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# Single-beam optical bottle for cold atoms using a conical lens

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**Abstract.** We report a new method to generate an optical dipole potential with a null intensity region surrounded in all directions by light walls. This is achieved with a simple scheme based on a conical lens. Applications to optical trapping of neutral atoms are discussed.

**PACS.** 32.80.Pj Optical cooling of atoms; trapping – 42.50.Vk Mechanical effects of light on atoms, molecules, electrons, and ions

For neutral atoms, it has become experimental routine to produce ensembles with temperatures in the micro-Kelvin region or even lower. Cold atoms can be stored even in shallow traps. There are basically two different kinds of conservative traps: magnetic traps and optical dipole traps. Magnetic traps are based on the interaction between the atomic magnetic dipole moment and an inhomogeneous magnetic field [1]. Because of Maxwell's equations a static magnetic field cannot have local maxima and only atoms in a weak field seeking state can be confined. The trapping mechanism which relies on the internal atomic state prevents, for example, from producing ensembles of unpolarized atoms. Optical dipole traps [2] rely on the force experienced by the atom in a far-detuned radiation field. The trapping potential originates from the light shift induced on atomic energy levels by the external field. The potential is attractive towards high intensity regions for light frequencies lower than the unperturbed frequency transition (red-detuned optical traps) and repulsive in the opposite case (blue-detuned optical traps). The use of far detuned laser beams in optical traps has two advantages: first of all, heating processes such as spontaneous scattering of photons, inelastic collisions induced by light or radiation trapping are strongly reduced and atoms can move in a nearly conservative potential; second, with detunings greatly exceeding the hyperfine splitting of the ground state, a trapping potential independent of the particular electronic sub-level can be obtained. In red-detuned optical traps atoms are confined where the light intensity is maximum. This limits the trap lifetime and moreover, as the atoms spend most of their time in a strong radiation field, energy levels are deeply perturbed by the ac Stark effect. Using a radiation field detuned to the high frequency side of an atomic transition it is possible to confine the atoms in low intensity regions. Long trap coherence times and very little perturbations on hyperfine atomic levels can be achieved in blue-detuned optical dipole traps. The main problem of blue-detuned traps is the realization of a laser beam geometry where a dark region is surrounded by light. This usually involves the use of several laser beams.

Different methods have been developed to produce the required repulsive optical walls: light sheets can be used to achieve nearly flat optical walls [3]; hollow laser beam geometries are obtained by refractive [4,5] or holographic [6] methods for confinement in two dimensions; trapping in evanescent waves is realized by total reflection on the horizontal surface of a dielectric medium [7]. Recently some methods have been proposed for 3D blue-detuned optical trapping based on a single laser beam. In [8], a gravito optical trap is used to confine an ensemble of cesium atoms; a conical blue detuned laser beam together with gravity produces the required 3D trapping potential. The confining field in [9] is obtained by passing a focused Gaussian beam through a holographic phase plate of appropriate size; the center of the beam is shifted by a phase angle of $\pi$ and in the focus of such a beam a destructive interference leads to a vanishing light intensity. A computer-generated hologram is used in [10] to form an optical beam with a localized intensity null at its focus; the beam is a superposition of two Laguerre-Gauss modes that are phased so that they interfere destructively to give a beam focus that is surrounded in each direction by regions of high intensity. In [11], a tightly focused and rapidly rotating laser beam is used to trap rubidium atoms in a quasistatic time-averaged potential. In [12], the blue-detuned dipole trap is created by two counter-propagating beams of equal central

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intensity, but different diameters. Along the axis of such a standing wave configuration, completely destructive interference would lead to minima of the dipole potential with zero intensity; in the radial direction the trap would be closed because of the incomplete destructive interference at off-axis positions.

In this paper, we show how a single-beam blue-detuned optical trap can be obtained by using an axicon lens in combination with two spherical lenses. The experimental set-up is very simple and offers a versatile method to change the trap geometry. Moreover, as only refractive optics are used, the trapping potential only slightly depends on the wavelength of the light field and all the input power can be used to produce the confining beam.

The axicon is an excellent tool for the generation of hollow laser beam geometries; it is an optical element with a shape given by any figure of revolution that, by reflection or refraction or both, produces a line focus rather than a point focus from an incident collimated light beam along the symmetry axis of the system [13]. In our work the axicon is a conical lens. When a collimated light beam is incident on the refractive axicon, a cone of light is produced; for a small base angle $\alpha$ the divergence of the conical intensity distribution is $\theta = 2\alpha(n-1)$, where $n$ is the refractive index of the axicon. A converging lens placed just before the conical lens can be used to focus the refracted rays on its focal plane. Here with a CCD camera it is possible to observe a ring-shaped intensity distribution whose radius $R$ depends on the distance $d$ between lens and axicon [14],

$$R = \alpha(n-1)(f-d), \tag{1}$$

where $f$ is the lens focal length. This configuration allows to obtain bright rings whose diameter can be varied from few tens of microns to several millimeters by simply changing $d$. The radial profile of the intensity distribution is well approximated by a Gaussian centred around $R$. Its full $1/\mathrm{e}^2$ width is $3.3\lambda f/\pi w$, where $w$ is the typical waist of the input Gaussian laser beam; this value is comparable with the limit imposed by diffraction on the focusing of a Gaussian beam by a simple lens. The ring radius increases with the distance from the focal plane, showing the conical propagation of the hollow beam. When a far blue-detuned laser beam is used, the lens-axicon system provides a good tool to achieve slightly diverging tubes of light for a two-dimensional confinement (2D trap) [4].

We obtained a three dimensional intensity distribution with a well localized dark core surrounded in all directions by light walls. A single laser beam provides the boundary bright barriers of the optical bottle field. The experimental set-up is shown in Figure 1. A collimated laser beam passes through a converging lens and then enters the axicon. If the distance $d$ between the first lens and the axicon is greater than the lens focal length $f$, the optical rays produce a "virtual" ring shaped intensity distribution in the back focal plane of the first lens. This radiation field is imaged by the second lens and in the plane of image it is possible to observe a dark region surrounded by light. If $G$ is the magnification produced by the second lens, the ring-shaped intensity distribution in the plane of image has a radius

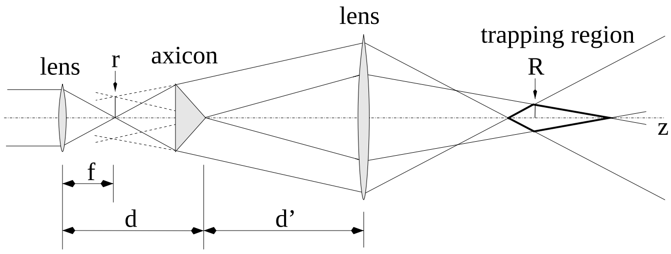


**Fig. 1.** Schematic of the experimental arrangement for the generation of a single-beam optical bottle intensity distribution. The first lens produces a "virtual" ring of radius $r$. The second lens images this ring and generates a dark region of radius $R$. In this figure $f$ is the first lens focal length, $d$ is the distance between the first lens and the axicon and $d'$ is the distance between the axicon and the second lens.

$$R = G\alpha(n-1)(d-f). \tag{2}$$

The generated optical potential is cylindrically symmetric and bounded in all directions.

Our axicon is a BK7 conical lens with refractive index $n = 1.51$ and base angle $\alpha \simeq 100$ mrad. In the experimental set-up the radiation field is produced by a diode laser ($\lambda = 780$ nm). The output beam is symmetrized by an anamorphic prism pair and successively expanded to a diameter of 15 mm. In order to investigate the shape of the hollow beam a CCD camera is moved along the optical axis ($z$-axis) and a series of beam profiles is recorded as a function of the displacement along $z$. The experimental data form a three-dimensional grid which describes the intensity distribution of the radiation field in the free space. In Figure 2 the beam profile in grey levels is reported. In this configuration the first lens has a diameter of 2.5 cm and a focal length $f = 12.5$ cm; the second one has a diameter of 5.0 cm and a focal length $f' = 10.0$ cm. The distance between the first lens and the axicon is $d = 14$ cm, while the distance between the axicon and the second lens is $d' = 93$ cm. In the plane of image we measure a ring radius of 43 $\mu$m. It is in qualitative agreement with the theoretical prediction of 90 $\mu$m given by equation (2); the discrepancy is justified by the indetermination affecting the measurement of the distance $d$. Figure 2a represents the intensity distribution of the hollow beam in the plane of image of the second lens; Figure 2b is the intensity profile in a plane containing the $z$-axis. The optical bottle appears around the focal plane of the second lens. Inspection of the intensity distribution around the dark core shows that there are no holes generated by interference effects and that the optical bottle beam is complete. However, a closer analysis shows secondary minima around the central dark region. In order to estimate the dimensions of the dark region it is useful to look at the contour plot of Figure 3, where isolines of constant light intensity are shown. The core has a diameter of 50 $\mu$m and an axial length of 1.2 mm; this corresponds to an aspect ratio of 24. The light intensity is weaker on the end region far

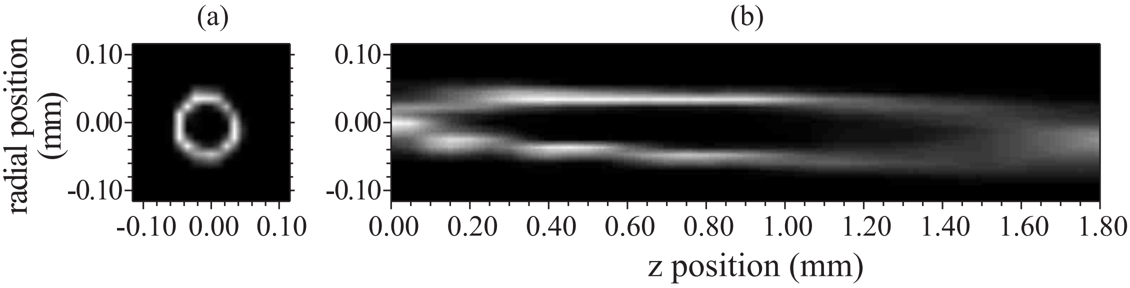


**Fig. 2.** The optical bottle beam. With the CCD camera perpendicular to the optical axis of the system a series of beam profiles is recorded as a function of the displacement along $z$. The experimental data form a three dimensional grid which describes the intensity distribution of the radiation field in the free space. (a) Intensity profile of the optical trap in the plane of image of the second lens reported in grey levels. (b) Section of the beam profile in a plane containing the optical axis.

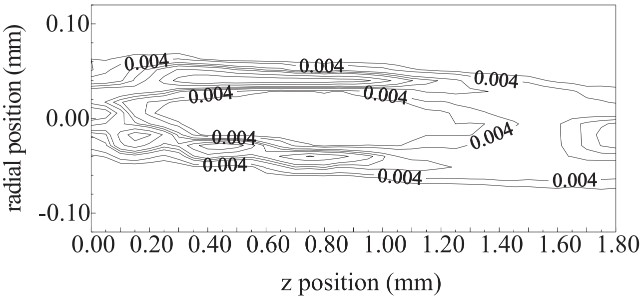


**Fig. 3.** Contour plot of the optical potential obtained in the following conditions: $f = 12.5$ cm, $f' = 10.0$ cm, $d = 14$ cm, $d' = 93$ cm. Isolines of constant light intensity in W/m$^2$ are drawn; the separation between isolines is 0.002 W/m$^2$ for a total incident power on the CCD detector of 0.2 nW. The aspect ratio calculated following the marked isoline is 24.

from the second lens. Here it is 25% of the peak value in the plane of image. Axicon imperfections or lenses aberrations can give rise to a finite intensity in the center of the bottle. However, our data show no scattered light in the central region above the CCD camera noise level. We can estimate it to be less than 1% compared to the peak intensity in the plane of image.

It is worth comparing our scheme to previously described methods for the generation of a 3D blue-detuned optical trap for cold atoms. In the gravito-optical trap, atoms are confined in the vertical direction by means of gravity. This prevents from compressing the cloud of trapped atoms. Using holographic methods the transfer efficiency is limited and only a fraction (around 50%) of the input light is converted into the trapping field; with these techniques it is also very difficult to change in situ the geometry of the trap without changing the generating hologram. The rotating-beam trap represents indeed a versatile method to generate a 3D optical potential. However, both the laser power coupled in the trapping region and the possibility to change the size of the dipole potential can be limited by the typical operating range of the acousto-optic modulators.

We are planning to use this field configuration for optical confinement of rubidium atoms cooled down to Bose-Einstein condensation, first by evaporatively cooling the atoms in a magnetic cloverleaf trap and then by transferring them into the optical potential. With this technique atomic temperatures can be reduced well below 1 $\mu$K so that only some milliwatts of laser power are needed for the optical confinement. If spontaneous emission of photons from the light field is the only heating mechanism, it is possible to give a simple estimate of the trap lifetime. We assume a separable power law potential with a constant offset $U_0$ in the form

$$U(x,y,z) = U_0 + a_1|x|^{n_1} + a_2|y|^{n_2} + a_3|z|^{n_3}. \qquad (3)$$

The heating rate is described by [2]

$$\dot{T} = \frac{2/3}{1+k} T_{\mathrm{rec}} \overline{\Gamma}_{\mathrm{sc}}, \qquad (4)$$

where $T_{\mathrm{rec}} = \hbar^2 k_{\mathrm{L}}^2/(k_{\mathrm{B}} m)$ is the recoil temperature, $k_{\mathrm{B}}$ is the Boltzmann constant, $k_{\mathrm{L}}$ is the wave vector of the laser field and $k = 2(1/n_1 + 1/n_2 + 1/n_3)/3$ is the ratio between potential and kinetic energy given by the virial theorem. $n_1$, $n_2$ and $n_3$ are coefficients obtained by fitting the measured optical potential. In the configuration of Figure 3, $n_1 = n_2 = 7$ and $n_3 = 6$. The light scattered in the trapping region is taken into account by $U_0$. In our case $U_0$ is assumed to be 1% of the peak value in the plane of image which is a conservative estimate based on our data. The mean scattering rate of photons $\overline{\Gamma}_{\mathrm{sc}}$ can then be expressed as

$$\overline{\Gamma}_{\mathrm{sc}} = \frac{\Gamma}{\hbar\Delta}\left(U_0 + \frac{3k}{2} k_{\mathrm{B}} T\right), \qquad (5)$$

where $\Gamma$ is the atomic decay rate and $\Delta$ is the frequency detuning from resonance. With a total laser power of 50 mW and a blue detuning from the $D_2$ line of 20 nm the trap depth is 8 $\mu$K. If the atomic sample has an initial temperature of 300 nK, the estimated trap lifetime is 280 s. The achievement of long lifetimes will impose strong requirements on the laser intensity noise and the beam pointing fluctuations [15].

Using the experimental set-up of Figure 1, it is very easy to vary the geometry of the optical confining potential. By changing the distance $d$ between the axicon and the first lens and/or the magnification $G$, the radius of

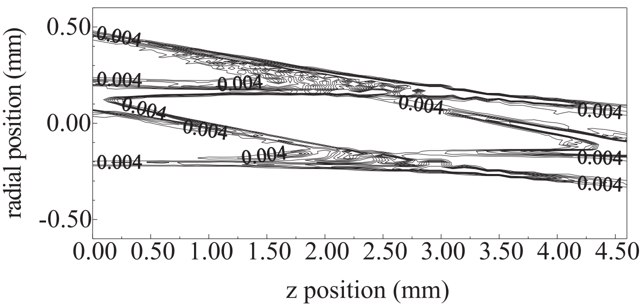


**Fig. 4.** Contour plot of the optical potential obtained in the following conditions: $f = 12.5$ cm, $f' = 15.0$ cm, $d = 15$ cm, $d' = 106$ cm. Isolines of constant light intensity in W/m$^2$ are drawn; the separation between isolines is 0.002 W/m$^2$ for a total incident power on the CCD detector of 1.5 nW. The aspect ratio calculated following the marked isoline is 14.

the bright ring in the plane of image of the second lens and the aspect ratio of the whole trapping potential can be modified. The ring diameter of the dark region can go from several millimeters to tens of microns so that this beam can be used to confine macroscopic particles or atomic samples of very different size. As an example of a more symmetric and larger trap, in Figure 4 we show the contour plot of a hollow intensity distribution with a diameter of 280 $\mu$m and an aspect ratio of 14. In this case, the first lens has a diameter of 2.5 cm and a focal length $f = 12.5$ cm; the second one has a diameter of 3.8 cm and a focal length $f' = 15.0$ cm. The distance between the first lens and the axicon is $d = 15$ cm, while the distance between the axicon and the second lens is $d' = 106$ cm. In this case, $n_1 = n_2 = 12$ and $n_3 = 9$. This configuration could be used, for example, to confine atoms loaded in a compressed magneto-optical trap. If the laser beam has a power of 1 W and a blue-detuning from resonance of 1 nm, the depth of the optical potential is 70 $\mu$K. Assuming an initial temperature of 20 $\mu$K for the atomic sample, the estimated trap lifetime is 10 s.

In conclusion, we found a simple experimental set-up to obtain a single laser beam with a well localized intensity null surrounded in all directions by regions of high intensity. It is composed by an axicon lens and two spherical lenses. With this configuration it is very easy to change the shape of the laser beam and the linear dimensions of the dark region. This beam can be used to trap cold atomic samples in a low-intensity region, where the interaction with the light field and the perturbations on energy levels are considerably reduced [16]. We estimated the heating rate inside the trap. If only spontaneous emission of photons is taken into account long trap lifetimes can be expected with relatively small values of laser detuning and power.

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## References

1. For a review on magnetic trapping techniques and recent developments in cold atom physics see, for example, *Bose-Einstein condensation in atomic gases*, edited by M. Inguscio, S. Stringari, C.E. Wieman, *Proceedings of the International School of Physics "Enrico Fermi", Course CXL* (IOS Press, 1999).
2. For a review on optical dipole traps, see: R. Grimm, M. Weidemüller, Y.B. Ovchinnikov, Adv. At. Mol. Opt. Phys. **42**, 95 (2000).
3. H.J. Lee, C.S. Adams, M. Kasevich, S. Chu, Phys. Rev. Lett. **76**, 2658 (1996).
4. I. Manek, Y.B. Ovchinnikov, R. Grimm, Opt. Commun. **147**, 67 (1998).
5. T. Kuga, Y. Torii, N. Shiokawa, T. Hirano, Phys. Rev. Lett. **78**, 4713 (1997).
6. S. Kuppens, M. Rauner, M. Schiffer, K. Sengstock, W. Ertmer, F.E. Dorsselaer, G. Nienhuis, Phys. Rev. A **58**, 3068 (1998).
7. Y.B. Ovchinnikov, I. Manek, R. Grimm, Phys. Rev. Lett. **79**, 2225 (1997).
8. Y.B. Ovchinnikov, I. Manek, A.I. Sidorov, G. Wasik, R. Grimm, Europhys. Lett. **43**, 510 (1998).
9. R. Ozeri, L. Khaykovich, N. Davidson, Phys. Rev. A **59**, R1750 (1999).
10. J. Arlt, M.J. Padgett, Opt. Lett. **25**, 191 (2000).
11. N. Friedman, L. Khaykovich, R. Ozeri, N. Davidson, Phys. Rev. A **61**, 031403(R) (2000).
12. P. Zemánek, C.J. Foot, Opt. Commun. **146**, 119 (1998).
13. J.H. McLeod, J. Opt. Soc. Am. **44**, 592 (1954).
14. P.A. Bélanger, M. Rioux, Appl. Opt. **17**, 1080 (1978).
15. T.A. Savard, K.H. O'Hara, J.E. Thomas, Phys. Rev. A. **56**, R1095 (1997).
16. A similar scheme was reported by L.A. Orozco in a poster presented at the *XIV International Conference on Laser Spectroscopy*, Innsbruck, 1999.