Atom trapping in an interferometrically generated bottle beam trap

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We demonstrate an optical bottle beam trap created by interfering two fundamental Gaussian beams with different waists. The beams are derived from a single laser source using a Mach–Zehnder interferometer whose arms have unequal magnifications. Destructive interference of the two beams from the Mach–Zehnder leads to a three-dimensional intensity null at the mutual focus of the beams. We demonstrate trapping of cold cesium atoms in a blue detuned bottle beam trap. © 2009 Optical Society of America

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The use of neutral atoms for quantum information processing is a topic of great current interest. The quantum states of single atoms can be manipulated by first localizing them in tightly confining traps. A simple method to achieve this is a far off-resonance optical trap (FORT). This trap can take two forms. A bright trap using red detuned light where the atoms are attracted to a region of high intensity [1] or a dark trap using blue detuned light based on repulsion of the atoms from a surrounding region of high intensity. The dark trap has several advantages over the bright trap. The atoms (or other trapped particles) are held in an area of low intensity and therefore scatter fewer photons when compared to a bright trap of the same depth. This significantly decreases the atomic heating and decoherence rates. In addition trap induced ac Stark shifts are minimized, which simplifies coherent control of internal states using additional optical fields. We are especially interested in dark traps for application to coherent control of Rydberg atoms [2] since the wavelength can be chosen to give equal trapping potentials for both ground and Rydberg states [3].

Several methods have been used to produce bottle beams (BoBs) that have an intensity null surrounded by light in all directions [4–9]. Some of these approaches require optical access from several sides or the use of custom optical polarization plates, holograms, or spatial light modulators. Here we demonstrate a method that is closest to that in [8] to produce a BoB using a single laser source with a Gaussian TEM_{00} spatial profile and a Mach–Zehnder interferometer. Our approach can readily handle powers of several watts and can be scaled from micrometer to centimeter sized traps simply by changing the final focusing lens.

We create a BoB trap by destructive interference of two lowest order Gaussian beams with different waists. The beams of wavelength λ propagating along $\hat{z}$ are assumed to have the same polarization and are both focused with their waists w_1, w_2 located at $z=0$. Provided the beam powers satisfy $P_1/w_1^2=P_2/w_2^2$ there is an intensity null at $x=y=z=0$. Using standard expressions for TEM_{00} Gaussian beams we find the axially symmetric intensity pattern shown in Fig. 1. Surrounding the intensity zero there are axial maxima at $z_m=\pm\pi q w_1^2/\lambda$ and a radial maximum at $\rho_m=\sqrt{2}qw_1(\ln(q)/(q^2-1))^{1/2}$, where we have introduced $q=w_2/w_1$. The BoB provides a three-dimensional (3D) trapping potential with the lowest escape barrier at the saddle points on the line $\theta=\tan^{-1}(z/\rho)\sim 20°$. As we show below the 3D localization is optimized for $q=q_0\simeq 1.89$. Setting $q=q_0$, as in Fig. 1, the peak axial intensity is $I_{\max}\simeq 0.069P/\pi w_1^2$ with $P=P_1+P_2$ as the total power. The radial intensity and the intensity at the saddle point reach, respectively, 61% and 32% of $I_{\max}$.

The spatial localization of cold atoms in the BoB trap is an important figure of merit for quantum information applications. To quantify the localization we evaluate the optical intensity near the null along the axial and radial directions as

$$I(\rho=0,z)=\frac{2P\lambda^2}{\pi^3 w_1^6}\frac{(1-q^2)^2}{(1+q^2)q^4}z^2+\mathcal{O}(z^4), \qquad (1)$$

$$I(\rho,z=0)=\frac{2P}{\pi w_1^6}\frac{(1-q^2)^2}{(1+q^2)q^4}\rho^4+\mathcal{O}(\rho^6). \qquad (2)$$

Let us assume that $w_2>w_1$ so $q>1$, then for given values of the power, wavelength, and smaller waist w_1 the localization in both z and r is strongest when $q=q_0=\sqrt{(3+\sqrt{17})/2}\simeq 1.89$. The dipole potential for an atom with scalar polarizability α is $U=-(\alpha/(2\epsilon_0 c))I$, where c is the speed of light. The axial motion is har-

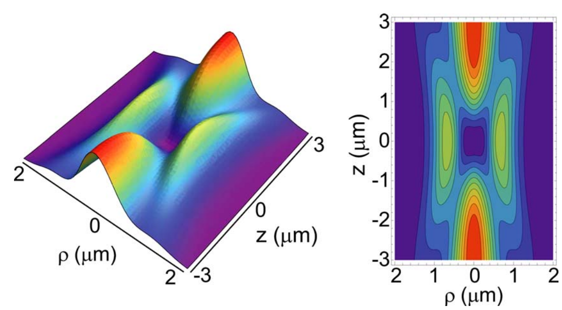

Fig. 1. (Color online) BoB intensity distribution for $w_1=0.5$, $w_2=0.94$, and $\lambda=0.532$ μm.

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monic and the oscillation frequency for an atom of mass m and polarizability α is given by $\omega_z = (2\alpha\tilde{q}\lambda^2 P/(\pi^3 c\epsilon_0 w_1^6 m))^{1/2}$, where m is the atomic mass and we have introduced $\tilde{q}=(1-q^2)^2/[(1+q^2)q^4]$. For an atom with kinetic temperature T the root mean square axial displacement is $z_{\rm rms}=\sqrt{k_B T/m\omega_z^2}$ with k_B as the Boltzmann constant.

In the radial direction the potential is quartic and we can use the virial theorem to write $\langle\rho^4\rangle = (2/(3U_{\rho 4}))k_B T$, where $U_{\rho 4}$ is the coefficient of ρ^4 in the expansion of the potential. Assuming a Maxwell–Boltzmann distribution of atoms in the quartic potential we find $\langle\rho^2\rangle/\langle\rho^4\rangle=(2/\sqrt{\pi})(U_{\rho 4}/(k_B T))^{1/2}$ and $\rho_{\rm rms}=(2/(3^{1/2}\pi^{1/4}))(k_B T/U_{\rho 4})^{1/4}$. Using the parameters of Fig. 1, $\alpha\times 10^6/4\pi\epsilon_0 = 32\times 10^{-24}$ cm^3 for Cs atoms at $\lambda=0.532$ μm, $T=10$ μK, and $P=10$ mW we find $z_{\rm rms}=0.28$ μm and $\rho_{\rm rms}=0.22$ μm. We can compare this with a red detuned FORT created by focusing a single beam to a waist w_1. Using $\lambda=1.064$ μm, $w_1=1$ μm, $\alpha\times 10^6/4\pi\epsilon_0=170\times 10^{-24}$ cm^3, and the same temperature and power as for the BoB trap we find [3] $z_{\rm rms}=0.16$ μm and $\rho_{\rm rms}=0.055$ μm. The BoB gives somewhat worse localization than the red detuned FORT, largely because the polarizability is much smaller at the shorter wavelength. Nevertheless we can readily obtain spatial localization to much better than 1 μm in all three dimensions with a power of only 10 mW and a much lower photon scattering rate than in the FORT. It is also worth noting that the motional decoherence properties of the BoB trap are slightly better than the FORT due to the quartic nature of the radial potential.

We have demonstrated trapping of cold Cs atoms in a BoB trap using the approach shown in Fig. 2(a). A Mach–Zehnder interferometer generates two beams with different waists by using telescopes of different magnification in each arm. A feedback circuit is used to lock the two beams out of phase by controlling a piezoelectric mirror mounted into one arm. The BoB created at $z=0$ can then be reimaged into the desired experimental location with relay lenses. This setup allows variation of the trap aspect ratio by varying the ratio of the two beam waists, or variation of the trap size by changing the magnification of the relay optics.

To demonstrate the feasibility of the method we used an injection locked Ti:sapphire laser to produce light detuned 40 GHz to the blue of the $|6S_{1/2},F=4\rangle \rightarrow |6P_{3/2}\rangle$ $D2$ transition of Cs. The light was coupled to the Mach–Zehnder interferometer using a single mode polarization preserving fiber. Each arm of the interferometer contained a telescope to change the beam size. These telescopes had a magnification of 0.75× and 1.33× giving a waist ratio of $q=1.78$, which is not far from the ideal q_0 discussed above. One output port of the interferometer was used to lock the two beams out of phase by maximizing the signal hitting a photodiode monitoring that output. To lock to this maximum a small dither was applied to the piezocontrolled mirror for use with a lock-in amplifier. The other output went through a telescope (2.5× magnification) and a final focusing lens

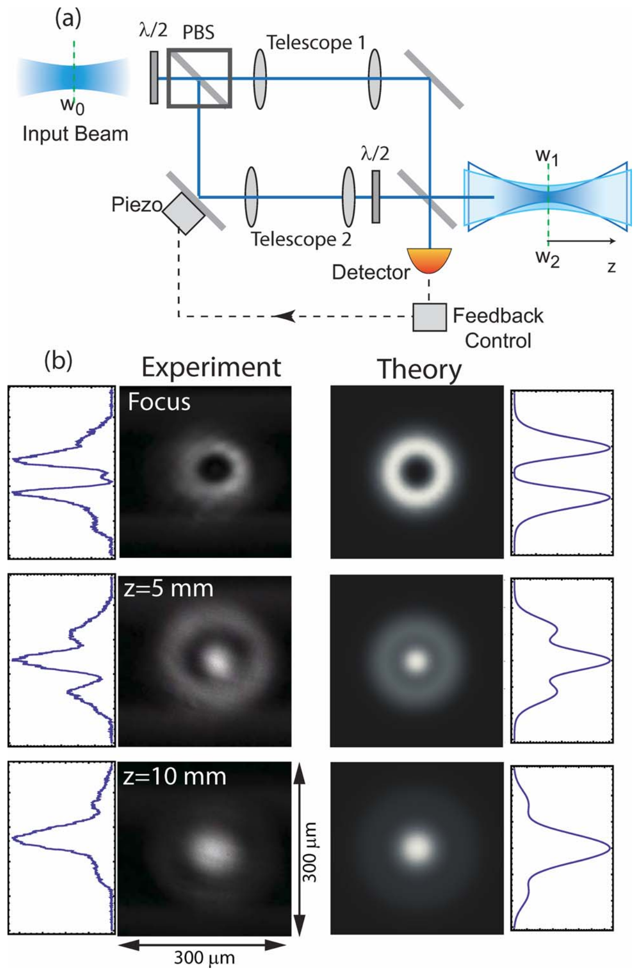

Fig. 2. (Color online) (a) Schematic of the interferometer used to generate the two beams. (b) Cross sections of the intensity along the beam path for beam waists of $w_1=37$ and $w_2=63$ μm.

($f=150$ mm) to focus the two beams onto a magneto-optical trap (MOT). We obtained approximately 40 mW of trapping light at the atoms split between the two beams. The beam waists were $w_{1,2}=12$, 22 μm (w is defined as the beam radius at the $1/e^2$ intensity point). The power was split between the two beams by adjusting a $\lambda/2$ plate before the input to the interferometer to obtain an intensity null at the focus.

We took images of the bottle beam to measure the output waists and to compare them with the theoretical predictions. To do this we used a lens and CCD camera system, which had a magnification of 11, to image various axial planes of the bottle beam. First we looked at each beam individually to measure each beam's waist and waist position. This allowed us to verify that each beam was focused at the same plane. The measured values for the beam waists were then used to create theoretical plots for comparison with pictures of both beams together. The results are shown in Fig. 2(b).

We then used the BoB to trap Cs atoms from a MOT. The atoms in the MOT had an initial temperature of about 50 μK measured using a time of flight method. With our power and beam sizes, this gives

Table 1. Trap Parameters Calculated from Our Measured Beam Waists and Power for 50 μK Cs atoms

Quantity	BoB Trap
Wavelength	$\lambda = 0.852$ μm
Optical power	$P = 40$ mW
Detuning	$\Delta/2\pi = +40$ GHz
Beam waists	$w_{1,2} = 12, 22$ μm
Trap depth (axial,radial,saddle)	4.4, 2.7, 1.4 mK
Position of axial intensity peak	$z_m = \pm 970$ μm
Position of radial intensity peak	$\rho_m = 16$ μm
Spatial confinement	$(z_{\mathrm{rms}}, \rho_{\mathrm{rms}}) = (31, 3.0)$ μm
Axial vibrational frequency	$\omega_z/2\pi = 290$ Hz
Photon scattering rate	730 s^{-1}

the parameters shown in Table 1. To look for trapping we allowed the MOT to load for 1 s then turned on the BoB allowing both to overlap for about 1 ms. We then turned off the MOT beams for a time t allowing the MOT to fall away. Finally the MOT beams were briefly turned on to take a flourescence image of the atoms using a cooled electron multiplying CCD camera. By varying the delay time t between extinction of the MOT beams and measuring the atom number we extracted an exponential trap lifetime of $\tau \sim 20$ ms as shown in Fig. 3. The atom distribution in the inset is consistent with a pencil of atoms of size $2z_m \times 2\rho_m$. This is expected since at $t = 40$ ms the atoms have been heated above the saddle temperature and essentially fill the volume between the axial and the radial peaks.

The finite trap lifetime is due to several factors [10], including heating due to photon scattering, spatial noise of the trapping beams, and collisions with background atoms. We believe the dominant factor limiting the lifetime is substantial initial heating of the atoms by the nonadiabatic transfer from the MOT to the BoB trap followed by photon scattering. An initial temperature of 500 μK would imply a mean scattering rate of 5×10^3 s^{-1}, which in turn would heat the atoms to 1 mK in a time of 20 ms. Since the escape barrier at the saddle is $\sim$1 mK, this estimate is consistent with the observed lifetime of $\tau = 20$ ms. Heating due to laser intensity noise is also of concern, particularly with our use of a dither lock on the Mach–Zehnder. With optimization of the lock we observed a relative intensity noise at the Mach–Zehnder output of RIN$\sim 10^{-8}$/Hz for all frequencies above 300 Hz. This implied a heating rate that was about five times lower than that due to photon scattering.

In conclusion we have demonstrated trapping of cold Cs atoms in a novel BoB trap. Our method only requires access through a single window, is relatively simple, and uses standard optical components. It has the potential for submicrometer trapping in 3D with very modest optical power. Atoms were visible in our trap for more than 100 ms, and we believe that with a larger detuning and the addition of a cooling phase after trap loading, lifetimes limited by collisions with background atoms should be possible. In future work we will explore methods for cooling inside the BoB trap as in [11]. Finally we note that this technique can be easily generalized to create other types of dark traps. By putting $P_2 < P_1 w_2^2/w_1^2$ and $q > 1$ there will be finite intensity at the origin but an intensity null at $z=0$, $\rho = (w_1 q/(q^2-1))\sqrt{\ln(q\sqrt{P_1/P_2})}$. In this way microscopic toroidal traps can be generated, which may be useful for studies of persistent currents and superfluid flow with cold atoms [12].

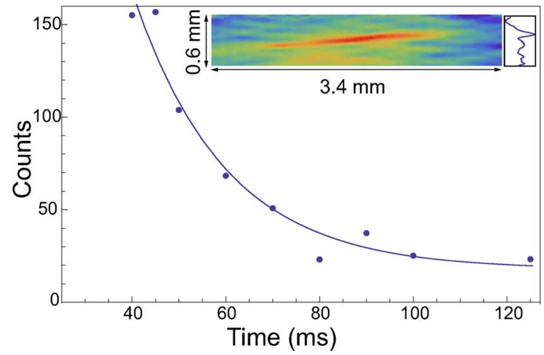

Fig. 3. (Color online) Measurement of trap decay versus time. The curve is a least squares fit to the function $b + ae^{-t/\tau}$ resulting in $a = 1100$, $b = 18$, and $\tau = 20$ ms. The inset shows the spatial distribution at $t = 40$ ms formed by averaging 200, 1 ms exposures. To the right is a transverse line profile through the center of the trap.

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References

1. J. D. Miller, R. A. Cline, and D. J. Heinzen, Phys. Rev. A **47**, R4567 (1993).
2. T. A. Johnson, E. Urban, T. Henage, L. Isenhower, D. D. Yavuz, T. G. Walker, and M. Saffman, Phys. Rev. Lett. **100**, 113003 (2008).
3. M. Saffman and T. G. Walker, Phys. Rev. A **72**, 022347 (2005).
4. T. Kuga, Y. Torii, N. Shiokawa, and T. Hirano, Phys. Rev. Lett. **78**, 4713 (1997).
5. R. Ozeri, L. Khaykovich, and N. Davidson, Phys. Rev. A **59**, R1750 (1999).
6. J. Arlt and M. J. Padgett, Opt. Lett. **25**, 191 (2000).
7. S. Kulin, S. Aubin, S. Christe, B. Peker, S. L. Rolston, and L. A. Orozco, J. Opt. B: Quantum Semiclassical Opt. **3**, 353 (2001).
8. D. Yelin, B. E. Bouma, and G. J. Tearney, Opt. Lett. **29**, 661 (2004).
9. S. E. Olson, M. L. Terraciano, M. Bashkansky, and F. K. Fatemi, Phys. Rev. A **76**, 061404(R) (2007).
10. T. A. Savard, K. M. O'Hara, and J. E. Thomas, Phys. Rev. A **56**, R1095 (1997).
11. S. L. Winoto, M. T. DePue, N. E. Bramall, and D. S. Weiss, Phys. Rev. A **59**, R19 (1999).
12. C. Ryu, M. F. Andersen, P. Clade, V. Natarajan, K. Helmerson, and W. D. Phillips, Phys. Rev. Lett. **99**, 260401 (2007).