The trapping and detection of single atoms using a spherical mirror

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New Journal of Physics 14 (2012) 093007 (11pp)
Received 13 June 2012
Published 5 September 2012
Online at http://www.njp.org/
doi:10.1088/1367-2630/14/9/093007

Abstract. We fabricate a miniature spherical mirror for tightly focusing an optical dipole trap for neutral atoms. The mirror formation process is modelled to predict the dimensions for particular fabrication parameters. We integrate the spherical mirror with a neutral atom experiment to trap and detect a single atom with high efficiency. The mirror serves the dual purpose of focusing the dipole trap as well as collecting the atomic fluorescence into an optical fibre.

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1. Introduction

For quantum information applications based on atoms, large atom–photon interactions can be used to interface photonic and atomic qubits. Enhancement of the interaction can be achieved using either high-finesse optical cavities [1] or strongly focused laser fields [2]. High-finesse cavities enhance the atom–photon interaction by repeated reflection of a single photon so that the field from a single photon is enhanced by the cavity finesse. Although this approach has been successful with neutral atoms, cavity experiments are complicated to implement for the ion trap system due to technical problems associated with the proximity of the cavity mirrors to the ion [3]. Cavity-based systems are also difficult to scale up to a large system of atom–photon interfaces [4]. In contrast, the strong focusing approach is easy to implement [5] and a number of approaches towards scalability have been considered.

For the purposes of scaling to a large number of atoms, it is also desirable to provide the means to trap and individually address single atoms. A large number of individually addressable single atoms have been trapped by spatial light modulators combined with custom-made microscope objectives [6] but the method is neither simple nor low cost. Micro-lens arrays have also been used to create arrays of approximately 80 individually addressable optical dipole traps [7], but ensuring single-atom occupancy was not possible. An alternative approach is to use spherical mirrors.

Spherical mirrors are easy to integrate with both ion traps [8] and neutral atom experiments. In the case of neutral atoms, an optical dipole trap can be formed by focusing collimated light with the spherical mirror [9]. If the radius of curvature of the mirror is small, the focus is tight enough to engage the collisional blockade phenomenon [10], which ensures that only one atom can be trapped under weak loading conditions. Alternatively, light-assisted collisions in a tightly confining dipole trap can be used to prepare single atoms [11]. Moreover, the interaction light can be focused by the same mirror to a tight spot for free space atom–photon coupling. Although spherical mirrors suffer from aberrations, these can be corrected with proper optical elements outside the vacuum chamber [8] and become less significant with decreasing mirror dimensions. For sufficiently small radii of curvature, there can be significant coupling of the light reflected by the mirror into a single-mode fibre [12].

Current methods of producing spherical mirrors involve either silicon-based fabrication [13] or conventional glass polishing techniques. Although arrays of spherical mirrors can be produced by the silicon fabrication method, the radius of curvature is limited to hundreds of microns, making it difficult to integrate it with any practical atom trapping experiments. Conventional glass polishing produces mirrors of large dimensions and cannot be used to tightly focus trapping light. Recently, we developed a fabrication technique that bridges the gap between the existing technologies, producing mirrors with large enough dimensions for easy integration with experiments but small enough to enable tight focusing of the dipole trap [14].

In this paper, we demonstrate the use of our spherical mirrors for trapping single atoms at the focus of the mirror. We obtain a tightly focusing dipole trap with a waist ($1/e^2$ radius) of $\sim 2 \mu\text{m}$ by illuminating the mirror with a collimated 850 nm laser. We use light-assisted collisions [11] to prepare single atoms in this trap with $\sim 70\%$ efficiency. Fluorescence collected using the mirror is coupled into a multi-mode optical fibre giving an atom detection efficiency of 99% in a 100 $\mu\text{s}$ integration time.
Figure 1. The fabrication process. (a) Glass slide of thickness $\delta_0$ placed on a cylindrical hole of radius $r_0$ and depth $d$. (b) After deformation, the dimple has a depth $y$ and a radius of curvature $R$. In the case of the mirror for the optical dipole trap, typical dimensions are $\delta_0 = 150 \mu m$ and $r_0 \sim d \sim 2 \text{ mm}$.

The paper is organized as follows. We start with a model of the fabrication process, which illustrates how the mirror dimensions can be reliably controlled and predicted. We then characterize the focusing capability of the mirror. Details of our experimental setup are then given in which we characterize the optical dipole trap in terms of single-atom loading and detection efficiency.

2. Fabrication and modelling

Details of the mirror fabrication process have been reported elsewhere [14]. Briefly, the method uses borosilicate D263 glass and a ceramic substrate (Macor). Cylindrical holes are drilled into the ceramic and a borosilicate coverslip is placed over them. The substrate and the glass are then heated in a furnace at low pressure. When heated to $800^\circ C$, the glass softens and strongly adheres to the substrate sealing the holes at low pressure. Air at higher pressure is then introduced and the pressure difference causes the softened glass to curve inwards, creating smooth spherical dimples. The process results in ultra-smooth surfaces with sub-nanometre roughness.

To estimate the mirror parameters obtained using this process, we adopt the model developed in [15] for the fabrication of glass micro-spheres. Throughout the deformation process, we assume that the glass surface maintains a near-spherical shape with the spherical shell thus formed having a uniform thickness. Thus, the radius of curvature, $R$, is given by

$$ R = \frac{y^2 + r_0^2}{2y}, $$

(1)

where $r_0$ is the radius of the cylindrical hole and $y$ is the depth of the dimple as illustrated in figure 1(b). To determine $y$, we assume that the entire process takes place at a constant temperature. Thus, the pressure, $P$, and volume, $V$, of the trapped gas can be related to the initial values by the ideal gas law

$$ PV = P_0 V_0. $$

(2)

Macor is a glass ceramic sold by Corning Incorporated, New York, USA.
From geometric considerations the volumes $V$ and $V_0$ are given by

$$V_0 = \pi r_0^2 d,$$

$$V = V_0 - V_d = \pi r_0^2 d - \pi \left( \frac{y^3}{6} + \frac{r_0^2 y}{2} \right),$$

where $V_d$ is the volume of the dimple. Thus, the pressure of the trapped gas is given by

$$P = \frac{P_0 V_0}{V} = P_0 \frac{\pi r_0^2 d}{\pi r_0^2 d - \pi \left( \frac{y^3}{6} + \frac{r_0^2 y}{2} \right)},$$

giving a pressure difference, $\Delta P = P_{\text{ext}} - P$, of

$$\Delta P = P_{\text{ext}} - P_0 \frac{\pi r_0^2 d}{\pi r_0^2 d - \pi \left( \frac{y^3}{6} + \frac{r_0^2 y}{2} \right)},$$

where $P_{\text{ext}}$ is the external pressure introduced after the holes were sealed. Setting $\Delta P = 0$ then provides an equation for the equilibrium depth $y$ as a function of $r_0$, $P_0$ and $P_{\text{ext}}$. The solution can then be used in equation (1) to determine the radius of curvature.

The time variation of $y$ can also be modelled using the methods given in [15]. The softened glass at 800°C behaves like an incompressible Newtonian fluid, and it can be shown that time variation of $y$ satisfies

$$\frac{dy}{dt} = \frac{1}{24 \eta r_0^2 \delta_0} \left( \frac{r_0^2 + y^2}{y^2} \right)^3 (\Delta P),$$

where $\eta$ is the viscosity of borosilicate glass at 800°C and $\delta_0$ is the thickness of the glass. Taking $\eta = 10^{6.6}$ Pa s, $\delta_0 = 150 \mu$m, $r_0 \sim d \sim y \sim 1$ mm and $\Delta P \sim 150$ mbar gives an estimated time scale of several minutes.

For a fixed value of $r_0 = 1$ mm and $\Delta P \sim 150$ mbar, we fabricate glass dimples for various hole depths and deformation times and we plot the depth $y$ in figure 2. Error bars on the theoretical plot reflect the uncertainty in pressure due to limitations of the furnace. Although the general trend of $y$ as a function of $d$ is correct, there are two notable deviations from the model predictions: the measured depth does not converge to the predicted equilibrium value, and the time scale to reach equilibrium differs by more than an order of magnitude.

In the actual process, the sealing temperature is not known for sure. If it occurs below 800°C, the enclosed gas in the cylindrical hole is heated up as the furnace reaches the final temperature and the pressure enclosed will be higher than what we assumed. For example, if the hole is sealed at 700°C instead of the 800°C, the pressure inside the hole will be larger than the estimated value by approximately 10%. This could account for the reduced equilibrium value of $y$. Although in our model we assumed that the formed spherical shell has a uniform thickness, in reality the thickness in the middle of the shell is thinner than that at the sides [15]. In most cases, the thickness of the middle of the shell is only 10% less than the sides and can be ignored.

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3 D263T is a highly resistant borosilicate glass manufactured by Schott.
in the simple model. It is not clear why there is such a large discrepancy between the predicted rate of formation and the actual rate. However, we do note that the viscosity has a very strong dependence on temperature. In any case, the resulting deformation is easily reproducible and the general trend allows us to estimate the parameters needed to achieve a particular mirror geometry.

3. Mirror characterization

There are only two independent parameters that determine the geometry of a spherical mirror, namely the clear aperture and the radius of curvature. The clear aperture is given by the hole radius, $r_0$, and the radius of curvature, $R$, can be controlled by the pressure difference established during fabrication. In our experiments, we aimed at a clear aperture of 4 mm as this enables easy alignment of input beams with waists up to around 1 mm without significant clipping. Allowing for a 1 mm working distance for the optic constrains the curvature to be about 3.3 mm. With this as the target, we fabricated a mirror that gave a measured curvature of 3.2 mm or, equivalently, a focal length of 1.6 mm. The mirror surface was then coated with evaporated silver giving a reflectivity greater than 95% at both 780 and 850 nm.

The focusing performance of the optic was tested using the setup shown in figure 3(a). A collimated beam of waist 1 mm was incident on the mirror and the resulting focus was imaged using a calibrated 20× long working distance microscope objective. A 50:50 beam splitter was used as shown so that the focus could be imaged directly. Figure 3(b) shows the actual focus imaged by the microscope objective. A strong central peak can be seen along with the presence of a secondary ring. Fitting the cross-section of the image shown in figure 3(c) to a Gaussian profile gave a waist of $2 \pm 0.1 \mu m$. Subtracting a two-dimensional Gaussian profile from the
Figure 3. (a) The setup used for measuring the spot size of the reflected light from the spherical mirror. (b) Image of the spot showing the main peak and secondary rings. (c) Cross-section of the beam intensity, showing a main Gaussian peak profile and a smaller secondary ring.

profile in figure 3(b), we then estimate, from the residuals, that 12% of the total power lies in the outer ring.

The secondary ring is due to spherical aberration and not due to some clipping of the input beam. Clipping of the beam could be perceived as the cause when we have a beam with a waist of 1 mm and a clear aperture of 4 mm of the mirror. To confirm spherical aberrations, we shrunk our incident beam down to 300 µm to avoid any clipping but still got the secondary ring. Note that, although an ideal optic with a focal length of 1.6 mm would yield a sub-µm spot size, spherical aberrations limit the achievable spot size. However, a waist of 2 µm still enables us to use light-assisted collisions to prepare a single atom [11].
4. Implementation of a tightly confining optical dipole trap

In our experiment, we implement a dipole force trap using light at 850 nm. The trap is loaded directly from a magneto-optical trap (MOT) located at the focus of the spherical mirror, and after the loading, we utilize light-assisted collisions induced by the MOT cooling beams to obtain a single trapped atom. In this section, we discuss the details of our setup and the procedure for loading and detecting single atoms.

4.1. The experimental setup

Our experimental setup is illustrated in figures 4 and 5. The dipole force trap is formed using laser light at 850 nm. This light is obtained from an extended cavity diode laser which is spatially filtered by a single-mode fibre. Light from the fibre is collimated with an aspheric lens giving a beam waist of 1 mm with a maximum available power of about 40 mW. The light is then combined along the path of the collection optics using a dichroic mirror as shown in figure 5. Assuming a 2 μm focused waist as determined in the previous section, we estimate a trap depth of 2.5(2) mK [17].

The trap is loaded directly from a magneto-optical trap located at the focus of the spherical mirror. We use a six-beam MOT configuration consisting of two retroflected, near-vertical beams and a third retroflected horizontal beam. The near-vertical beams have a waist of 500 μm with an angle of 5° from the vertical to facilitate making a MOT close to the surface of the optic. The horizontal beam has a waist of 4.5 mm, which gives maximum overlap with the
Figure 5. The optics setup for dipole trapping and detection. Dipole trapping light at 850 nm is combined along the collection beam path using a dual-coated mirror. The dichroic mirror is reflective at 850 nm and transmissive at 780 nm. A retroflected light sheet is used to excite the atoms trapped at the focus of the dipole trap. The fluorescence light is reflected into a near-collimated beam by the spherical mirror. Inset: beam profile of the light sheet. A narrow-band interference filter at 780 nm gets rid of spurious external light at the collection coupler.

Intersection region of the two near-vertical beams. All cooling beams are red detuned below the $(F = 2 \rightarrow F' = 3)$, $D_2$ cooling transition. A re-pumping laser locked to the $(F = 1 \rightarrow F' = 2)$ transition is mixed with the vertical beams. The magnetic field for the MOT is provided by circular coils in anti-Helmholtz configuration providing a magnetic field gradient of $20 \text{ G cm}^{-1}$. Under these conditions, we create a MOT with approximately 2 million atoms.

In our experiment, we detect the presence of an atom using fluorescence measurements. Since light from the cooling beams generates a large background contribution, we use an independent detection beam to excite the atoms. We use a linearly polarized light sheet that has a $1 \text{ mm} \times 100 \mu\text{m}$ cross-section. As illustrated in figure 5, the light sheet is retro-reflected to reduce the effects of radiation pressure during imaging. The power in the light sheet is such that it is five times the saturation intensity of the $(F = 2 \rightarrow F' = 3)$ transition for isotropic polarization [18] and operated at a blue detuning of $55 \text{ MHz}$. This detuning compensates for the ac Stark shifts induced by the dipole trap.

Light from the atoms is reflected into a nearly collimated beam by the spherical mirror. The light is focused using a 18 mm focal length aspheric lens into a multimode fibre connected to a single-photon counting module. Based on the induced Stark shifts and the detuning of the detection light, we estimate that the atom scatters 700 photons during the 100 $\mu$s detection time out of which 2% are detected by the photon counting module. The 62.5 $\mu\text{m}$ core diameter of the fibre also acts as a spatial filter cutting down the off-axis background light.
4.2. Loading a single atom

In general, the number of trapped atoms in the dipole trap, \( N \), is governed by

\[
\frac{dN}{dt} = R_l - \gamma N - \beta N(N - 1),
\]

where \( R_l \) is the loading rate, \( \gamma \) is the loss rate due to background collisions and \( \beta \) is the two-body decay rate. Under typical vacuum conditions, the loss rate due to background collisions can be ignored, and at equilibrium we have

\[
R_l = \beta N(N - 1).
\]

If \( R_l \ll \beta \), the equilibrium number will be approximately zero or one atom. In such an experiment, one can monitor the trap continuously for the loading of a single atom and proceed with the subsequent experiment once a single atom is detected. However, in our experiment, continuous monitoring of the dipole trap for a single atom is not possible as light from the MOT beams saturates our detector. We use an alternative approach of using light-assisted collisions with our cooling beams in order to get down to one atom and only one atom.

In the absence of loading, \( R_l = 0 \), the atom number decays according to the two-body loss term. In the presence of resonant light, two-body losses rapidly eliminate atoms from the dipole trap until \( N = 0 \) or 1. At this point, no further two-body losses can occur. To implement this, we first maximize our loading rate, which typically gives \( N \approx 15 \). We then switch off our magnetic coils, which reduces the loading rate to zero, and the cooling light is kept on for the next 100 ms to engage light-assisted collisions. At the end of the 100 ms, we check for the presence of an atom using a 100 µs pulse of light from our detection beam.

A histogram of the counts detected from 2000 experiments is shown in figure 6. It exhibits a bimodal Poissonian distribution with contributions from zero and one atom distributions.
The distribution from zero atoms has a mean of 1 count per 100 µs exposure time, consistent with that obtained from independent background measurements. The remaining part of the distribution is from a single atom and has a mean of 16 counts. Based on this, we can detect the presence of an atom with greater than 99.7% confidence and in more than 70% of the cases.

5. Conclusion

We have fabricated and demonstrated the use of a miniature spherical mirror to trap and detect a single atom. The mirror was easily integrated with a standard neutral atom experiment and has the dual function of tightly focusing an optical dipole trap as well as collecting light from the single atom. Using the system, we have demonstrated a single-atom detection efficiency of more than 99% and a single-shot loading probability of greater than 70% of the cases.

The simplicity of the setup along with the scalability of the fabrication process would make it suitable for creating an array of addressable single-atom traps. The accurate modelling of the process allows us to repeatedly fabricate mirrors to specific dimensions. Our experiment serves as a proof of concept for focusing a tight optical dipole trap using a spherical mirror. In future work, both the focusing and the light collection efficiency can be further improved by using a mirror of smaller dimensions.

Acknowledgments

We thank Cecilia Muldoon of Oxford University for her suggestions that led to the success of this experiment and Markus Baden, Radu Cazan and Kyle Arnold for proofreading this paper. We also thank Aarthi Dhanapaul for the mirror coatings and Joven Kwek for the machining of the substrates. We acknowledge support from the National Research Foundation and the Ministry of Education of Singapore, as well as A-STAR under project no. SERC 052 123 0088.

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