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Improved detection of small atom numbers through image processing

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Application Note

Introduction

Trapped ultracold atoms and quantum degenerate gases are novel systems for the study of many-body quantum physics and are key to new technologies such as trapped atom interferometer and atomic clocks. Essential to such applications is the ability to precisely measure the populations of a pair of atomic ensembles in, for example, a double-well potential for Josephson physics or atom interferometry or the spin states of an atomic clock.

Experimental Setup

We have recently demonstrated [1] improved detection of trapped ensembles of ultracold atoms through advanced post-processing and optimal analysis of laser-illuminated absorption images. This crucially depends on the properties of the camera used for absorption imaging. This allows us to better measure the intrinsic atom number fluctuations in a magnetic lattice potential [3], but has important implications for most experiments on ultracold atoms relying on absorption imaging for data acquisition.

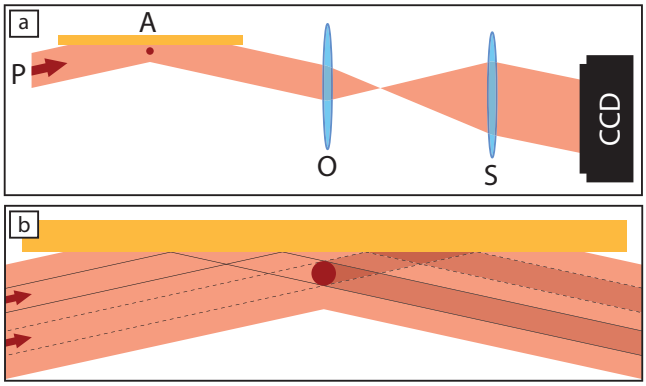

FIG. 1. (a) Schematic depiction of the mirror imaging setup, showing the atom chip (A), probe beam (P), lens system (O, S) and CCD camera. The angle of the probe beam has been exaggerated to illustrate the reflection setup. (b) Close-up around the atom chip surface. Part of the probe light is reflected before and part after passing through the atoms, depicted by solid and dashed lines, respectively. The two separate shadows cast by the atoms are then imaged onto separate regions of the CCD camera.

Absorption imaging is the standard method for detecting trapped neutral atoms. Here atoms are briefly exposed to a nearly homogeneous probe laser, typically tuned to resonance with an atomic transition and the resulting absorption signal A is imaged onto a CCD camera. Subsequently the atoms are ejected from the trap and a reference image R is recorded to normalize intensity variations of the probe. A dark image may also be recorded without the probe to subtract any stray light or CCD dark counts. From this data it is possible to extract information on the two-dimensional density distribution of the atoms.

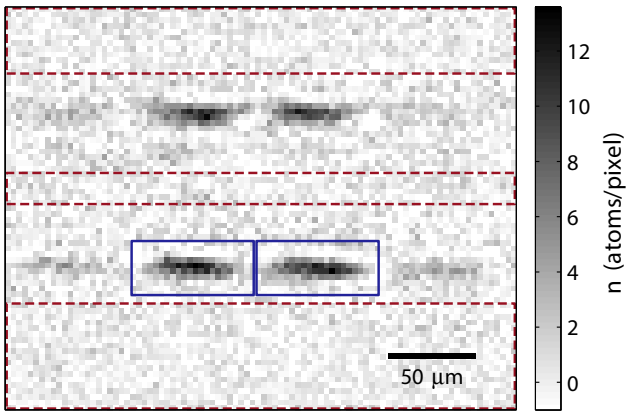

FIG. 2. Typical absorption image of the atomic distribution (90 x 71 pixels) for a hold time of 1.6 s. Four independent atomic ensembles are visible (horizontally distributed) with two mirror images (vertically separated). The two center-most clouds each contain ~400 atoms. Dashed boxes indicate the background pixels for the fringe removal algorithm and the signal regions are indicated by solid lines.

Our experiments employ a back-illuminated deep-depletion CCD camera (Andor iKon-M DU934N-BR-DD) with a quantum efficiency of $Q_e \approx 0.9$ at = 780 nm, a measured gain of g = 0.87 ±0.05 counts/photon and a readout noise level of $\sigma_{rd} \approx 14$ electrons (A/D rate 2.5 MHz, pre-amplifier gain 4.6 electrons/count). The resolution of our optical system is 9.6 µm (Rayleigh criterion) with a pixel area of $\Delta = (3.3 \pm 0.1\ \mu m)^2$ in the object plane. The probe is slightly inclined with respect to the gold-coated chip surface to create two mirror images of the atoms (fig. 2). The imaging setup is depicted in figure 1 and an example of the resulting images can be seen in figure 2.

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Results

Figure 3 shows the imaging noise with and without fringe removal [2], var(A/Q) and var(A/R) respectively, calculated for a signal-free region (separate from the fringe-removal background region) for various probe intensities.

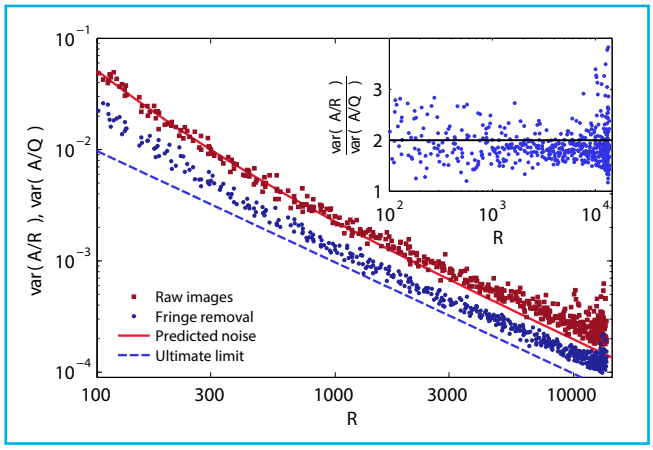

FIG. 3. Imaging noise for various probe intensities with and without fringe removal, var(A/Q) (circles) and var(A/R) (squares) respectively. The predicted photon shot-noise plus camera readout noise is shown as a solid line. The dashed line shows the ultimate photon shot-noise limit.

Without fringe removal the measured noise is in good agreement with the expected photon shot noise and readout noise given our CCD parameters. Application of the fringe removal algorithm with a basis of 250 reference images reduces the measured variances by a factor of 1.9 ± 0.3 over the full range of intensities. Remarkably, even in the absence of fringes, the algorithm reduces the photon shot-noise contribution originating from R. This is possible since the optimal reference image is the (weighted) average over many reference images, allowing an additional decrease of uncorrelated noise by up to a factor of 2. For our chosen imaging parameters the remaining noise from pixel to pixel is σn = 1.3 ±0.3 atoms, close to the ultimate limit of 1.1 atoms due to photon shot noise in A. There is also a small residual correlated noise component which fluctuates on a length scale comparable to our cloud size with an rms amplitude of 0.06 ±0.01 atoms.

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