

Prospects of Trapping Atoms with an Optical Dipole Trap in a Deep Parabolic Mirror for Light–Matter-Interaction Experiments

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The prospects of employing a deep parabolic mirror as a focusing device for trapping neutral atoms in an optical dipole trap are evaluated. It is predicted that such a dipole trap will result in a deep trapping potential as well as in a small spatial spread of the atom's center of mass wave function already for a Doppler cooled atom. This strong confinement is beneficial for many applications, one of which is the increase of the interaction strength between an atom and a light field focused from full solid angle.

from a perfect parabolic shape.^[7,8] The influence of such aberrations is especially severe at blue and ultraviolet wavelengths common to the intense transitions in atomic ions, as was already confirmed in experiments.^[6,7]

The maximum possible coupling is also affected by the thermal motion of the trapped ion.^[5,6,9] This thermal motion results in a spatial averaging over the electric field in the tight focal spot and thus in

an effective reduction of the amplitude experienced by the ion. The same effect was also observed for neutral atoms in an optical dipole trap^[10,11] and counteracted by polarization gradient cooling.^[12] Here, we propose to overcome both hurdles by trapping a neutral atom in a dipole trap. The optical trap is achieved by using much the same geometry as was used in experiments toward the perfect excitation of an atom in free space.^[13,14] The general layout of such an experiment is depicted in **Figure 1a**.

The influence of residual phase front errors is less pronounced at longer wavelengths. The resonance lines of neutral atoms typically have longer wavelength than atomic ions. Therefore, we explore experimenting with a neutral atom in a parabolic mirror held in place by a dipole trap. As detailed below, there is another advantage associated with an off-resonant optical dipole trap established by focusing with a deep parabolic mirror: The spatial confinement of the atom is small enough to have a negligible effect on the interaction with a tightly focused beam that excites the atom on resonance. This benefit is due to the fact that the intensity in the focus of the mirror has the maximum possible value per input power while the focal volume shrinks to sub-wavelength size along all spatial dimensions. This results in an optical potential of large depth and a large trap stiffness as discussed below.

Optical dipole traps are ubiquitous in many quantum optics laboratories. Whereas for a long time the focus of most experiments using dipole traps has been on trapping neutral atoms,^[15] more lately also the trapping of atomic ions has been pursued.^[16,17] While optical traps were first established for solid state objects,^[18,19] there has also been renewed interest in the optical trapping of such targets for force sensing and quantum optomechanics (see ref. [20] for a recent review). Moreover, also solid-state quantum emitters have been stored and manipulated in optical traps.^[21–27]


Most experiments with optical tweezers use lenses for focusing the trapping light, such as, for example, trapping a single atom for light–matter-interaction experiments in free

1. Introduction

Maximizing the interaction between light and a single atom can be achieved by either placing the atom in a cavity^[1,2] or by providing a light field which overlaps with an in-going dipole wave of light as much as possible.^[3] Here we focus on this latter scenario. Using some approximation of an in-going dipole wave for exciting an atom requires placing this atom at the origin associated with this dipole wave, which in turn requires trapping the atom in one way or another. In the past, there have been efforts toward maximizing the coupling of a single quantum target and light by generating an electric dipole wave focused tightly onto a single trapped atomic ion with a parabolic mirror.^[4–6] One of the remaining obstacles is the full compensation of optical aberrations imprinted by the parabolic mirror which stem from deviations

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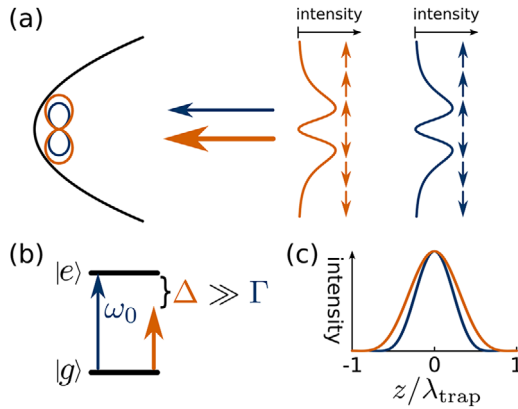


Figure 1. a) The central elements for the efficient coupling of a single atom with light focused tightly by a parabolic mirror. The atom is held in an optical dipole trap (orange) which is generated relying on the same principles used for tailoring the beam for the light–atom–interaction experiment (blue). Both beams incident onto the mirror have a ring-shaped transverse intensity distribution and are radially polarized, such that after reflection off the mirror the radiation pattern is the one of a linear electric dipole wave. b) Energy level diagram. The trap laser is detuned by Δ from the atomic resonance at ω_0 . The spontaneous decay rate of the excited state is Γ . c) Normalized axial intensity distribution of the focused trap beam and the beam exciting the atom on resonance.

space.^[28] There are few exceptions of using mirrors, including the usage of parabolic mirrors for setting up the optical trap. Here, among the trapped species are neutral atoms,^[29] dielectric microspheres,^[30] and nanospheres^[31] as well as colloidal dot-in-rod nanocrystals.^[25,27] A particular advantage of parabolic mirrors is that they are practically achromatic. This makes them especially suitable for quantum optics experiments with atoms and ions, since such experiments typically have to be run with several light sources operating in different spectral regions. Furthermore, using a mirror which covers almost the full solid angle also enables efficient collection of light from a trapped quantum emitter.^[4,27] Therefore, other quantum optics experiments might also benefit from an optical trap based on a deep parabolic mirror.

2. Characteristics of the Optical Trap

We start the discussion with recalling the dependence of the optical trapping potential $U_{\text{dip}}(\mathbf{q})$ on the intensity of the trapping beam $I(\mathbf{q})$ for the common case that this beam oscillates at a detuning Δ from the atom's resonance that is much larger than the spontaneous emission rate Γ of the atom's excited state.^[15]

$$U_{\text{dip}}(\mathbf{q}) = \frac{3\pi c^2}{2\omega_0^3} \cdot \frac{\Gamma}{\Delta} \cdot I(\mathbf{q}) \quad (1)$$

c denotes the speed of light, ω_0 the frequency of the atomic transition under consideration, and \mathbf{q} is the position of the atom. We define $\mathbf{q} = 0$ to coincide with the focal point of the parabolic mirror used to focus the trapping beam. In the absence of optical aberrations the minimum of the trapping potential is then found at $\mathbf{q} = 0$ for red detuned light $\Delta < 0$.

The intensity in the mirror's focus can be written as [32]

$$I(0) = P \cdot \Omega \eta^2 / \lambda^2 \quad (2)$$

where λ is the wavelength of the trapping beam and P its power. The important parameters determining the quality of the focusing are the solid angle Ω covered by the parabolic mirror and the overlap η of the trapping beam's electric field distribution with the radiation pattern of an electric dipole. Ω is defined as the solid angle when weighting with the angular intensity pattern of an electric dipole, that is, $0 \leq \Omega \leq 8\pi/3$ for linear as well as circular dipoles. Using this definition and introducing the fraction Ω_N of the solid angle from which the trapping light is focused, we write $\Omega = 8\pi/3 \cdot \Omega_N$. In order to find the spatially dependent trapping potential we write $I(\mathbf{q}) = I(0) \cdot u(\mathbf{q})$ with a normalized intensity distribution $u(\mathbf{q})$. When focusing from the complete solid angle with a perfect dipole radiation pattern ($\Omega_N = \eta = 1$), one obtains a so-called standing dipole wave for which $u(\mathbf{q})$ can be expressed analytically.^[33] In the presence of imperfections, for example, when η or $\Omega_N < 1$, $u(\mathbf{q})$ has to be determined numerically. As an example, a cross-section through $u(\mathbf{q})$ along the optical axis of a parabolic mirror with the parameters used below is shown in Figure 1c. Finally, we arrive at a simple expression for the potential of the dipole trap

$$U_{\text{dip}}(\mathbf{q}) = \frac{\Gamma}{\omega_0 \Delta} \cdot P \Omega_N \eta^2 \cdot u(\mathbf{q}) \quad (3)$$

This expression is strictly valid only for a two level atom.^[15] However, for the example chosen below this is a good approximation.

We illustrate the capabilities of a parabolic mirror based dipole trap by calculating the trapping potential for a neutral ^{174}Yb atom. Due to its level structure, this atomic species is suitable for the efficient coupling of light to a linear-dipole transition, where the coupling is maximized for a lower state with zero total angular momentum (a similarly suitable species is ^{40}Ca).^[14] The far-off-resonant trap (FORT) is used on the $^1S_0 \leftrightarrow ^1P_1$ transition of the Yb atom ($\lambda_0 = 2\pi c/\omega_0 = 389.8 \text{ nm}$, $\Gamma = 1.92 \times 10^8 \text{ s}^{-1}$) and operates at the wavelength $\lambda_{\text{trap}} = 532 \text{ nm}$ (see. e.g., ref. [34]). The parabolic mirror is chosen to have the same geometry as the one used previously in experiments with ions,^[4,5] where the mirror has a depth of 5.7 times its focal length. The corresponding fraction of the covered solid angle is $\Omega_N = 0.94$. As the overlap of the trapping beam with linear-dipole radiation we set $\eta = 0.98$, which is a realistic value that can be achieved in experiments when using a radially polarized mode.^[35] The corresponding electric field of the focused trap beam is polarized along the optical axis of the mirror. The resulting trapping potential as a function of the trap beam power is shown in Figure 2a. Already at moderate trapping beam powers on the order of 100 mW (cf. blue dot in Figure 2) a potential depth of a few hundred mK can be achieved. This is more than two orders of magnitude larger than typical temperatures of atoms after Doppler cooling. Hence, stable trapping is to be expected.

The spatial spread of the atom is important for experiments requiring strong interaction of the atoms with tightly focused light and needs to be small in comparison to the size of the focal spot.^[9–11] This requirement is particularly stringent when

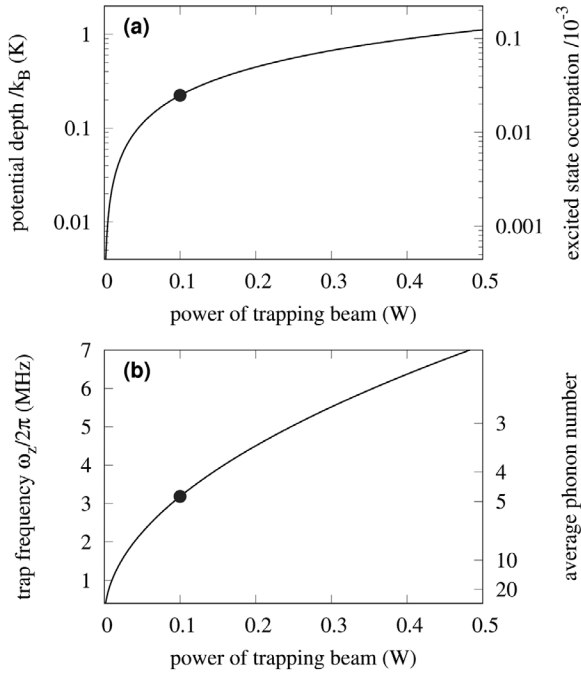


Figure 2. a) Depth of trapping potential (left) and excited state occupation due to the trapping beam (right) as a function of the trapping beam power for a ^{174}Yb atom in a dipole trap operated at a wavelength of 532 nm. The dot marks the example discussed in the text. b) Trap frequency along the axial (z) direction (left) and mean phonon number upon cooling to a temperature of $\hbar\Gamma/2k_B$ (right) for the same configuration. The cooling laser is set to $\Delta = -\Gamma/2$ with $\Gamma = 1.92 \times 10^8 \text{ s}^{-1}$. Other parameters are $\omega_0 = 2\pi c/389.8 \text{ nm}$, $\eta = 0.98$, and $\alpha_N = 0.94$.

focusing a dipole wave from full solid angle, where the full widths at half maximum of the point spread function are 0.4 wavelengths in the lateral direction and about 0.6 wavelengths along the optical axis, respectively. The spatial spread of the atom along direction i is given by

$$\sigma_i = \sigma_{0,i} \cdot \sqrt{1 + \bar{n}_i} \quad (4)$$

with $\sigma_{0,i} = \sqrt{\hbar/2m\omega_i}$ the spread of the atom in the ground state of an harmonic oscillator of mass m and trap frequency ω_i . \bar{n}_i is the corresponding mean phonon number in a thermal state.

In order to obtain ω_i we have to analyze the focal intensity distribution $u(\mathbf{q})$ of the optical trap. We therefore approximate the numerically computed $u(\mathbf{q}_i)$ with the harmonic function $1 - \kappa_i q_i^2/2$ around its maximum. Fitting a line to $\partial u(\mathbf{q}_i)/\partial q_i$ near $q_i = 0$ yields $\kappa_z = 10.6/\lambda_{\text{trap}}^2$ and $\kappa_{x,y} = 33.2/\lambda_{\text{trap}}^2$. Using these curvatures we obtain the trap frequencies according to

$$\omega_i = \sqrt{|U_{\text{dip}}(0)|\kappa_i/m}.$$

Figure 2b shows the trap frequency ω_z along the mirror's optical axis as a function of trapping beam power. For the exemplary power of 100 mW one finds $\omega_z/2\pi = 3.1 \text{ MHz}$. The values for $i = x, y$ are larger by a factor of ≈ 1.8 . These trap frequencies are considerably larger than the ones which have been achieved in an ion trap suitable for the parabolic mirror experiment.^[4,6] The spread of the ^{174}Yb atom in the ground state of motion along the mirror axis is $\sigma_{0,z} = 8 \times 10^{-3} \lambda_0$. However, thanks to the large trap stiffness, ground state cooling is not necessary at all. Assum-

ing standard Doppler cooling with a final temperature of $\hbar\Gamma/2k_B$ results in $\bar{n}_z \approx 5$ and $\sigma_z \approx 0.02\lambda_0$, warranting that the spread of the Yb atom is still two orders of magnitude smaller than λ_0 .

These favorable numbers are due to the fact that the parabolic mirror focuses the light to a tight focal spot with a peak intensity close to the maximum possible one in free space.^[3,32] This raises the question about the impact of recoil heating. The recoil heating rate is given by $1/3 \cdot (2\pi\hbar/\lambda_{\text{trap}})^2/2m \cdot \Gamma_{\text{sc}}$ with the scattering rate for trap light photons $\Gamma_{\text{sc}} = \Gamma \cdot \rho_{ee}$.^[15] The occupation ρ_{ee} of the excited state of the atom is also depicted in Figure 2a. At a trapping power of 100 mW one has $\rho_{ee} = 2.5 \times 10^{-5}$. This results in a heating rate of two phonons per second, which is practically negligible.

While ^{174}Yb was chosen for the example calculations due to its suitability for experiments on efficient coupling of light to a linear-dipole transition, the optical trapping scheme proposed here might also prove to be beneficial for atomic species with a ground state with non-zero total angular momentum. In such a case, the potential depth, and hence also the trap frequencies, will be modified according to the actual atomic energy level structure and the relevant Clebsch–Gordan coefficients.^[15]

3. Experimental Implications

As outlined in the previous section, trapping an atom at the focus of a parabolic mirror in a FORT beam focused from a full solid angle should confine the atom sufficiently for light–matter-interaction experiments. Furthermore, the number of involved beams at different wavelengths should reduce in an experiment with a neutral atom in comparison to an ion, where one uses photo-ionization to produce the ion.

However, there are several technical challenges, of which the preparation of precooled atoms is the most difficult one. The data in Figure 2a implies that at trapping beam powers of a few Watts the potential depth is raised to several Kelvin. This might already be sufficient to capture atoms decelerated by a suitably designed Zeeman slower.^[36] Alternatively, precooled with an optical molasses^[37,38] or by a continuously chirped cooling beam^[39] appears to be feasible. Such measures will result in a more complex setup, in which some of the additional beams have to be coupled into the parabolic mirror via its front aperture. For comparison, in the experiments with a single ion in a Paul trap it suffices to supply cooling beams via a small aperture slightly off the mirrors axis.^[4] No matter how the optical trap is loaded, the collisional-blockade mechanism^[28,40,41] is expected to warrant that no more than one atom will be held in the extremely narrow optical trap.

Another complication arises from the fact that in contrast to the ion experiment the positioning of the atom is also achieved optically. Naturally, any beam focused by a strongly curved surface such as a parabola is phase shifted upon reflection off the surface. This phase shift is position dependent due to the variation of the angle of incidence, which is increasing for increasing distance to the optical axis. Thus, even for a mirror free of shape distortions a small but finite amount of defocus is imprinted onto any incident beam. Due to the dispersion of the mirror material the FORT beam and the beam used for exciting the atom close to resonance will be focused to slightly different axial positions.

Although the relative shift of these two foci can be calculated to be on the order of $\lambda/50$ for a mirror made of aluminum, it might be necessary to overlap both foci by imprinting a suitable conjugate defocus onto one of the incident beams in order to maximize the coupling of the atom and the excitation beam.

4. Concluding Remarks

Based on straightforward calculations we found that focusing light with a deep parabolic mirror can create an optical dipole trap in which a single neutral atom is held in an unusually deep and tight potential well. As emphasized above, this setup is particularly suitable for experiments in which a second beam is focused tightly onto the atom by the same parabolic mirror. At first sight, such an optical trap might appear to be useful only for this demanding experiment. But it was already emphasized some time ago that arrays of micro-mirrors, in which neutral atoms are trapped optically, might be useful for applications in quantum information processing.^[42] Such an array of micro-mirrors could be produced by two-photon lithography.^[43] The absolute size of the mirrors will have to be determined by a compromise between maximizing the solid angle covered by a single paraboloid, practical aspects such as, for example, the accessibility of auxiliary laser beams to the mirror, and avoiding a modification of the spontaneous emission rate of the atom occurring at too small focal lengths.^[44] With respect to expectable difficulties in aligning an array of trapping beams onto an array of mirrors, the increased potential depth found when using a deep parabolic mirror could deliver the necessary reserves for tolerating a certain amount of misalignment, eventually enabling up-scaling in applications.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

light-matter interaction, optical trapping, parabolic mirror

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