We discuss a new direction in the field of quantum information processing with neutral atoms. It is based on the use of microfabricated optical elements. With these elements versatile and integrated atom optical devices can be created in a compact fashion. This approach opens the possibility to scale, parallelize, and miniaturize atom optics for new investigations in fundamental research and applications towards quantum computing with neutral atoms. The exploitation of the unique features of the quantum mechanical behavior of matter waves and the capabilities of powerful state-of-the-art micro- and nanofabrication techniques lend this approach a special attraction.

I. INTRODUCTION

Following the spectacular theoretical results in the field of quantum information processing of recent years [1], there is now also a growing number of experimental groups working in this area. Among the many currently investigated approaches, which range from schemes in quantum optics to superconducting electronics [2], the field of atomic physics seems to be particularly promising due to the experimentally achieved remarkable control of single qubit systems and the understanding of the relevant coherent and incoherent processes. While there have been successful implementations of quantum logic with charged atomic particles in ion traps [3], quantum information schemes based on neutral atoms [4,5] are an attractive alternative due to the weak coupling of neutral atoms to their environment. A further attraction of neutral atoms lies in the fact that many of the requirements for the implementation of quantum computation [6] are potentially met by the newly emerging miniaturized and integrated atom optical setups.

These miniaturized setups can be obtained by using different types of microfabricated structures: The trapping and guiding of neutral atoms in microfabricated charged and current carrying structures has been pursued by a number of groups in recent years [7,8,9]. A new approach to generate miniaturized and integrated atom optical systems has been recently introduced by our group [10]: We proposed the application of microfabricated optical elements (microoptical elements) for the manipulation of atoms and atomic matter waves with laser light. This enables one to exploit the vast industrial and research interest in the field of applied optics directed towards the development of micro-optical elements, which has already lead to a wide range of state-of-the-art optical system applications [11,12] in this field. Applying these elements to the field of quantum information processing, however, constitutes a novel approach. Together with systems based on miniaturized and microfabricated mechanical as well as electrostatic and magnetic devices, the application of microoptical systems will launch a new field in atom optics which we call ATOMICS for ATom Optics with MICro-Structures. This field will combine the unique features of devices based on the quantum mechanical behavior of atomic matter waves with the tremendous potential of micro- and nanofabrication technology and will lead to setups that are also very attractive for quantum information processing.

II. MICROOPTICAL ELEMENTS FOR QUANTUM INFORMATION PROCESSING

A special attraction of using microoptical elements lies in the fact, that most of the currently used techniques in atom manipulation are based on the optical interaction with the atoms. The use of microfabricated optical elements is therefore in many ways the canonical extension of the conventional optical methods into the microregime, so that much of the knowledge and experience that has been acquired in atom optics can be applied to this new regime in a very straightforward way. There are however, as we will show in the following, a number of additional inherent advantages in using microoptics which significantly enhance the applicability of atom optics and will lead to a range of new developments that were not achievable until now: The use of state-of-the-art lithographic manufacturing techniques adapted from semiconductor processing enables the optical engineer to fabricate structures with dimensions in the micrometer range and submicrometer features with a large amount of flexibility and in a large variety of materials (glass, quartz, semiconductor materials, plastics, etc.). The flexibility of the manufacturing process allows the realization of complex optical elements which create light fields not achievable with standard optical components. Another advantage lies in the fact, that microoptics is often produced with many identical elements fabricated in parallel on the same substrate, so that multiple realizations of a single conventional setup can be created in a straightforward way. A further attraction of the flexibility in the
neutral atoms can be realized with microoptical elements. We show how crucial components for miniaturized systems for quantum information processing with neutral atoms if one employs microfabricated optical elements. Excellent overviews of microoptics can be found in [18–19]. To our knowledge, of all these elements only computer generated holograms and phase gratings have been used in atom optics so far for guiding [20] and trapping [21–23] of atoms, while a new type of atom trap based on the near field of laser radiation has been proposed in [24].

A particularly simple atom trap is based on the dipole trapping potential (Fig. 3). Microlenses have typical diameters of 150 µm to 1 mm and focal lengths of typically 100 µm to 1 mm, their numerical aperture can be as high as 0.5, resulting in foci whose size $q$ (defined as the radius of the first minimum of the Bessel function which results from the illumination of an individual microlens with a plane wave) can be as low as $q=1$ µm for visible laser light.

By focusing a single red-detuned laser beam extending over multiple microlenses with a spherical microlens array, we obtain one- or two-dimensional arrays of a large number of dipole traps (Fig. 4), in which we store multiple-atom samples. For frequently used atomic species and commonly used laser sources one can easily obtain a large number of atom traps of considerable depth with rather moderate laser power. For typical laser parameters and 100 atom traps, the trap depth is significantly larger than the kinetic energy of the atoms achievable with Doppler cooling (0.141 mK $\times k_B$ for rubidium) [7]. The low rates of spontaneous scattering that are achievable with sufficiently far-detuned trapping light ensure long storage and coherence times as required for successful quantum information processing, while a strong localization of the atoms strongly suppresses heating of the atoms and makes it possible to cool the atoms to the ground state of the dipole potential via sideband cooling in all dimensions. For the parameters given in [17] the size of the atomic wavefunction reaches values that are significantly smaller than 100 nm, even approaching 10 nm in many cases, thus making microlens arrays well suited for the generation of strongly confined and well localized atom samples.

The lateral distances between the individual traps (typically 100 µm) make it easy to selectively detect and address the atom samples in each dipole trap. While the natural way of addressing an individual trap consists in sending the addressing laser beams through the corresponding microlens, there are also more sophisticated methods possible, e.g. with a two-photon Raman-excitation technique as depicted in Fig. 4. This technique has been applied frequently to create superposition states in alkali atoms [23] and can be used to implement single qubit rotations for quantum information processing. It relies on the simultaneous interaction of the atoms with two mutually coherent laser fields. For a sufficiently large detuning from the single photon resonance, only the

### IV. MULTIPLE ATOM TRAPS

A new approach arises from the application of one- or two-dimensional arrays of spherical microlenses for atom trapping (Fig. 3). Microlenses have typical diameters of 150 µm to 1 mm, their numerical aperture can be as high as 0.5, resulting in foci whose focal size $q$ (defined as the radius of the first minimum of the Bessel function which results from the illumination of an individual microlens with a plane wave) can be as low as $q=1$ µm for visible laser light.

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atoms in the trap that is addressed by both laser beams are affected by them. These factors open the possibility to prepare and modify quantum states in a controlled way ("quantum engineering") in each trap, which is a necessary ingredient for quantum computing. As a first and easily achievable implementation, single qubits associated with long-lived internal states can be prepared and rotated in each individual trap of a two-dimensional dipole trap array (Fig. 3), stored and later read out again. Thus, this device can serve as a quantum state register.

The manipulation of atoms with microlens arrays is extremely flexible: It is easily possible to temporarily modify the distances between individual traps if smaller or adjustable distances between traps are required. This can be accomplished either by using two independent microlens arrays which are laterally shifted with respect to each other or by illuminating a microlens array with two beams (possibly of different wavelength) under slightly different angles, thereby generating two distinct sets of dipole trap arrays. Their mutual distance can be controlled by changing the angle between the two beams. With a fast beam deflector, this can be done in real-time during the experiment.

Due to this flexibility, setups based on microlens arrays are also well suited for the implementation of two-qubit gates. Considering, for example, quantum phase gates based on dipole-dipole interactions between atoms, all requirements are fulfilled in the configuration depicted in Fig. 1. Atoms localized in neighboring traps can be first initialized and then be brought close to each other with a definable separation in the single-micron range and for a predefined duration, in order to inscribe the required phase shift. Especially well suited is this configuration also for quantum gates based on the dipole-dipole interaction of low-lying Rydberg states in constant electric fields, as proposed in 3.

V. INTEGRATION

The huge potential for integration of microoptical components can be used for a large variety of further atom optical purposes. Due to their large numerical aperture, microoptical components can also be used for efficient spatially resolved read-out of quantum information (Fig. 3). In most cases the state of a qubit is recorded by exciting the atom state-selectively with resonant light and collecting the fluorescence light. Microoptical components can be used for the collection optics. Furthermore, the optical detection of quantum states with microoptical components is not restricted to optical trapping structures (Fig. 3 (a)): Since the same techniques are applied for the fabrication of microoptical components and microstructured wires on surfaces, microoptical components can be easily combined with the magnetic and electric structures of 9-10 (Fig. 3 (b)). In addition, microfabricated atom-optical components can be integrated with optical fibres and waveguides so that quantum information after being read-out by detection of the scattered light can be further processed by optical means (Fig. 3 (c)).

Another canonical extension is given by the integration of microoptical components with optoelectronic devices such as semiconductor laser sources and photodiode detectors. In this case, the communication with the outside world can take place fully electronically, with the required laser light created in situ and the optical signals converted back to electrical signals on the same integrated structure. Fig. 4 illustrates a simple but powerful configuration based on this approach. The depicted setup utilizes vertical cavity surface emitting lasers (VCSELs) 13-28 which are directly mounted onto a two-dimensional microlens array. VCSELs emit circular symmetrical non-astigmatic beams while their structure is optimized for the lithographic fabrication of densely packed 2D arrays. Since VCSELs generally emit a single longitudinal mode at a wavelength which can be tuned by changing the current, the light coming from a two-dimensional array of VCSELs can be directly focused by the microlens array to create a two-dimensional array of stable dipole traps (Fig. 3). With VCSELs it becomes now possible to selectively switch on and off individual traps or to selectively change their potential depth resulting in further flexibility in the atom manipulation.

VI. CONCLUSION

In this paper we have discussed the new research direction of using microfabricated optical elements for quantum information processing with neutral atoms. This application hugely benefits from the many inherent advantages of microoptical components. Specifically, an approach based on microoptical systems addresses two of the most important requirements for the technological implementation of quantum information processing: parallelization and scalability. In addition, the possibility to selectively address individual qubits is essential for most schemes proposed for quantum computing with neutral atoms.

Thus, all steps required for quantum information processing with neutral atoms - i.e. the preparation, manipulation and storage of qubits, entanglement and gate operations as well as the efficient read-out of quantum information - can be performed using microfabricated optical elements.
VII. ACKNOWLEDGEMENTS

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FIG. 1. Experimental setup. The light of an incoming red-detuned laser beam is shaped by a microoptical component and the focal plane is imaged into the vacuum chamber. The atoms are first collected in a MOT and then transferred into the optical microstructure.

FIG. 2. Inset: Density distribution of atoms in single dipole trap obtained by using a single microlens in the setup depicted in Fig. 1. Main picture: Number of atoms remaining in dipole trap as a function of time. An exponential fit to the data yields a storage time of 166 ms.

FIG. 3. Refractive (a) and diffractive (b) array of spherical microlenses.

FIG. 4. Two-dimensional array of dipole traps created by focusing a red-detuned laser beam with an array of microlenses. Due to their large separation (typically 100 µm) individual traps can be addressed selectively, e.g. by two-photon Raman-excitation, as depicted.

FIG. 5. Spatially resolved readout of the internal and external states of atoms (e.g. the state of a qubit) using microlens arrays: (a) Integration of two spherical microlens arrays creates a combined system of dipole traps and efficient detection optics. (b) Integration of a microlens array (for readout) with microfabricated magnetic or electrostatic trapping structures. (c) Optical waveguides and fibres can also be integrated on the substrate.

FIG. 6. Integration of microoptical components and laser sources. An array of vertical cavity surface emitting lasers (VCSELs) illuminates a microlens array with matched lens separation. Each trap of the resulting two-dimensional array of dipole traps can be individually switched on and off because the individual VCSELs are selectively addressable.