Towards a Scalable Dipole-Trapping Scheme for Neutral Atoms

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Abstract: We present a new scheme for trapping single atoms in separate dipole-traps and manipulating them individually. It relies on a spatial light-modulator to create the traps and will find applications in cavity-QED.

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1. Introduction
For quantum information processing and related areas, the ultimate control of individual qubits relies on the ability to arbitrarily manipulate, address and couple individual information carriers, like single atoms or single photons. Moreover, the interfacing of atoms and photons, the storage and retrieval of single photons and the state mapping between distant atoms are the essential building blocks of scalable quantum communication and distributed quantum-information processing networks [1].

Cavity-QED with neutral atoms provides a very promising physical platform for implementing most of these elementary building blocks [2,3]. However, controlling and positioning atoms in optical micro-cavities still remains a challenging task. A flexible and scalable scheme for displacing atoms in or out of optical cavities is highly desirable.

Here, we report on a new dipole-trapping scheme that will allow to trap single neutral atoms in separate dipole traps and to displace them individually in a plane on a length scale of about fifty microns.

2. Description of the setup
In order to reach a high degree of control on single atoms, we are implementing a scheme that enables us to trap them in an array of individual optical dipole-traps. As shown in Fig. 1, these dipole-traps are created by imaging the surface of a digital light-modulator (about 1 cm²) to the surface of a plane mirror lying just below a cloud of cold atoms in a vacuum chamber. The light-modulator is a micro-mirror device whose surface consists of 1024 x 780 micro-mirrors (13 x 13 μm²). The micro-mirrors can be individually switched between two positions ("on" or "off"). The inset (a) in Fig. 1 shows a part of the surface of the digital micro-mirror device (DMD). By switching the micro-mirrors, the dipole-trap array can be dynamically rearranged. Because of the ability to move the individual traps, the dipole-traps will act as single-atom optical tweezers. Note also that the trapping beams are actually standing waves since the light propagating from the DMD is reflected back by the plane mirror.

We will implement the scheme with 87Rb atoms. The cloud of cold Rb atoms is prepared in a magneto-optical surface trap [4]. In our setup, the same plane mirror used to create the standing-wave optical tweezers is also used to reduce the number of optical cooling beams, compared with a standard magneto-optical trap. The required quadrupolar magnetic field is generated by superimposing the field produced by a U-shaped wire to a constant field.
produced by a pair of coils in Helmholtz configuration. To cool the atoms, we use the $^{87}$Rb $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ transition, which lies at a wavelength $\lambda=780$ nm. The inset (b) of Fig. 1 shows an image of the trapped atomic cloud taken with a CCD camera. The cloud has a diameter of 120 μm and is laying 240 μm above the surface of the mirror.

The light used to create the dipole-traps is red-detuned by 5 nm ($\lambda=785$ nm) with respect to the $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ resonance. It will be emitted from a diode laser with an available power of 1 W. The optical system that images the DMD surface consists of two lenses: a long focal length collimator ($f_1=750$ mm) placed at the focal distance from the DMD and a focusing aspheric lens ($f_2=12$ mm) placed inside the vacuum chamber. This lens has a high numerical aperture (NA=0.58) and is able to focus light down to a 1-μm spot size. The lenses are set in a telescopic arrangement. 50-μm spots patterns loaded on the DMD have been successfully imaged to 1-μm spots on the flat mirror surface. The inset of Fig. 2 shows an optical image of nine nearly diffraction-limited spots created on the flat mirror. This picture has been taken during preliminary tests with the flat mirror and the aspheric lens outside the vacuum chamber. A typical intensity profile of a 1-μm spot obtained in this way is plotted in Fig. 2 and fitted by Gaussian function. The fit provides the value of the experimental spot diameter: $d_{exp} = 0.78 \mu$m (full width half-maximum). This is slightly larger than the diffraction limit $d_{dyr} = 0.69 \mu$m.

From the 1-W power delivered by the trapping laser, barely about 250 μW will be available for each individual trap. However, this power is sufficient to produce a trap depth equivalent to about 500 μK. The tweezer will only catch the coldest atoms from the atomic cloud prepared in the surface MOT. In principal, a single-atom-per-trap regime could be reached by increasing the optical power [5]. The number of atoms per trap can be deduced from the collected fluorescence.

In order to collect the fluorescence from the atoms, we use a confocal geometry (see Fig. 1). The fluorescence light ($\lambda=780$ nm) is collected by the same aspheric lens that was used for focusing the optical tweezer and processed through several interference filters to a CCD camera (with enhanced sensitivity). The camera signal will be automatically analyzed to determine the number of atoms in each trap.

3. Conclusion

We propose a new set-up for implementing atom dipole trapping in a scalable way. We have already demonstrated trapping and cooling of atoms in a surface magneto-optical trap and have designed the optical system needed to produce multiple nearly diffraction-limited 1-μm spots that will act as optical tweezer for atoms.

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4. References