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Title	Atom microtraps based on near-field Fresnel diffraction
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Publication date	2008-07-01
Original Citation	BANDI, T. N., MINOGIN, V. G. & NIC CHORMAIC, S. 2008. Atom microtraps based on near-field Fresnel diffraction. Physical Review A, 78(1), 013410.
Type of publication	Article (peer-reviewed)
Link to publisher's version	http://link.aps.org/doi/10.1103/PhysRevA.78.013410 - 10.1103/PhysRevA.78.013410
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Download date	2026-11-05 23:20:05
Item downloaded from	https://hdl.handle.net/10468/362



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http://link.aps.org/doi/10.1103/PhysRevA.78.013410

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Atom microtraps based on near-field Fresnel diffraction

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(Dated: May 26, 2008)

Abstract

We propose and present quantitative analysis of neutral atom microtraps based on optical near-fields produced by the diffraction of a laser wave on small apertures in a thin screen. We show that the near-field atom microtraps are capable of storing atoms in micron-sized regions, with estimated trap lifetimes of about 1 second, when using a moderate laser intensity of about 10 W/cm^2. The depth of the proposed Fresnel atom microtraps is about 0.1 mK. An array of such atom microtraps could have applications in site-selective manipulation of cold atoms.

PACS numbers: PACS: 37.10.Gh, 42.50.-p, 42.25.Fx

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I. INTRODUCTION

In recent years there has been a growing number of experimental and theoretical studies on the development of, and applications for, neutral atom traps [? ? ? ? ? ?]. A new and poorly studied approach to the development of miniature atom traps stems from the optical near-fields formed by laser diffraction on small apertures in thin screens. Such an approach could lead to the fabrication of an array of atom microtraps and, accordingly, the production of a large number of trapped atomic microensembles from a single initial atomic cloud or beam. Earlier work [?] has shown that an array of atom dipole traps can be produced by focusing a laser beam on an array of spherical microlenses. The work presented here relies on a more recent proposal [?], whereby microlenses, formed in thin screens, can be used to focus atomic beams. We show that such a system can be modified to produce a microtrap array, using a moderate incident laser intensity of about 10 W/cm^2.

Similar to other approaches employing laser fields, the operation of neutral atom, near-field microtraps relies on dipole potentials and their corresponding dipole gradient forces. However, in other approaches the gradient force arises from the non-uniform field distribution over the laser beam cross-section or over the wavelength of the laser light, whereas for near-field microtraps the gradient force stems from the optical field non-uniformity over the *aperture* diameter. Consequently, atom microtraps can store atomic microclouds with characteristic dimensions equivalent to or less than the field wavelength. Such microclouds could be used for site-selective manipulation of atoms in the field of quantum information technologies [? ? ?].

In this paper, we propose and present a quantitative analysis of near-field Fresnel atom microtraps with a characteristic aperture size about or exceeding the optical wavelength. Such traps rely on the near-field diffraction pattern, characterized by a Fresnel number, $N_F \geq 1$. We analyze the field distribution in the vicinity of a small, circular aperture in a thin screen, and calculate the dipole potential of the atom in the diffracted near-field. Our analysis of the Fresnel microtraps shows that, at a moderate intensity of the light field of about 10 W/cm^2, the traps are able to store atoms with a kinetic energy of about 100 μK during time intervals of around one second.

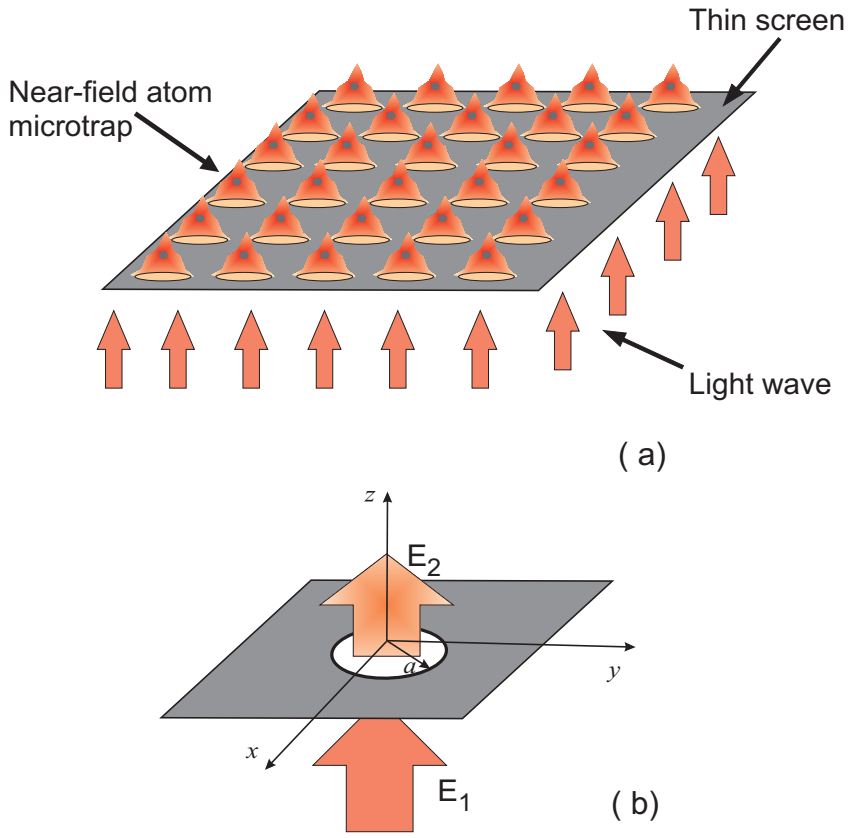


FIG. 1: (a) An array of atom microtraps produced by diffracted optical near-fields; (b) Schematic of a single microtrap formed by a circular aperture of radius a. E_1 represents the incoming light field and E_2 the diffracted near-field.

II. TRAPPING POTENTIAL

An array of Fresnel atom microtraps is schematically shown in Fig. 1. The traps can be analyzed by considering the diffraction of a travelling light wave of arbitrary polarization on a circular aperture

$$\mathbf{E}_1 = \mathbf{e}E_0 \cos(kz - \omega t), \tag{1}$$

where $\mathbf{e}$ is a unit polarization vector, E_0 is the amplitude and $k = \omega/c$ is the wave vector. When the size of the aperture exceeds or is equivalent to the wavelength of the optical field, the electric field behind the aperture can be represented in the scalar approximation as

$$\mathbf{E}_2 = \mathbf{e}E = \mathbf{e}\mathrm{Re}(\mathcal{E}\mathrm{e}^{-i\omega t}), \tag{2}$$

where $\mathcal{E} = \mathcal{E}(\mathbf{r})$ is the complex field amplitude. The diffracted field can be evaluated by applying the Rayleigh-Sommerfeld diffraction formula [**?** **?**]

$$\mathcal{E}(x,y,z) = \frac{E_0}{2\pi}\int\int \frac{\exp(ikr)}{r}\left(\frac{z}{r}\right)\left(\frac{1}{r}-ik\right)dx'dy', \tag{3}$$

where the distance between the point (x,y,z) in the observation plane and the point $(x',y',0)$ in the aperture plane is $r = [z^2+(x-x')^2+(y-y')^2]^{1/2}$, and the integral (**??**) is considered to be taken over the aperture region.

The evaluation of the Rayleigh-Sommerfeld integral can be simplified by taking into account the axial symmetry of the diffracted field. By introducing cylindrical coordinates ρ', ϕ' in the aperture plane and cylindrical coordinates ρ, ϕ in the observation plane one can rewrite the diffracted electric field as

$$\mathcal{E}(\rho,z) = \frac{E_0}{2\pi}\int_0^a\int_0^{2\pi} \frac{\exp(ikr)}{r}\left(\frac{z}{r}\right)\left(\frac{1}{r}-ik\right)d\varphi\rho' d\rho', \tag{4}$$

where now $r = \left[z^2+\rho^2+\rho'^2-2\rho\rho'\cos\varphi\right]^{1/2}$, $\varphi = \phi'-\phi$ is the relative angular coordinate, and a is the aperture radius.

For a red-detuned light field, the potential of a single microtrap is defined by the value of the light shift according to the usual equation [**?**],

$$U = -\hbar\frac{\Omega^2}{|\delta|}, \tag{5}$$

where $\Omega = dE/2\hbar$ is the Rabi frequency, d is the dipole matrix element, and $\delta = \omega-\omega_0$ is the detuning of the light field with respect to the atomic transition frequency, ω_0. Accordingly, for the diffracted field represented by Eqs. (**??**)-(**??**), the potential of an atom in a single microtrap can be written as

$$U = -U_0\frac{|\mathcal{E}|^2}{E_0^2}, \tag{6}$$

where

$$U_0 = \frac{3}{8}\frac{\gamma}{|\delta|}\frac{E_0^2}{k^3} \tag{7}$$

is a characteristic value of the potential and γ is half the spontaneous decay rate. In what follows, we consider the case when the radius of the aperture, a, only slightly exceeds the optical wavelength, λ. In this case the Fresnel number, N_F, is expected to be approximately equal to one, i.e.

$$N_F = \frac{a^2}{\lambda z_m} \approx 1, \tag{8}$$

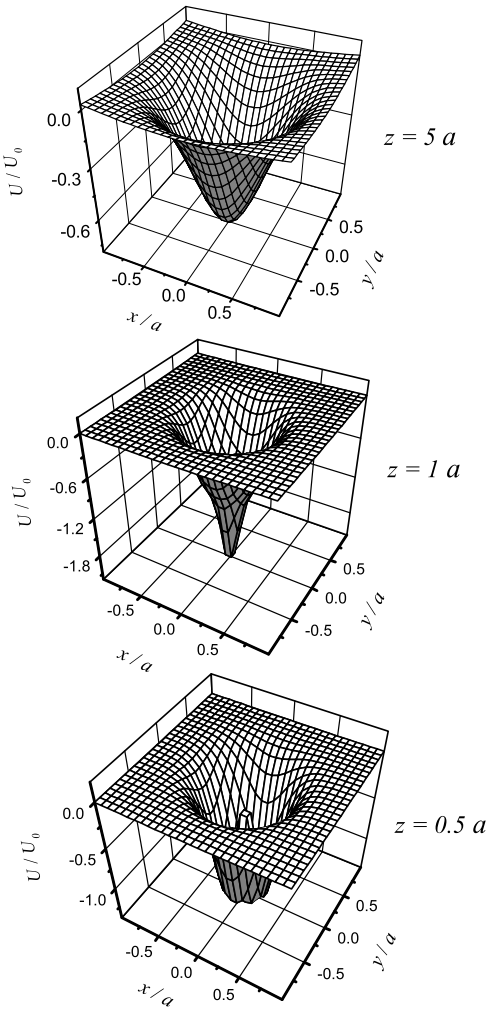


FIG. 2: Atom potential in a Fresnel atom microtrap as a function of transverse coordinates for radius $a = 1.5\lambda$ ($ka = 9.4$), at distances above the aperture $z = 0.5a, 1a, 5a$.

where z_m is a characteristic vertical distance from the aperture to the maximum of the electric field intensity. Accordingly, the electric field intensity is expected to have a single diffraction maximum, and the atom potential will also have a single minimum. An example of the single-minimum atom potential is shown in Fig. **??** for different values of the vertical coordinate, z.

Alongside the integral representation of the diffracted field, and the corresponding potential of the atom, one can also find an analytical representation of the atom potential near the symmetry axis of the microtrap. This can be done by decomposing the integrand in Eq.

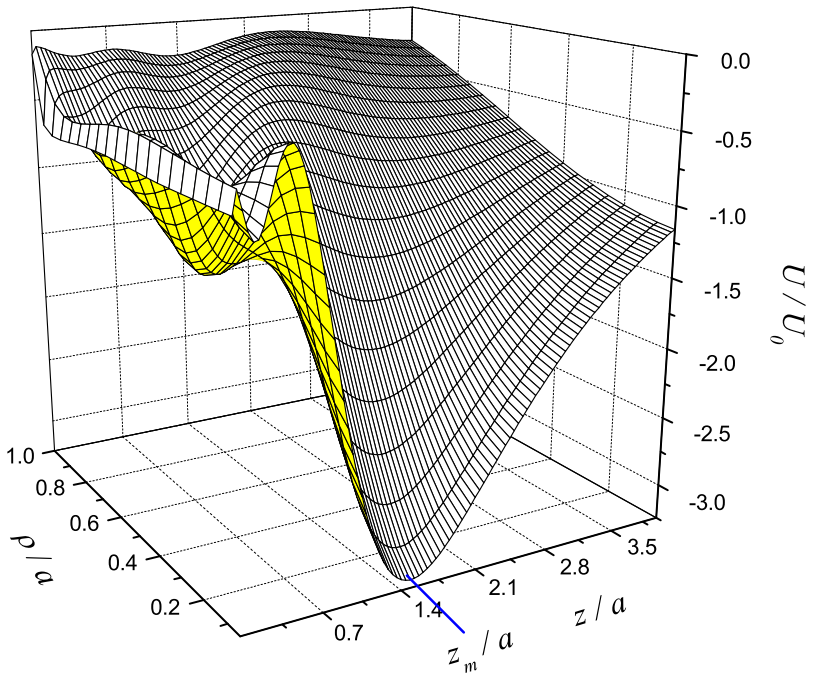


FIG. 3: Atom potential of the Fresnel atom microtrap as a function of the coordinates, z and ρ, for $a = 1.5\lambda$.

(**??**) into a series in small radial displacements, $\rho \ll a$ [**?** **?**]. Considering the second order in ρ, one can represent the near-axis atom potential as parabolic in the transverse direction,

$$U(\rho,z) = -U_0\left\{1+\frac{z^2}{R_a^2}-\frac{2z}{R_a}\cos k(R_a-z) \right. \\ \left. -\frac{k^2a^2z\rho^2}{2R_a^3}\left[\left(1-\frac{3}{k^2R_a^2}\right)\left(\frac{z}{R_a}-\cos k(R_a-z)\right)+\frac{3}{kR_a}\sin k(R_a-z)\right]\right\}, \tag{9}$$

where $R_a = \sqrt{a^2+z^2}$. The potential represented in (**??**), when considered as a function of the vertical coordinate, z, has a minimum at $z = z_m$, defined by the transcendental equation

$$\cos\left[k(R_a-z)-\chi\right] = \frac{a^2z}{\left(a^2+z^2\right)^{3/2}}\frac{1}{\left(A^2+B^2\right)^{1/2}}, \tag{10}$$

where $\tan\chi = B/A$, with $A = a^2/(a^2+z^2)$ and $B = kz\,(1-z/R_a)$.

The dependence of the potential $U = U(\rho,z)$ on the coordinates z and ρ is shown in Fig. **??** for the same aperture size as used in Fig. **??**. The near-axis potential represented by Fig. **??** has a minimum at $z_m = 1.47a = 2.2\lambda$. In accordance with our expectations, the Fresnel number, $N_F \simeq 1$ at this value of z_m, and the atom potential has a well defined minimum near the z-axis.

III. PARAMETERS OF NEAR-FIELD MICROTRAPS

We evaluate parameters of the Fresnel atom microtraps for (i) ^{85}Rb atoms, which interact with a far-red detuned light field at the dipole transition $5^2S_{1/2}(F=3) \to 5^2P_{3/2}(F=4)$ with wavelength $\lambda = 780$ nm, and (ii) ^{133}Cs atoms interacting with the light field at dipole transition $6^2S_{1/2}(F=4) \to 6^2P_{3/2}(F=5)$ with wavelength $\lambda = 852$ nm. For the dipole transition in ^{85}Rb, the natural linewidth is $2\gamma = 2\pi \times 5.98$ MHz and the saturation intensity is $I_S = 1.6$ mW/cm^2. For ^{133}Cs the corresponding values are $2\gamma = 2\pi \times 5.18$ MHz and $I_S = 1.1$ mW/cm^2 [**?**].

We choose the radius of the microtraps to be $a = 1.5\lambda$, with $a = 1.2$ μm for ^{85}Rb atoms and $a = 1.3$ μm for ^{133}Cs atoms. For these two cases the minimum of the trap potential is located at distances above the aperture, $z_m = 1.76$ μm and 1.91 μm, respectively. Choosing a laser intensity, $I = 10$ W/cm^2, and a large negative detuning, $\delta = -10^4\gamma$, we can evaluate the depth of the potential, U_d, as 0.13 mK for Rb and 0.17 mK for Cs, respectively. The energy levels near the bottom of the trapping potential,

$$E = h\nu_\rho \left(n_\rho + \tfrac{1}{2}\right) + h\nu_z \left(n_z + \tfrac{1}{2}\right), \tag{11}$$

can be evaluated by representing the potential (9) near the minimum as a harmonic potential,

$$U(\rho, z) = \frac{1}{2}M\omega_\rho^2\rho^2 + \frac{1}{2}M\omega_z^2 \left(z - z_m\right)^2, \tag{12}$$

where M is the atom mass. This procedure shows that at chosen parameters of the microtraps, typical oscillation frequencies are of the order of 10 kHz. Specific values of the transverse frequencies, $\nu_\rho = \omega_\rho/2\pi$, and longitudinal frequencies, $\nu_z = \omega_z/2\pi$, for ^{85}Rb and ^{133}Cs atoms are shown in Table I, together with values of the characteristic oscillation amplitudes in the ground state, $\overline{\rho} = \sqrt{\hbar/M\omega_\rho}$, and $\overline{z} = \sqrt{\hbar/M\omega_z}$. Note that the number of quantized energy levels in the microtrap potential is estimated to be about 50, with a typical energy separation of about $\Delta E = 1$ μK.

It is worth noting that the optical potential of a Fresnel atom microtrap could generally be distorted by the Casimir-Polder potential due to the presence of the screen [**?**]. Since the considered optical potential is localized at distances z from the screen, where $z > \lambda/2\pi$, the contribution of the Casimir-Polder potential for the case of a perfect metal screen and

in the absence of any opening can be evaluated as [**?** **?** **?**]

$$U_{\rm CP}(z) = -\frac{3\hbar\gamma}{8\pi}\left(\frac{\lambda}{2\pi z}\right)^4 . \tag{13}$$

We estimate the value of the potential $U_{\rm CP}(z)$ at two important points: (i) at the position of the potential well minimum, $z_m = 2.2\lambda$, and (ii) at the position of a local maximum of the optical potential, $z_M = 0.7\lambda$. Near the bottom of the optical potential the Casimir-Polder potential is about $4 \cdot 10^{-4}$ μK for both ^{85}Rb and ^{133}Cs atoms. At the position of the local maximum the Casimir-Polder potential is about $5 \cdot 10^{-2}$ μK. Since the depth of the optical potential well is estimated to be about 100 μK the above estimates show that for the Fresnel atom microtraps considered here the Casimir-Polder potential can be neglected.

Similar to conventional far-off-resonance dipole traps, atoms can be lost from the Fresnel atom microtrap due to diffusive heating of the atoms and collisions with the background gas [**?**]. Assuming the rest gas pressure is chosen to be sufficiently low, we can evaluate the lifetime of the atoms in the Fresnel atom microtrap by considering the diffusion broadening of atomic velocities due to photon recoil fluctuations. For this process, the velocity diffusion coefficient has a standard evaluation as $D = \gamma v_r^2 (I/I_S)(\gamma/\delta)^2$, where $v_r = \hbar k/M$ is the recoil velocity, I is the light field intensity, and I_S is the saturation intensity [**?**]. Assuming that the kinetic energy of an atom escaping from the trap is approximately equal to the potential well depth, $Mv^2/2 = U_d$, and the atomic velocity is defined by the diffusion broadening, $v^2 \approx D\tau$, we can evaluate the trap lifetime, τ, as

$$\tau = \gamma^{-1}\frac{2U_d}{Mv_r^2}\left(\frac{I_S}{I}\right)\left(\frac{\delta}{\gamma}\right)^2 . \tag{14}$$

For the above chosen parameters, a trap lifetime of about 1 s can be achieved, as given in Table I. The lifetime can be increased by increasing the input laser power, which, in turn, increases the trap depth.

IV. CONCLUSION

We have proposed a system of neutral atom microtraps based on a series of circular apertures in a thin screen. Laser light incident on the screen produces an array of potential minima for atoms in the near-field. Our analysis shows that these near-field atom microtraps can store cold atoms for times up to seconds. The potential well depth of the microtraps is

TABLE I: Parameters of a near-field Fresnel diffraction trap for ^{85}Rb and ^{133}Cs atoms with an input laser power of 10 W/cm^2 and detuning $\delta = -10^4\gamma$ for an aperture radius $a = 1.5\lambda$.

Atom	U_d [mK]	ν_ρ [kHz]	ν_z [kHz]	$\bar{\rho}$ [nm]	$\bar{z}$ [nm]	τ [s]
^{85}Rb	0.13	34	19	60	80	0.6
^{133}Cs	0.17	29	14	51	73	1

mainly determined by the intensity of the incident laser field and the detuning. By varying these two parameters one can achieve robust control over the trap parameters. A numerical analysis for ^{85}Rb and ^{133}Cs atoms shows that a trap depth of 0.1 mK can be achieved, with storage times up to a second at an incident laser intensity of 10 W/cm^2. With such trap lifetimes one can perform atom optics experiments by blending micro-fabrication technology with cold atoms [**?**]. An important point to note is that each individual microtrap uses only about 0.5 μW in the above considered case, where the aperture radius $a = 1.5\lambda$.

We also note that, in the present consideration, we have limited our analysis to the case of apertures that are well separated in the screen. For a periodic array of densely spaced microtraps, one may expect even further reduction to the required incoming laser power due to an enhancement of the diffracted field during light transmission through the micro-aperture array [**? ?**].

Finally, we note that the above-considered microtraps possess the same basic properties as for far-off-resonance dipole traps. Hence, the proposed traps are free of some perturbations that are significant in other types of atom traps. In particular, such processes as spin-flips near surfaces [**?**], which redistribute trapped atoms over magnetic sublevels, cannot influence the lifetime of atoms in the proposed Fresnel atom microtraps. Another advantage of near-field microtraps is that they are capable of storing atoms at relatively large distances from the material screen which produces the diffracted light field. Accordingly, the internal and translational states of the atoms stored in the near-field microtraps are primarily defined by the dipole interaction with a far-detuned light field only. In particular, we have shown by numerical evaluation, that the influence of the Casimir-Polder potential on the atomic states in a Fresnel atom microtrap can be neglected. The van der Waals energy shifts [**?**] can also be shown to have a small influence on the atomic states trapped in a Fresnel atom microtrap.

It can also be noted that the presence of the opening in the screen can be considered as an advantage for loading the atoms into near-field microtraps, as such microtraps ease the application of standard loading techniques widely used for other types of dipole traps [**?** **?**]. An alternative loading scheme using optical tweezers may be feasible [**?**], due to the dimensions being considered within the proposed trap geometry.

Acknowledgments

This work was funded by Science Foundation Ireland under grants 02/IN1/128 and 06/W.1/I866. Part of the work was supported by the Russian Foundation for Basic Research (project no. 07-02-00748).

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