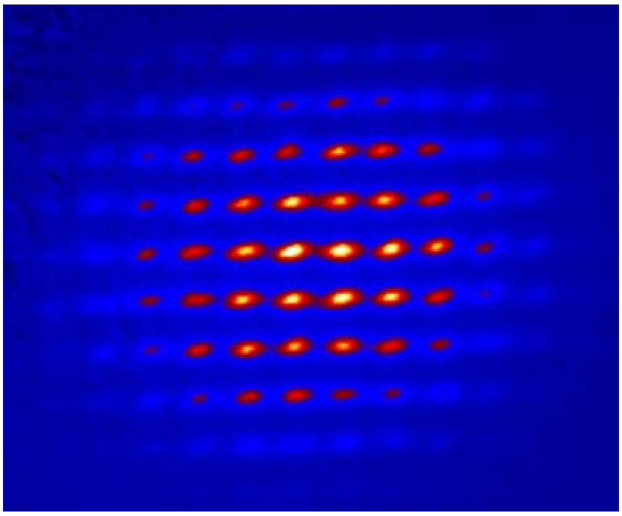


Figure 1 A two-dimensional set of atom ensembles in optical dipole traps based on arrays of micro-lenses can serve as a qubit register. Individual traps in this fluorescence image have a lateral separation of 125 μm [68].

Similar to other investigations in modern atomic physics and quantum optics, alkali atoms – especially rubidium and caesium – have become the preferred atomic species for research in quantum information processing. This is caused by the fact that alkali atoms can be efficiently manipulated by laser light. Fig. 2 shows a typical setup for quantum information processing with neutral atoms. Central elements in this setup are a glass vacuum cell, laser beams for the trapping, cooling, and manipulation of atoms, and coils providing the necessary magnetic fields. Under typical vacuum conditions, atoms can be stored for seconds, under optimized conditions for minutes.

3. Experimental approaches

In a typical quantum processor, atomic qubits are first prepared and initialized and then one- and two-qubit quantum operations are applied according to the quantum algorithm to be implemented. The final task consists of a low-noise readout of the final quantum state resulting from the operation. An essential requirement is a suitable register for the

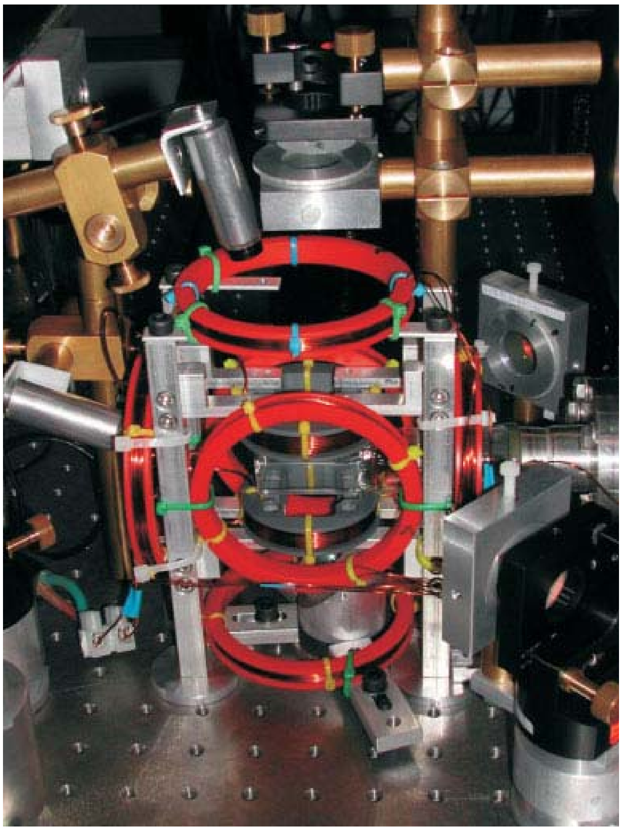


Figure 2 Typical experimental setup. Alkali atoms are trapped and cooled in a configuration called 'magneto-optical trap' inside a glass vacuum cell at the center of a set of coils for magnetic fields. Temperatures in the range of 10 to 100 µK can be achieved. This prepares atomic quantum systems for further experiments on quantum information processing and matter wave interferometry [68].

reliable storage and manipulation of qubits – which present the hardware of the quantum processor. The demonstration of qubit registers with typical dimensions of the individual register cell in the range of a few microns presents an important step towards the successful implementation of quantum information processing with neutral atoms. Important examples are magnetic micro traps [14, 16, 27, 54], optical micro traps based on micro-fabricated optical elements [2,10], and optical lattices [19,32]. Important characteristics of these traps are depths in the range $k_B \times 1$ mK, which are about two orders of magnitude larger than the thermal energy achievable with laser cooling, and vibrational frequencies in the range of 10 kHz to 100 kHz or beyond. By further laser cooling or by making use of the phase transition to a Bose-Einstein condensate the vibrational ground state of the trapping potentials can be populated with high probability. Typical spreads of the ground state wave functions are on the order of 10 nm.

In the following we will discuss in detail approaches based on magnetic and on optical microstructures. We expect significant advance in using these systems due to their intrinsic scalability: their fabrication is based on state-of-the-art manufacturing technology in micro- and nanofabrication. Fundamental advantages of this technology are the mass production of identical individual systems as well as the integration of individual systems to larger functional units.

4. Magnetic microstructures / Atom-Chips

In a spatially inhomogeneous magnetic field, a paramagnetic atom experiences a spatially dependent energy shift due to the Zeeman effect. The energy shift corresponds to a conservative trapping potential with a depth of typically $k_B \times$a few millikelvin. Due to the topological properties of the magnetic field, in free space only minima but no maxima of the field can be produced. Therefore, only atoms in so called "low-field-seeking" states, states which minimize their energy in a magnetic field minimum, can be stored in the magnetic trap. This reduces at first the storable states of the atom, but in combination with time dependent or optical fields this restriction can be circumvented. Miniaturized and microstructured magnetic traps are promising candidates for quantum information processing. Taking advantage of highly advanced micro- and nanofabrication technologies, the integration of complex circuits of magnets, electromagnets and electrodes is possible on substrates (Fig. 3). Depending on size and shape of the conductor, different magnetic potentials are possible. Large scaled structures are routinely used for transport and nanopositioning of atomic clouds at the chip surfaces. Conductor widths on the order of tens or hundreds of microns allow for covering a large chip area of up to several centimetres [20, 43]. On the other hand, small scaled chips supporting micron wide conductors facilitate structuring coherent matter waves within their size [20, 21]. Recently, also a combination of static and radiofrequency magnetic fields has been successfully demonstrated to structure the potential for paramagnetic atoms on the micron scale, even at a large distance to the chip surface [58]. The development of electrodymanic traps for spinless neutral atoms has also started [36]. In analogy to structures of integrated electronics, microscopic atom traps are also referred to as "Atom-Chips".

In micro magnetic traps, the high magnetic field gradients and curvatures are produced in close proximity of the field generating elements. Thus for achieving "fast circuits", atoms have to be stored in close proximity of the micro trap surface. Below a certain atom-surface separation, however, the atoms cannot be regarded as isolated systems. The electromagnetic interaction of the atom with the surface has several consequences. The interaction influences the internal state of the atom, leading to decoherence and even to atom loss, and furthermore, it influences

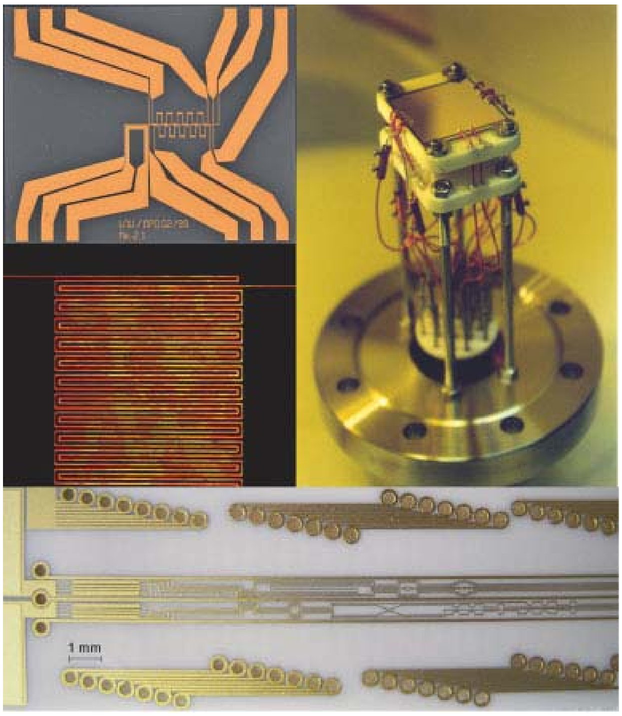


Figure 3 Magnetic micro traps are generated by the magnetic field of current carrying conductors fabricated on a chip surface. Conveyor belts for transporting atomic clouds (upper left [54]), magnetic lattices for structuring condensates within their coherence lengths (middle left [21,22]), and arrays of micro traps on dual-layer chips (bottom [20]) are examples of the experimental state-of-the-art. The chips are mounted on a vacuum flanch and operated under ultrahigh vacuum conditions (right [14]).

the trapping potential. Atom-surface interactions have been investigated by research groups of this field very intensively during the past few years. In particular, it has been pointed out that magnetic field fluctuations due to the thermal motion of electrons in the metallic conductors of micro chips (Johnson-noise) induce transitions between internal spin states of the atom trapped nearby the metallic surface [26,57]. This leads to decoherence of the internal quantum state and finally to losses because only low-field-seeking spin states are trapped in the magnetic trap. Related reductions of the lifetime of atomic clouds has been experimentally observed [24,35,42]. For typical micro traps, the effect becomes significant for atom-surface separations smaller than $\sim$10 µm. Nevertheless, it has been shown, that coherent manipulation of atomic clouds is possible at reasonably small distances to the chip surface [62]. In a Ramsey-spin-echo experiment (Fig. 4), the Munich group measured the coherence lifetime of the superposition of two internal states to be about $\sim$2.8 s at a distance of $\sim$9 µm to the surface of a metal foil. The measured coherence lifetime is consistent with theoretical predictions and is orders of magnitude longer than required for quantum information processing in general.

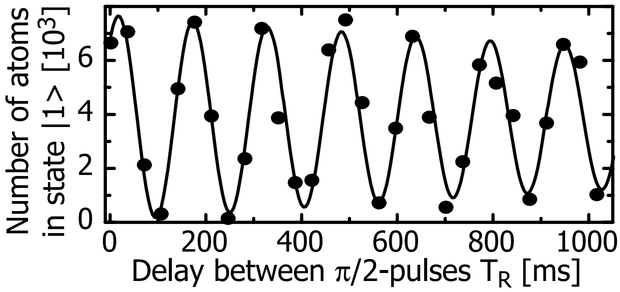


Figure 4 Ramsey fringes observed for a hyperfine transition of 87Rb atoms held at a distance of $d = 9$ µm from the metallic surface of a chip. The experiment demonstrates a single qubit operation. Adopted from [62].

Another important class of interactions between atoms and the chip surface are the dispersion forces (Van-der-Waals – London, Casimir-Polder forces). The impact of the attractive Casimir-Polder force to a magnetic micro trap has been first observed by losing atoms towards the chip surface [42] that became significant for atom-surface separations smaller than 5 µm. Subsequently, the Casimir-Polder force and its temperature dependence have been measured with high accuracy by an ingenious method exploiting the change of the trap oscillation frequency when the Casimir-Polder force is acting on the trapping potential [25,48]. Dispersion forces have a short decay length and are competing with the confining force of the trapping potential. Their impact can be reduced by using strong confinements. Due to their small decay length, dispersion forces are completely negligible for large atom-surface separations (> 5 µm). On the other hand, quantum reflection on the attractive Casimir-Polder potential can be exploited to realize high quality surface-mirrors for atoms at low incident velocity, as demonstrated by the MIT group [51,52].

After the successful implementation of a single-qubit operation by the Munich group (Fig. 4), the next important step towards the realization of the quantum processor with atom chips will be the detection of single atoms and the implementation of two-qubit operations. The detection of atoms, but also the state sensitive read out of the result of a quantum operation is generally done by resonant absorption or scattering of light. Therefore, several research groups develop microstructures combining magnetic potentials for storing atoms, and micro optical elements, e.g. micro cavities, fiber cavities [12,29,44,61] or micro lenses [2], for detection.

In order to perform two-qubit operations with magnetically stored atoms, it is necessary to coherently recombine and split individual trapping potentials. Depending on the coding, the qubit operation requires a different interaction mechanism between the atoms. For coding in internal states of the atom, the two-qubit operations based on the collisional interaction of atoms have been proposed [30]. Hereby, a state dependent interaction and, in general, the implementation of state selective trapping potentials are required. The limitation of purely magnetic traps to low-field-seeking spin states is thereby a real challenge. With a combination of magnetic, electrostatic, optical, and radiofrequency/microwave fields, however, it is possible to engineer the state sensitivity required for typical qubit-states.

5. Quantum processors based on microstructured optical elements

Another approach for the implementation of a quantum processor consists in the combination of the optical storage and the quantum control of neutral atoms with the micro- and nanofabrication technology of optical systems. Using two-dimensional arrays of refractive or diffractive micro lenses, it is possible to create two-dimensional systems of dipole traps (Fig. 5). Each trap can hold an ensemble of atoms or in the limiting case an individual atom. Thus a two-dimensional register of atomic qubit with excellent scaling properties is created. Already in the present realization, lens arrays with thousands of individual lenses are available in the lab. This is by far not limited by the available technology of micro-optics fabrication. Due to the large lateral separation of neighbouring sites, we can individually address each site. Depending on the respective operation to be implemented, individual sites but also rows and columns, or the array as a whole can be addressed with high flexibility. The lens systems currently used consist of 50×50 refractive or diffractive micro-lenses with a diameter and lateral separation of 125 μm and a focal length of 625 μm. The lenses are manufactured lithographically in quartz (Fig. 5a,b). Illuminating a section of the lens array with red-detuned laser light gives a two-dimensional set of diffraction limited laser foci (Fig. 5c).

Atoms can be trapped in the focal plane due to the dipole potentials created by the laser foci. Re-imaging the focal plane gives rise to ways of creating even more flexible trapping configurations. Re-imaging allows us for example to transfer the focal plane into our vacuum system without the necessity to put the micro-optical system itself into the vacuum. With this method we can test various optical systems in fast succession. In addition, demagnification allows for a reduction of the lateral separation of the dipole traps and the focal width of the individual traps and the superposition of different optical systems is possible during re-imaging. Both techniques have been applied in recent experiments: our current dipole trap arrays have a lateral separation of about 55 μm and a focal width smaller than 2 μm ($1/e^2$ radius).

The central goal of the work is the step-by-step implementation of a scalable quantum processor for neutral atoms in qubit-registers based on arrays of micro-lenses. In a first set of experiments, the feasibility of this approach has

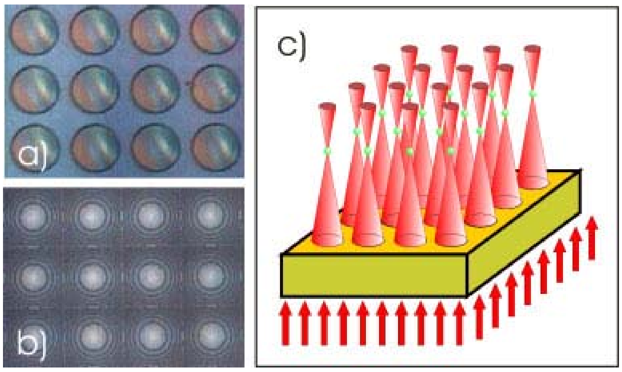


Figure 5 Illuminating a two-dimensional array of refractive (a) or diffractive (b) micro-lenses with near-resonant laser light gives a two-dimensional array of dipole traps for neutral atoms (c) which can serve as a quantum register for atomic qubits [68].

been demonstrated and arrays of more than 80 sites have been loaded with atom ensembles [10]. Fig. 1 shows a two-dimensional configuration of ensembles of rubidium atoms created in this way. The brightness reflects the atom number distribution in the traps. At the center of the configuration about 1000 at the edges about 100 atoms are trapped at each site. In additional experiments the individual addressing of register sites, and the state-dependent preparation and read-out of the qubit-states have been realized [10].

The next important step on the path to a functional quantum processor consists in the realization of one-qubit quantum gates. This can be demonstrated through the controlled coherent evolution of qubit states. In order to proof the scalability of this approach, we performed this operation simultaneously on several sets of atom ensembles in a two-dimensional dipole trap register [39], (Fig. 6).

An important feature of this experiment consists in the fact that the readout of the qubit states at the end of the coherent evolution is achieved via the spatially resolved detection of fluorescence light. This allows for the simultaneous analysis of a large number of sites of the register. In Fig. 6 this is shown for 16 selected sites. Qubits are encoded in two hyperfine ground states. Applying a pair of phase-locked Raman laser beams with a typical duration of 250 μs creates a coherent superposition of the qubit states. Interogating the coherent evolution for different times of free evolution allows the observation of the coherent dynamics as a periodic variation of the population of one of the qubit states and thus the demonstration of the availability of one-qubit operations. Through Ramsey- and spin-echo-type experiments the time constants for dephasing and decoherence of the qubit superposition can be extracted. As an important result we could observe a coherence time which is in full agreement with the inverse photon scattering rate caused by the trapping laser field [39]. This has two important consequences: (a) already in the present configuration coherence times exceeding the duration of a typical quan-

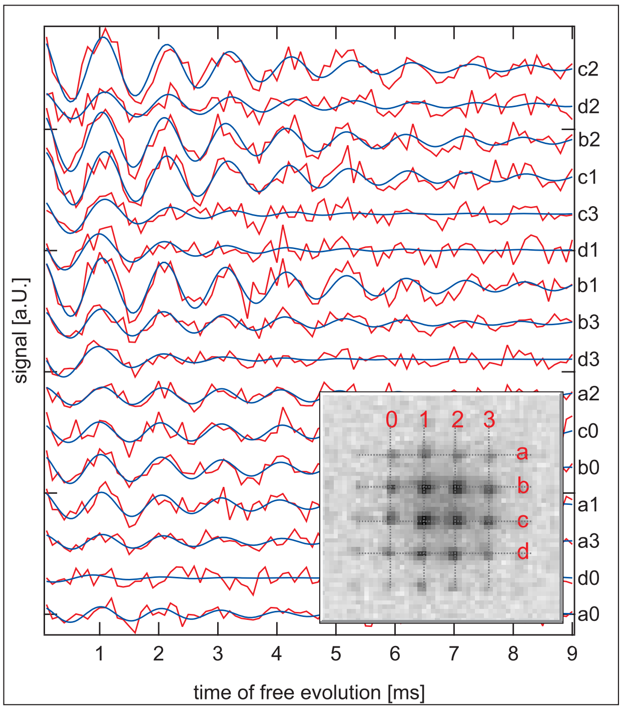
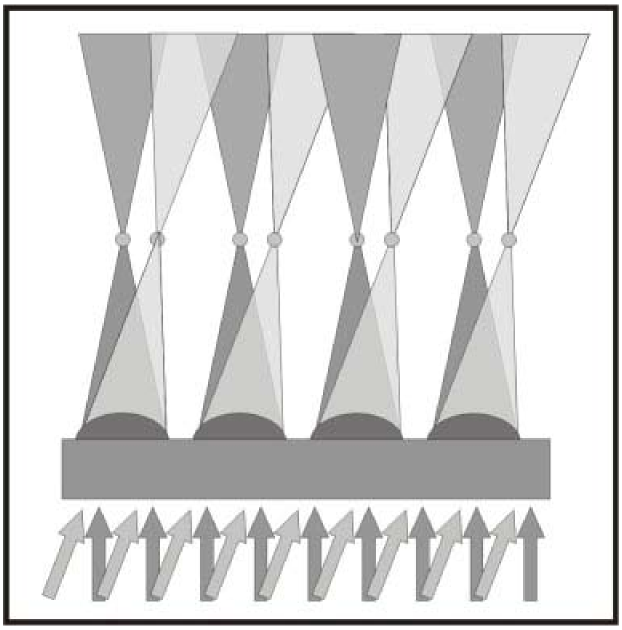
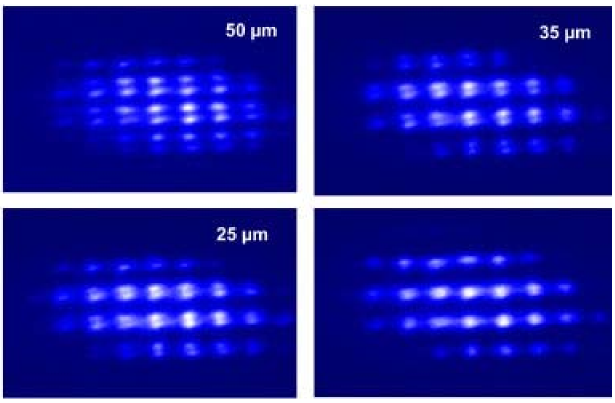


Figure 6 Simultaneous Ramsey measurements in 16 different dipole traps. The associated position of the traps is shown in the inset. The inset is a fluorescence image of the atoms trapped in the two-dimensional trap array Adopted from [39].



a)



b)

Figure 7 Registers of trapped atoms with varying mutual separation can be created by illuminating an array of micro-lenses with two laser beams under varying relative angles (a). This creates atom ensembles which can either be addressed separately (top center) or can be brought to complete overlap (b) [68].

tum gate operation by a factor of 100 are available and (b) by further detuning the frequency of the trapping light from atomic resonance the coherence time can be further increased.

Work on the implementation of two-qubit gates which shall be based on the phase shift induced by controlled cold collisions between trapped qubit states is underway. The key step is the realization of the spatial overlay of two qubits out of initially separated sites which is based on the controlled spatial transfer of respective dipole potentials. Illuminating an array of micro-lenses with two laser beams having a finite relative angle of progation (Fig. 7a) creates two interleaved sets of dipole trap arrays. Variation of the relative angle between the laser beams gives rise to a variation of the mutual separation of the dipole trap sets. Fig. 7b shows atom ensembles in two interleaved registers of dipole traps with different static separations as indicated. The trap separation within each of the two trap sets is 125 µm.

With this technique, the transition from a fully addressable trap configuration to a configuration of complete overlap of the traps can be achieved. Recently, also a dynamical setup has been demonstrated in which the atoms are moved in real time within arrays of traps.

In order to achieve a fully operational quantum processor, the demonstration of two-qubit gates has to be achieved. Additional necessary requirements are the realization of the reliable detection of single atoms, the cooling to the vibrational ground state of the trapping potential, and an efficient scheme for loading a large number of register sites with exactly one atom. Additional flexibility in the implementation of future generations of quantum processors can be expected through the continuous advance in micro- and nano-optics. As one example for these exciting new developments, we would like to mention the application of spatially resolved light modulators for the flexible and dynamically reconfigurable generation of multiple light fields for atom trapping [1,3]. In such a configuration, it is possible to move atoms within dipole traps with high flexibility, to combine and separate traps, and to implement complex quantum operations. An overview of potential directions for the future application of micro- and nano-optical systems for quantum information processing and intergrated matter-wave interferometry can be found in [2,4].

6. Chip based matterwave interferometer

The tremendous progress in trapping and manipulating neutral atoms with micro traps culminated very recently in the demonstration of on-chip matterwave interferometry by numerous research groups [21,22,33,58,60,63]. Thereby, different techniques have been utilized for coherent splitting and manipulation of Bose-Einstein condensates on chips. A beautiful demonstration of an atom-Michelson-interferometer was achieved in an experiment by the JILA group [63]. A magnetic waveguide potential is combined with an optical lattice potential which is used for coherent splitting, manipulation and recombination of Bose-Einstein condensates (Fig. 8). A first $\pi/2$ pulse splits the condensate into two momentum components propagating in opposite directions with $\pm 2\hbar k$, respectively. After some time of propagation in the magnetic waveguide, a second π pulse, inverts the direction of propagation. The interferometric path is then closed by a third $\pi/2$ pulse which recombines the condensates at their initial position. Without force acting on any of the condensates during the propagation period all atoms are recombined into the zero momentum state. So the original condensate is restored. With forces acting, the condensate after recombination is (partially) measured in the $|\pm 2\hbar k|$ momentum state. In the JILA experiment, a magnetic gradient was applied along the waveguide axis for tuning the force. With increasing gradient, periodic interference fringes (atoms being in the zero/$|\pm 2\hbar k|$ momentum state) were observed demonstrating the success of the interferometric force measurement.

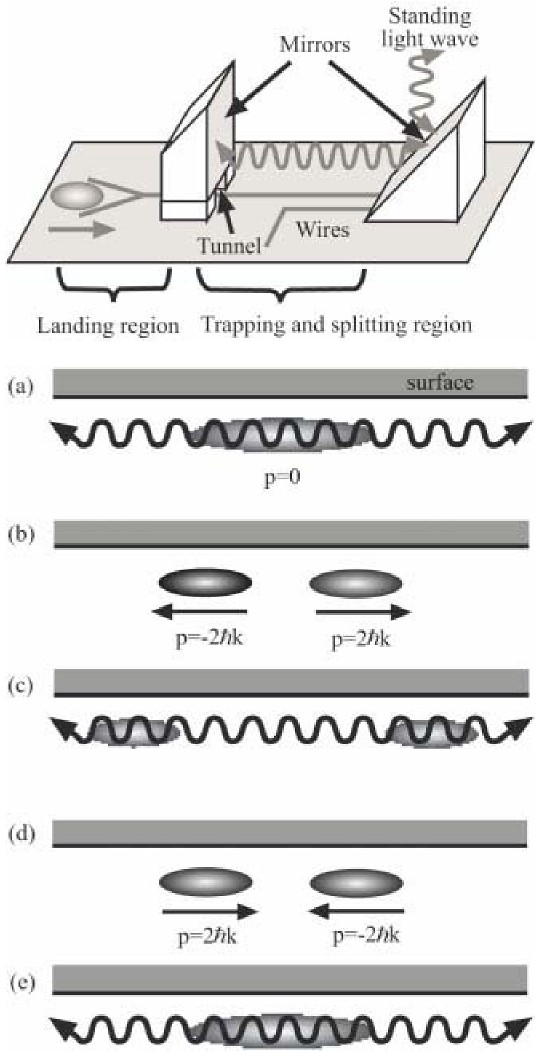


Figure 8 Schematic drawing of the atom-Michelson-interferometer (not to scale). The dimensions of the chip are 5 cm $\times$2 cm. a–e) Interferometric sequence (see text). Adopted from [63].

The Tübingen group demonstrated diffraction of a condensate on a magnetic lattice potential [21]. This is a promising alternative to optical lattices to split the condensate in momentum space because magnetic lattices can be easily integrated on micro chips. The experimental situation is shown in Fig. 9. The magnetic lattice potential with a lattice constant of 4 µm is generated by a meandering conductor pattern as shown in Fig. 3. The diffraction is initiated by a controlled oscillation of the condensate towards the lattice. At the turning point of the oscillation, the exponentially decaying periodic lattice potential imprints a phase modulation into the condensate wavefunction. Thereafter, the expansion of the wavefunction reveals discrete momentum components $n \cdot k$, where k is given by the inverse lattice constant ($k = 2\pi/a$). The relative amplitude of the diffracted orders is controlled by the modulation depth of the lattice. For weak lattices only lowest diffraction orders are populated. When increasing the modulation depth, up to five diffraction orders have been observed (Fig. 9). Diffraction is an intrinsically phase coherent process because the short interaction with the lattice only modulates the phase of the condensate and does not change its density distribution (Raman-Nath regime). After some time of propagation in a waveguide, the diffraction orders separate and the initial splitting in momentum space is converted into a spatial splitting. In a regime where the Bragg-momentum transferred by the lattice is smaller than the momentum of mean-field expansion of the cloud, the diffraction orders keep overlapping and produce interference. First results on this subject are described in [22]. Integrated magnetic lattices thus hold great promise for applications in chip based matterwave interferometers.

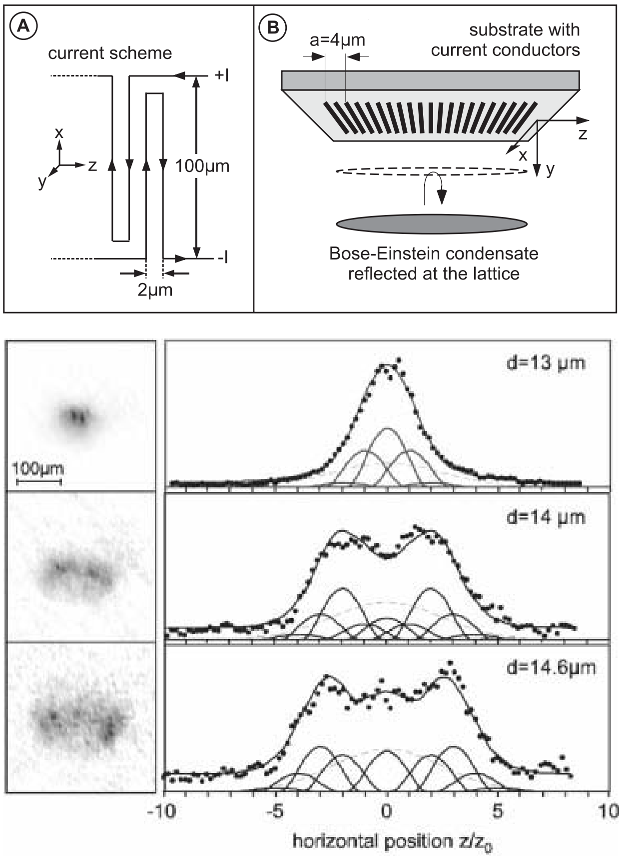


Figure 9 Diffraction of a condensate on a magnetic lattice. The diffraction is due to imprinting a periodic phase modulation into the condensate wave function by a magnetic lattice potential. The condensate interacts with the lattice for a short time, at the turning point of a controlled center of mass oscillation. Diffraction pattern as observed after $\tau = 20\ ms$ free expansion for increasing strength of phase imprinting (from top to bottom). The distance $z_0 = v \times \tau$ corresponds to one reciprocal lattice velocity v. The data points are described by the discrete sum of diffraction orders, deviation from this are due to the interference of the diffraction orders. Adopted from [21].

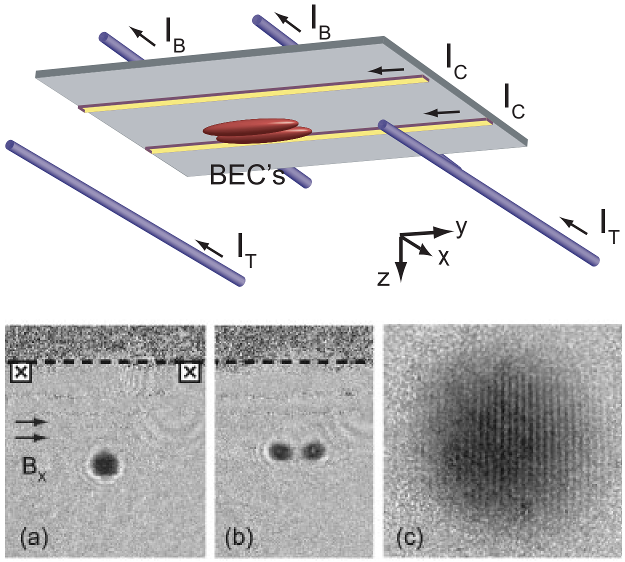


Figure 10 Schematic diagram of the two-wire beam splitter. A magnetic double-well potential is created by two chip wires with a current I_C in conjunction with an external magnetic field. Splitting of a condensate for increasing external field and (c) the interference pattern of condensates split to a distance of 25.8 µm as observed after 22 ms free expansion. Adopted from [60].

Remarkable progress has been made also in spatial splitting condensates from single well into double well potentials. A long outstanding proposal of the Sussex group [28] for splitting a condensate using a two-wire guide has been experimentally investigated by the MIT group [60]. The splitting was successful with regard that the two split condensates produced a high contrast interference pattern after recombination in ballistic expansion. The uniform phase inside each of the condensates was thus conserved. However, deterministic phase relation between the two condensates was observed only as long as the chemical potential was larger than the potential barrier between the two condensates. For full separation the phase relation went lost. This might be explained by the extreme sensitivity of the double-wire beam splitter on temporal magnetic field fluctuations and the sensitivity of the condensate on abrupt potential changes and trap anharmonicities [49]. A consequent elimination of technical noise in the chip conductors and shielding of ambient magnetic filed fluctuations were proposed to aid phase conserving splitting.

A novel splitting scheme based on dressed (adiabatic) potentials has been demonstrated by the Heidelberg group to preserve phase coherence, at least for a short time after splitting [58]. A quasi-one dimensional ^{87}Rb condensate ($\mu \sim \hbar\omega_\perp$) was initially loaded into a microscopic Ioffe-Pritchard trap with the axis of the underlying two-dimensional quadrupole magnetic field oriented in the vertical and horizontal directions (Fig. 11). Irradiating a radiofrequency magnetic field with horizontal polarisation and a frequency slightly below the Larmor frequency (related to the trap center) results in a horizontal splitting of the trap. This is due to the spatially dependent coupling of the atomic magnetic moment aligned by the static magnetic field to the rf-field. By continuously increasing the amplitude of the rf magnetic field from initially zero to a final value, the condensate initially located in the center of the single well splits into the double well. The phase relation of the split condensates was detected observing the interference pattern after ballistic expansion. For incomplete splitting, tunnelling between the two wells locked the relative phase. For complete splitting, a deterministic phase evolution was observed which spread out on the time scale of about four radial oscillation periods. The loss of phase

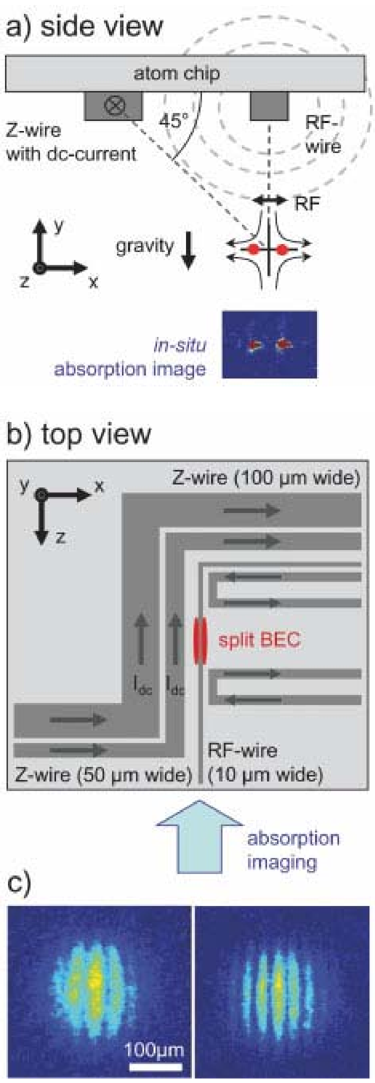


Figure 11 Operation principle of the rf-beam splitter [58]. a, b) The Ioffe-Pritchard trap is generated below the rf-wire, with the axis of the underlying magnetic quadrupole field oriented vertically and horizontally. The rf-wire radiates an rf magnetic field with horizontal polarization. The resulting spatially dependent coupling of atomic magnetic moments to the rf-field generates a horizontally split adiabatic double well potential. c) Interference of split condensates after 14 ms free expansion. The splitting distance can be derived from the fringe spacing [8].

relation was explained by possible phase fluctuations inside the quasi-one dimensional condensates but also the impact of any noise on the trapping potential was not excluded. In a similar experimental arrangement, the MIT group demonstrated splitting of a tree-dimensional condensate and observed coherence times up to 200 ms [33]. This exceptionally long coherence time was attributed to a non-classical number squeezed state that emerged during splitting the sodium condensate with repulsive atom-atom interactions. Above experiments show that the integration of radiofrequency and microwave sources on chips raises possible applications not only for coherent control of internal states as important for quantum information processing but also for the manipulation of the center of mass motion of atoms in a versatile way [7,40,41,66,67].

7. Outlook

Progress in the field of coherent manipulation of atoms in micro traps is extremely rapid. By combining the newly available interferometric techniques, the advanced nanopositioning of atoms using microscopic conveyors, the scalability and the high flexibility in possible trapping potentials and interaction mechanisms, as well as the progress in miniaturizing experimental system [9], the vision of portable sensors based on integrated matterwave interferometry may turn into reality in the near future. Also, these systems with neutral atoms represent promising alternatives for the realization of quantum processors. We expect a remarkable progress in the near future in this interdisciplinary, new field of quantum technology.

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References

[1] S. Bergamini, B. Darquié, M. Jones, A. Jacubowiez, A. Browaeys, and P. Grangier, Holographic generation of microtrap arrays for single atoms by use of a programmable phase modulator, J. Opt. Soc. Am. B, Opt. Phys. **21**, 1889 (2004).

[2] G. Birkl, F.B.J. Buchkremer, R. Dumke, and W. Ertmer, Atom optics with microfabricated optical elements, Opt. Commun. **191**, 67–81 (2001).

[3] V. Boyer, R.M. Godun, G. Smirne, D. Cassettari, C.M. Chandrashekar, A.B. Deb, Z.J. Laczik, and C.J. Foot, Dynamic manipulation of Bose-Einstein condensates with a spatial light modulator, Phys. Rev. A **73**, 031402 (2006).

[4] F.B.J. Buchkremer, R. Dumke, M. Volk, T. Müther, G. Birkl, and W. Ertmer, Quantum information processing with microfabricated optical elements, Laser Phys. **12**, 736–741 (2002).

[5] T. Campey, C.J. Vale, M.J. Davis, N.R. Heckenberg, H. Rubinsztein-Dunlop, S. Kraft, C. Zimmermann, and J. Fortágh, Atom counting in ultra-cold gases using photoionisation and atom counting, arXiv:cond-mat/0607170, 2006.

[6] E. Charron, E. Tiesinga, F. Mies, and C. Williams, Optimizing a phase gate using quantum interference, Phys. Rev. Lett. **88**, 077901 (2002).

[7] P.W. Courteille, B. Deh, J. Fortágh, A. Günther, S. Kraft, C. Marzok, S. Slama, and C. Zimmermann, Highly versatile atomic micro traps generated by multifrequency magnetic field modulation, IOP Publishing. J. Phys. B At. Mol. Opt. Phys. **39**, 1055 (2006).

[8] F. Dalfovo, S. Giorgini, L.P. Pitaevskii, and S. Stringari, Theory of Bose-Einstein condensation in trapped gases, Rev. Mod. Phys. **71**, 463–512 (1999).

[9] S. Du, M.B. Squires, L. Czaia, R.A. Saravanan, V.M. Bright, Y. Imai, J. Reichel, T.W. Hänsch, and D.Z. Anderson, Atom chip Bose-Einstein condensation in a portable vacuum cell, Phys. Rev. A **70**, 053606 (2004).

[10] R. Dumke, M. Volk, T. Müther, F.B.J. Buchkremer, G. Birkl, and W. Ertmer, Micro-optical realization of arrays of selectively addressable dipole traps: a scalable configuration for quantum computation with atomic qubits, Phys. Rev. Lett. **89**, 097903 (2002).

[11] K. Eckert, J. Mompart, X.X. Yi, J. Schliemann, D. Bruss, G. Birkl, and M. Lewenstein, Quantum computing in optical microtraps based on the motional states of neutral atoms, Phys. Rev. A **66**, 042317 (2002).

[12] S. Ericson et al., Eur. Phys. J. D **35**, 135 (2005).

[13] J. Estève, C. Aussibal, T. Schumm, C. Figl, D. Mailly, I. Bouchoule, C.I. Westbrook, and A. Aspect, Role of wire imperfections in micromagnetic traps for atoms, Phys. Rev. A **70**, 43629 (2004).

[14] R. Folman, P. Krüger, J. Denschlag, C. Henkel, and J. Schmiedmayer, Microscopic atom optics: from wires to an atom chip, Adv. At. Mol. Opt. Phys. **48**, 263–356 (2002).

[15] J. Fortágh, H. Ott, S. Kraft, A. Gunther, and C. Zimmermann, Surface effects in magnetic microtraps, Phys. Rev. A **66**, 041604 (2002).

[16] J. Fortágh and C. Zimmermann, Bose-Einstein chips, Rev. Mod. Phys. (in press).

[17] A. Griessner, A.J. Daley, D. Jaksch, and P. Zoller, Fault-tolerant dissipative preparation of atomic quantum registers with fermions, Phys. Rev. A **72**, 32332 (2005).

[18] S. Groth, P. Krüger, S. Wildermuth, R. Folman, T. Fernholz, J. Schmiedmayer, D. Mahalu, and I. Bar-Joseph, Atom chips: fabrication and thermal properties, Appl. Phys. Lett. **85**, 2980 (2004).

[19] G. Grynberg and C. Robilliard, Cold atoms in dissipative optical lattices, Phys. Rep. **355**, 335–451 (2001).

[20] A. Günther, M. Kemmler, S. Kraft, C.J. Vale, C. Zimmermann, and J. Fortágh, Combined chips for atom-optics, Phys. Rev. A **71**, 063619 (2005).

[21] A. Günther, S. Kraft, M. Kemmler, D. Koelle, R. Kleiner, C. Zimmermann, and J. Fortágh, Diffraction of a Bose-Einstein condensate from a magnetic lattice on a micro chip, Phys. Rev. Lett. **95**, 170405 (2005).

[22] A. Günther, S. Kraft, C. Zimmermann, and J. Fortágh, Atom interferometer based on coherent splitting of Bose-Einstein condensates with an integrated magnetic grating, arxiv:cond-mat/0603631, 2006.

[23] B.V. Hall, S. Whitlock, R. Anderson, P. Hannaford, and A. Sidorov, Condensate splitting in an asymmetric double well for atom chip based sensors, arXiv:cond-mat:0609014, 2006.

[24] D.M. Harber, J.M. McGuirk, J.M. Obrecht, and E.A. Cornell, Thermally induced losses in ultra-cold atoms magnetically trapped near room-temperature surfaces, J. Low Temp. Phys. **133**, 229–238 (2003).

[25] D.M. Harber, J.M. Obrecht, J.M. McGuirk, and E.A. Cornell, Measurement of the Casimir-Polder force through center-of-mass oscillations of a Bose-Einstein condensate, Phys. Rev. A **72**, 33610–33616 (2005).

[26] C. Henkel, P. Krüger, R. Folman, and J. Schmiedmayer, Fundamental limits for coherent manipulation on atom chips, Appl. Phys. B, Lasers Opt. **76**, 173–182 (2003).

[27] E.A. Hinds and I.G. Hughes, Magnetic atom optics: mirrors, guides, traps, and chips for atoms, J. Phys. D, Appl. Phys. **32**, R119–R146 (1999).

[28] E.A. Hinds, C.J. Vale, and M.G. Boshier, Two-wire waveguide and interferometer for cold atoms, Phys. Rev. Lett. **86**, 1462–1465 (2001).

[29] P. Horak, B.G. Klappauf, A. Haase, R. Folman, J. Schmiedmayer, P. Domokos, and E.A. Hinds, Possibility of single-atom detection on a chip, Phys. Rev. A **67**, 43806–43809 (2003).

[30] D. Jaksch, H.-J. Briegel, J.I. Cirac, C.W. Gardiner, and P. Zoller, Entanglement of atoms via cold controlled collisions, Phys. Rev. Lett. **82**, 1975–1978 (1999).

[31] D. Jaksch, J.I. Cirac, P. Zoller, S.L. Rolston, R. Cote, and M.D. Lukin, Fast quantum gates for neutral atoms, Phys. Rev. Lett. **85**, 2208–2211 (2000).

[32] P. Jessen and I. Deutsch, Optical lattices, Ad. At. Mol. Opt. Phys. **37**, 95–136 (1996).

[33] G.-B. Jo, Y. Shin, S. Will, T.A. Pasquini, C.V. Saba, W. Ketterle, D.E. Pritchard, M. Vengalattore, and M. Prentiss, Long phase coherence time and number squeezing of two Bose-Einstein condensates on an atom chip, arXiv:cond-mat/0608585, 2006.

[34] M.P.A. Jones, C.J. Vale, D. Sahagun, B.V. Hall, C.C. Eberlein, B.E. Sauer, K. Furusawa, D. Richardson, and E.A. Hinds, Cold atoms probe the magnetic field near a wire, J. Phys. B, At. Mol. Opt. Phys. **37**, L15–L20 (2003).

[35] M.P.A. Jones, C.J. Vale, D. Sahagun, B.V. Hall, and E.A. Hinds, Spin coupling between cold atoms and the thermal fluctuations of a metal surface, Phys. Rev. Lett. **91**, 080401 (2003).

[36] T. Kishimoto, H. Hachisu, J. Fujiki, K. Nanato, M. Yasuda, and H. Katori, Electrodynamix trapping of spinless neutral atoms with an atom chip, Phys. Rev. Lett. **96**, 123001 (2006).

[37] S. Kraft, A. Günther, H. Ott, D. Wharam, C. Zimmermann, and J. Fortágh, Anomalous longitudinal magnetic field near the surface of copper conductors, J. Phys. B At. Mol. Opt. Phys. L469–L474 (2002).

[38] A.E. Leanhardt, A.P. Chikkatur, D. Kielpinski, Y. Shin, T.L. Gustavson, W. Ketterle, and D.E. Pritchard, Propagation of Bose-Einstein condensates in a magnetic waveguide, Phys. Rev. Lett. **89**, 040401 (2002).

[39] A. Lengwenus, J. Kruse, M. Volk, W. Ertmer, and G. Birkl, Coherent manipulation of atomic qubits in optical micropotentials, Appl. Phys. B, Lasers Opt. (in press) 2006

[40] I. Lesanovsky, S. Hofferberth, J. Schmiedmayer, and P. Schmelcher, Manipulation of ultracold atoms in dressed adiabatic radio-frequency potentials, Phys. Rev. A **74**, 033619 (2006).

[41] I. Lesanovsky, T. Schumm, S. Hofferberth, L.M. Andersson, P. Krüger, and J. Schmiedmayer, Adiabatic radio frequency potentials for the coherent manipulation of matter waves, Phys. Rev. A **73**, 033619 (2006).

[42] Y. Lin, I. Teper, C. Cheng, and V. Vuletic, Impact of the Casimir-Polder potential and Johnson noise on Bose-Einstein condensate stability near surfaces, Phys. Rev. Lett. **92**, 050404 (2004).

[43] R. Long, T. Rom, W. Hänsel, T.W. Hänsch, and J. Reichel, Long distance magnetic conveyor for precise positioning of ultracold atoms, Eur. Phys. J. D **35**, 125 (2005).

[44] R. Long, T. Steinmetz, P. Hommelhoff, W. Hänsel, T.W. Hänsch, and J. Reichel, Magnetic microchip traps and single-atom detection, Philos. Trans. R. Soc. A, Phys. Sci. Eng. **361**, 1375–1389 (2003).

[45] H. Mabuchi, Q.A. Turchette, M.S. Chapman, and H.J. Kimble, Real-time detection of individual atoms falling through a high-finesse optical cavity, Opt. Lett. **21**, 1393–1395 (1996).

[46] J.M. McGuirk, D.M. Harber, J.M. Obrecht, and E.A. Cornell, Alkali-metal adsorbate polarization on conducting and insulating surfaces probed with Bose-Einstein condensates, Phys. Rev. A **69**, 62905–62906 (2004).

[47] S. Nussmann, M. Hijlkema, B. Weber, F. Rohde, G. Rempe, and A. Kuhn, Submicron positioning of single atoms in a microcavity, Phys. Rev. Lett. **95**, 173602 (2005).

[48] J.M. Obrecht, R.J. Wild, M. Antezza, L.P. Pitaevskii, S. Stringari, and E.A. Cornell, Measurement of the temperature dependence of the Casimir-Polder force, arXiv:cond-mat:0608074, 2006.

[49] H. Ott, J. Fortágh, S. Kraft, A. Gunther, D. Komma, and C. Zimmermann, Nonlinear dynamics of a Bose-Einstein condensate in a magnetic waveguide, Phys. Rev. Lett. **91**, 040402 (2003).

[50] A. Öttl, S. Ritter, M. Köhl, and T. Esslinger, Correlations and counting statistics of an atom laser, Phys. Rev. Lett. **95**, 090404 (2005).

[51] T.A. Pasquini, M. Saba, G.-B. Jo, Y. Shin, W. Ketterle, D.E. Pritchard, T.A. Savas, and N. Mulders, Low velocity quantum reflection of Bose-Einstein condensates, Phys. Rev. Lett. **97**, 093201 (2006).

[52] T.A. Pasquini, Y. Shin, C. Sanner, M. Saba, A. Schirotzek, D.E. Pritchard, and W. Ketterle, Quantum reflection from a solid surface at normal incidence, Phys. Rev. Lett. **93**, 223201 (2004).

[53] J.M. Raimond, M. Brune, and S. Haroche, Manipulating quantum entanglement with atoms and photons in a cavity, Rev. Mod. Phys. **73**, 565–582 (2001).

[54] J. Reichel, Microchip traps and Bose-Einstein condensation, Appl. Phys. B, Lasers Opt. **B74**, 469–487 (2002).

[55] G. Rempe, N.P. Bigelow, J.H. Eberly, C.R. Stroud, and I.A. Walmsley, Coherence and Quantum Optics VIII (Kluwer Academic / Plenum Publishers, New York, 2003).

[56] Webpage of the EC-funded project SCALA, www.scala-ip.org/index.php (2006).

[57] S. Scheel, P.K. Rekdal, P.L. Knight, and E.A. Hinds, Atomic spin decoherence near conducting and superconducting films, Phys. Rev. A **72**, 042901 (2005).

[58] T. Schumm, S. Hofferberth, L.M. Andersson, S. Wildermuth, S. Groth, I. Bar-Joseph, J. Schmiedmayer, and P. Krüger, Matter-wave interferometry in a double well on an atom chip, Nat. Phys. **1**, 57–62 (2005).

[59] Y. Shin, M. Saba, T.A. Pasquini, W. Ketterle, D.E. Pritchard, and A.E. Leanhardt, Atom interferometry with Bose-Einstein condensates in a double-well potential, Phys. Rev. Lett. **92**, 050405 (2004).

[60] Y. Shin, C. Sanner, G.-B. Jo, T.A. Pasquini, M. Saba, W. Ketterle, D.E. Pritchard, M. Vengalattore, and M. Prentiss, Interference of Bose-Einstein condensates split with an atom chip, Phys. Rev. A **72**, 21604 (2005).

[61] I. Teper, Y. Lin, and V. Vuletic, Resonator-aided single-atom detection on a microfabricated chip, Phys. Rev. Lett. **97**, 023002 (2006).

[62] P. Treutlein, P. Hommelhoff, T. Steinmetz, T.W. Hänsch, and J. Reichel, Coherence in microchip traps, Phys. Rev. Lett. **92**, 203005 (2004).

[63] Y.-J. Wang, D.Z. Anderson, V.M. Bright, E.A. Cornell, Q. Diot, T. Kishimoto, M. Prentiss, R.A. Saravanan, S.R. Segal, and W. Saijun, Atom Michelson interferometer on a chip using a Bose-Einstein condensate, Phys. Rev. Lett. **94**, 090405 (2005).

[64] S. Wildermuth, S. Hofferberth, I. Lesanovsky, S. Groth, I. Bar-Joseph, P. Krüger, and J. Schmiedmayer, Sensing

electric and magnetic fields with Bose-Einstein Condensates, arXiv:cond-mat/0512520, 2005.

[65] S. Wildermuth, S. Hofferberth, I. Lesanovsky, E. Haller, L.M. Andersson, S. Groth, I. Bar-Joseph, P. Krüger, and J. Schmiedmayer, Bose-Einstein condensates microscopic magnetic-field imaging, Nature **435**, 440 (2005).

[66] O. Zobay and B.M. Garraway, Atom trapping and two-dimensional Bose-Einstein condensates in field-induced adiabatic potentials, Phys. Rev. A **69**, 23605–23615 (2004).

[67] O. Zobay and B.M. Garraway, Two-dimensional atom trapping in field-induced adiabatic potentials, Phys. Rev. Lett. **86**, 1195–1198 (2001).

[68] G. Birkl et al.: www.iap.physik.tu-darmstadt.de/apq/.