Manipulating single atoms in microscopic dipole traps: a new generation apparatus

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Abstract. We have built a new apparatus in order to manipulate single ⁸⁷Rb atoms for quantum computing. Single atoms will be loaded from a cold vapor into a microscopic dipole trap. Tests of the cooling system are under progress and first fluorescence signals have been observed in the magneto-optical trap. A high numerical aperture objective has been designed to perform tight focusing of the trapping light as well as high efficiency collection of the single atom fluorescence.

1. INTRODUCTION

We are interested in the manipulation of atomic clouds consisting of a small number of atoms trapped in a microscopic dipole trap. Our set-up uses ⁸⁷Rb atoms and is very similar to the apparatus used in previous experiments [1]. A key-point of these experiments is the ability to focus a laser beam, far detuned with respect to the atomic fluorescence transition (D₂ line at 780nm), onto a spot diameter of ~1μm. This ensures a large trap depth (~1mK/mW), accessible with low power laser diodes, as well as high oscillation frequencies in the trap (~150kHz transversally, and ~30kHz longitudinally): a prerequisite for accurate addressability of the atomic levels in the dipole trap, and operation in the “collisional blockade” regime [2]. In our case, the dipole trap operates at 850nm, and a few milliwatts are sufficient to achieve these conditions. Another key-point is to efficiently collect single atom fluorescence for rapid diagnostic purposes [3]. Both key-points can be fulfilled by focusing the 850nm beam and collecting the 780nm fluorescence with a single high numerical aperture objective. A dichroic plate separates the two radiations. To benefit from the large numerical aperture, however, the objective should be “nearly” diffraction limited at both trapping and imaging wavelengths. This is particularly true for imaging arrays of micro-trapped atoms [4]. This means that the wave front should satisfy the Maréchal criterion:

\[ \sigma_w \leq \frac{\lambda}{14} \quad (1) \]

where \( \sigma_w \) denotes the standard deviation of the actual wave front from the ideal wave front.

2. OUR NEW SINGLE ATOM APPARATUS

In previous experiments, we used a home-made objective consisting of nine spherical lenses, with a numerical aperture N.A.=0.7. Careful design and positioning of the lenses, along and perpendicular to
the optical axis, resulted in a diffraction-limited resolution of 0.7μm, while the collection efficiency was ~15%. This excellent performance was valid for a beam focusing no further than 12.5μm off-axis. The working distance was 10mm, and the objective operated under ultra high vacuum.

By contrast, our new apparatus uses a single commercial aspheric lens (LightPath 350240), with N.A.=0.5. The lens is mounted under vacuum, and the working distance is ~5.7mm. This lens was designed to be diffraction limited at 780nm: when irradiated by a collimated laser beam, we expect a spot diameter of 0.95μm in the focal plane. Best performance is expected, however, when the lens is combined with a 0.25mm thick glass window. Hence, absence of this glass window results in an enhanced aspheric aberration in our case. The best focus quality can be restored, however, by slightly defocusing the aspheric lens, and operating with a weakly converging (diverging) beam at 850nm (780nm). Trap parameters comparable to values mentioned above are expected, with a collection efficiency of 7.6%. Beam shaping and residual aberration compensation is performed by two commercial spherical lenses, which operate with weakly diverging beams outside the vacuum chamber. Tight focusing proves to be robust against inaccurate (+/-2mm) positioning of the lenses along the optical axis. Transverse positioning of the lenses proves to be more critical, though, and fine control (within 0.01mm) on the centering of the lenses is necessary. This was also the case for our previous generation objective, however. The main improvement of our new system, apart from its simplicity, is that it remains nearly diffraction limited for beams focusing as far as 30μm off-axis.

Our new aspheric lens based dipole trap is presently under alignment procedure. The aspheric lens has been tested separately in the best focus configuration with a Michelson interferometer: its performance outcomes our expectancies, with $\sigma_{\lambda}\sim\lambda/30$ at 633nm.

Apart from the dipole trap, a new vacuum apparatus has been built, together with a new laser diode based optical bench. The new dipole trap will be loaded from a cold vapor of $^{87}$Rb, produced by a Zeeman slowed Rb beam and a magneto-optical trap. Preliminary fluorescence measurements indicate that approximately $10^7$ Rb atoms are captured presently. Optimization of the slowing and cooling parameters is under progress.

3. PERSPECTIVES

One goal of this new experiment is to study the controlled motion of the atom in the microscopic dipole trap. This optical tweezers would provide a “moving head”, to be used in the larger architecture of a future quantum computer, consisting of an array of micro-dipole traps. We are planning to use two atoms trapped in two tweezers and bring them together, thus realizing a controlled collision, along the idea of “adiabatic massage” proposed by T. Calarco [5]. Such a collision can also be controlled using an optical Feschbach resonance [6]. This will pave the road towards achieving a phase gate, and is part of our effort towards Neutral Atom Quantum Computing.

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References