Achieving very long lifetimes in optical lattices with pulsed cooling

Michael J. Gibbons, Soo Y. Kim, Kevin M. Fortier, Peyman Ahmadi, and Michael S. Chapman
School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430, USA
(Received 19 May 2008; published 28 October 2008)

We have realized a one-dimensional optical lattice for individual atoms with a lifetime >300 s, which is 5× longer than previously reported. In order to achieve this long lifetime, it is necessary to laser-cool the atoms briefly every 20 s to overcome heating due to technical fluctuations in the trapping potential. Without cooling, we observe negligible atom loss within the first 20 s followed by an exponential decay with a 62-s time constant. We obtain quantitative agreement with the measured fluctuations of the trapping potential and the corresponding theoretical heating rates.

DOI: 10.1103/PhysRevA.78.043418 PACS number(s): 37.10.Jk, 37.10.De, 37.10.Vz

I. INTRODUCTION

Optical dipole traps have become an essential tool in ultracold atomic and molecular physics since the first demonstration in 1986 [1]. They have applications in important research areas including atomic frequency standards [2], tests of fundamental symmetries [3], quantum degenerate gases [4,5], single-atom trapping [6–9], and the development of scalable quantum information processing systems [10]. Optical trapping potentials can be tailored through the choice of optical wavelengths and laser beam configurations to yield a wide variety of trapping arrangements. Optical lattices are particularly useful for confining neutral atom qubits with subwavelength precision [11], for coupling neutral atoms into a cavity mode [12,13], and for studying quantum phase transitions in quantum gases [14].

Early work with optical dipole traps focused on overcoming short trap lifetimes and excessive atom heating in the traps. These limitations are due to both fundamental heating mechanisms associated with trap light absorption by the atoms as well as heating mechanisms due to fluctuating trapping forces. The far-off-resonant trap (FORT) was developed to essentially eliminate fundamental lifetime and heating limits by utilizing large trap light detunings [15]. Nonetheless, early efforts to create ultracold atoms in FORTs were plagued by higher than anticipated heating rates. It was pointed out that fluctuations in the trap potential due to laser intensity noise and/or pointing instabilities can cause heating that limits the lifetime and temperature of optically trapped atoms [16,17]. By using sufficiently quiet lasers, very long lifetime traps were observed [18,19], and cooling to quantum degeneracy directly in an optical trap was achieved [4].

With the advent of very stable high-power diode and fiber lasers, quantum degenerate gases are now routinely created and studied in optical traps. Surprisingly, beyond the general appreciation that technical heating can limit the performance of optical traps, there has been little attempt to quantitatively study the lifetime limits due to heating in experiments. This is in part because observing any lifetime limits due to technical heating in a FORT made with today's low-noise lasers requires exceptional vacuum conditions ($<10^{-10}$ Torr) in order to overcome lifetime limits due to background collisions. One exception is the study by Alt and co-workers [20], who showed that their 3-s trap lifetime was limited by noise applied to their trap beams via an acousto-optic modulator (AOM) used to control the laser beam.

It is particularly important to study heating limitations in optical lattices, since the heating rates scale strongly with the trap frequencies [16], which are typically much higher in optical lattices. Indeed, while trap lifetimes exceeding 300 s have been observed in low frequency optical traps [19], the longest reported lifetime in an optical lattice is no more than 60 s [21].

In this paper, we examine heating sources and quantify their effects on the trap lifetime in an optical lattice. The paper is organized as follows. In Sec. II we describe the experimental setup and demonstrate continuous cooling of individual atoms in a lattice. The lifetime of trapped atoms without cooling is discussed in Sec. III, where we observe a nonexponential decay of the population with an asymptotic trap lifetime of 62 s. We measure potential trap heating sources in Sec. IV, obtaining good quantitative agreement with a numerical simulation. In Sec. V, we demonstrate a lattice lifetime >300 s by briefly laser-cooling the trapped atoms every 20 s to counteract heating.

II. EXPERIMENTAL SETUP

The experiment, as shown in Fig. 1, is performed in a vacuum system consisting of a $27\times27\times150$ mm^3 rectangular glass cell attached to a stainless steel vacuum chamber maintained at $<10^{-11}$ Torr. Laser-cooled ^{87}Rb atoms are loaded into a one-dimensional (1D) optical lattice created by

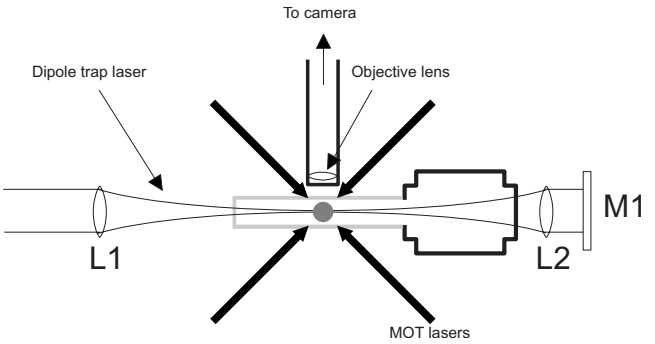

FIG. 1. Experimental setup. Rb atoms are trapped in a magneto-optical trap (MOT) and then transferred into an optical lattice.

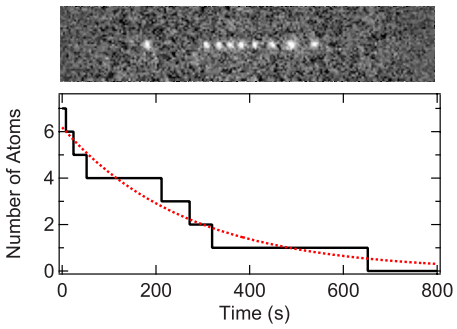

FIG. 2. (Color online) Top: continuously cooled array of ^{87}Rb atoms trapped in a 1D optical lattice. Bottom: number of atoms vs time, starting from seven atoms initially loaded in the lattice. Dashed line is an exponential fit to the data.

a retroreflected Yb fiber laser beam. The trap beam is focused to a minimum waist of $w_0=12.7$ μm, which produces an optical dipole trapping potential of $U_{\text{dipole}}=2$ mK for 1 W of power. A six-beam magneto-optical trap (MOT) is used to provide the sample of laser-cooled atoms. The laser-cooling beams are detuned -16 MHz from the $5S_{1/2}F=2\rightarrow 5P_{3/2}F=3$ transition of ^{87}Rb and have an intensity of 2.4 mW/cm^2 per beam. The magnetic field gradient for the MOT is created by two anti-Helmholtz magnetic coils. To load single atoms, a magnetic field gradient of 350 G/cm is utilized. For larger atomic samples, the field gradient is lowered to 18 G/cm in order to expand the trapping volume. Loading the laser cooled atoms into the optical lattice is accomplished by operating the MOT and lattice concurrently. After 10 s of loading, the magnetic field is turned off, leaving some of the atoms trapped in the lattice.

The trapped atoms are detected by imaging atomic fluorescence onto an electron multiplying charge-coupled-device (CCD) camera. The atoms are excited using the laser-cooling beams. For trap depths of >1 mK and with careful alignment and balance of the laser beams, the atoms can be simultaneously cooled and observed nondestructively [22]. The atomic fluorescence is collected with a high numerical aperture (NA=0.40) microscope objective. With this imaging system, it is possible to detect individual atoms, both in the MOT and in the optical lattice, with exposure times as short as 100 ms. Figure 2 (top) shows an image of a sparsely loaded optical lattice. A typical evolution of the trap population versus time is shown in Fig. 2 (bottom). For these data, the atoms were continuously cooled and monitored. Note that one of the atoms remains trapped for more than 600 s. An exponential fit to this limited data set indicates an $1/e$ lifetime of 270 s, which is consistent with a vacuum-limited lifetime [23] at our measured pressure of $\sim 10^{-11}$ Torr.

III. LIFETIME WITHOUT COOLING

Decay of the trap population versus time without the cooling beams is shown in Fig. 3. Surprisingly, we find that the lifetime of the atoms in the lattice is dramatically lower when the cooling light is not applied. Each data point is the average of 5 runs and the lattice is reloaded for each run because atom counting is destructive in this case. The total

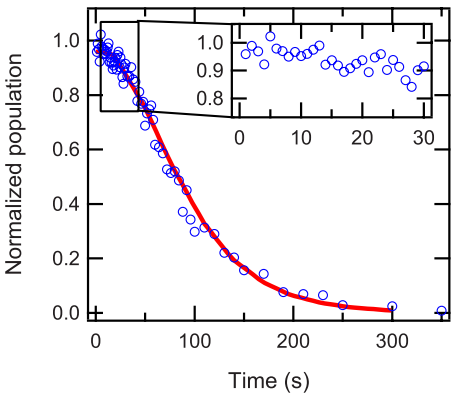

FIG. 3. (Color online) Atom population in the optical lattice vs time with no cooling. For each data point, the final population in the trap is normalized to the initial population. The asymptotic decay of the trap is exponential with a 62-s lifetime. Inset shows the trap population for the first 30 s. The solid line is a simulation including heating, as discussed in the text.

elapsed time for the data in this figure is 10 h. For these data, the initial number of atoms in the trap was $\sim$500–1000, and the population was measured by integrating the florescence over the trap area.

In addition to the shorter overall decay time, the uncooled atoms exhibit a nonexponential decay. Following loading, there is an initial period of $\sim$20 s during which the atom loss is minimal, as shown in the inset to Fig. 3. Subsequently, the population decays exponentially with a 62-s time constant. This behavior is consistent with a heating source which continuously increases the total energy of the atoms. The initial delay in the atom loss is due to the fact that the thermal energy of the atoms immediately after loading is considerably below the well depth. Thus, there is a time delay before atoms gain enough energy to leave the trap.

IV. HEATING MECHANISM

In order to quantitatively compare our results to possible heating sources, we determine the heating rate in the trap derived from measurements of the intensity noise power spectra [16] of the trap beam and the noise power spectra for fluctuations of the trap equilibrium position. Fluctuations in the laser intensity cause parametric heating of the atoms due to a modulation of the trapping potential. This leads to an exponential energy growth of the atoms with a time constant Γ given by [16]

$$\Gamma = \frac{1}{T_I} = \pi^2 \nu_{tr}^2 S_{\varepsilon_I}(2\nu_{tr}), \tag{1}$$

where T_I is the energy e-folding time, ν_{tr} is the trap frequency, $\varepsilon=[I(t)-I_0]/I_0$ is the fractional fluctuation in the laser intensity, and $S_I(2\nu_{tr})$ is the relative intensity noise power spectrum defined as

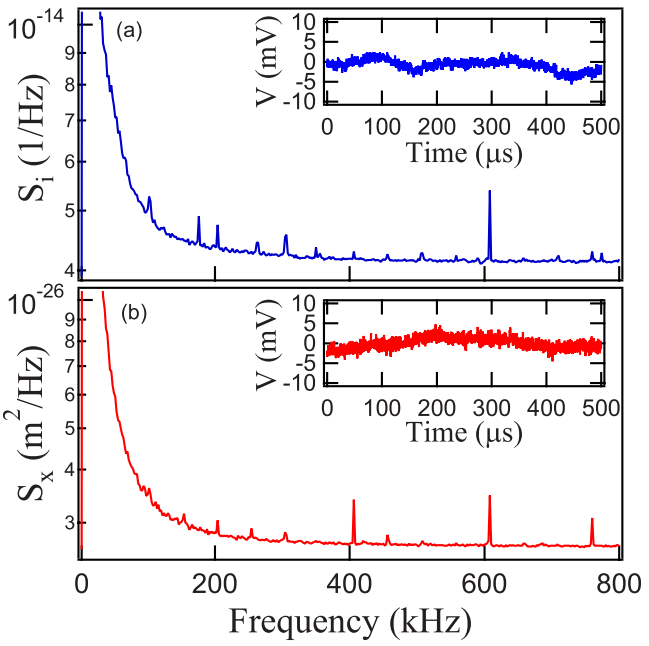

FIG. 4. (Color online) (a) Relative intensity noise power spectrum for the dipole trap laser, averaged over 50 runs. (b) Axial position noise power spectrum, averaged over 50 runs. Insets show the raw noise data for a typical run.

$$S_\varepsilon(\nu) \equiv \frac{2}{\pi}\int_0^\infty d\tau \cos(\nu\tau)\langle\varepsilon(t)\varepsilon(t+\tau)\rangle. \tag{2}$$

The other dominant heating mechanism results from fluctuations in the trap position (e.g., due to laser beam pointing or phase instabilities). In this case, the energy grows linearly with a heating rate $\dot{Q}$ given by

$$\dot{Q} = 4\pi^4 \nu_{tr}^4 m S_{\varepsilon_x}(\nu_{tr}), \tag{3}$$

where ε_x is the fluctuation in the location of the trap center and $S_x(\nu_{tr})$ is the trap position noise power spectrum, which can be calculated using Eq. (2).

We measure the intensity noise and the position noise in the radial direction of the trapping beam using a balanced detection method [24] in which the laser beam is separated by a 50-50 beam splitter and each beam is focused onto a different detector. One of the beams is half blocked by a razor blade, and the other is 50% attenuated to equalize the power received by each detector. The output of the first detector measures the power fluctuations, while the difference between the two detectors measures the pointing fluctuations. Figure 4(a) shows the relative intensity noise power spectrum averaged over 50 runs. An example of observed voltage noise due to intensity fluctuations is shown in the inset where 1 mV fluctuation corresponds to 10^{-4} relative fluctuation in laser intensity.

The position noise in the axial direction is measured using an interferometric technique. A beam splitter is placed in the path of the optical lattice laser before the focusing lens $L1$ in Fig. 1. A mirror is glued directly to one side of the beam splitter to form one arm of an interferometer. The beam passing through the beam splitter retroreflects from the mirror ($M1$ in Fig. 1) in the lattice setup, forming the second arm of the interferometer. These two beams interfere and are focused onto a detector. Once properly aligned, the phase fluctuations between the two arms are measured by monitoring the intensity fluctuation on the detector. Laser power fluctuations are simultaneously monitored on a separate detector. Subtracting these two signals isolates the phase fluctuations, which can then be used to calculate the position noise in the axial direction. Figure 4(b) gives the resulting position noise power spectrum averaged over 50 runs. An example of observed voltage noise due to axial position fluctuations is shown in the inset where 1 mV fluctuation corresponds to 2.4×10^{-5} relative fluctuation in laser intensity.. The corresponding heating rate $\dot{Q}$ and heating time constant Γ calculated from Eqs. (1) and (3) are shown in Fig. 5.

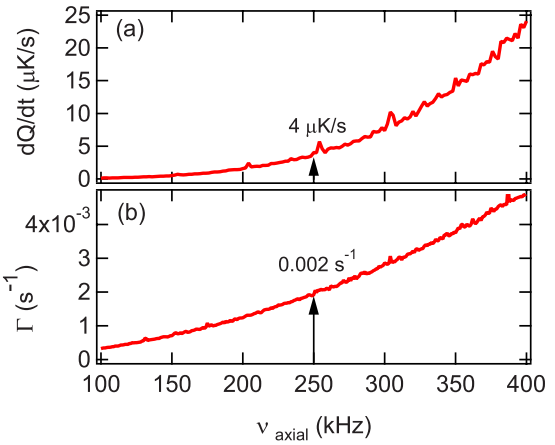

FIG. 5. (Color online) (a) Heating rate due to fluctuations in the axial trap position. (b) Heating time constant due to intensity fluctuations.

The axial and radial trapping frequencies of the optical lattice are measured using parametric excitation [25], resulting in values of ν_{axial}=250 kHz and ν_{radial}=2.8 kHz, respectively. The corresponding $\dot{Q}$ and Γ for the axial direction are 4 μK/s and 0.002 s^{-1}, respectively. The heating rates in the radial directions are negligible compared to the heating in the axial direction because these heating processes scale as ν_{tr}^2 and ν_{tr}^4 and are therefore not shown in the figure.

The time evolution of the trap population can be modeled with a Fokker-Planck equation for the energy distribution $n(E,t)$ given by [26]

$$\frac{\partial n}{\partial t} = \left(\frac{\Gamma}{4}E^2 + \dot{Q}E\right)\frac{\partial^2 n}{\partial E^2} - \dot{Q}\frac{\partial n}{\partial E} - \frac{\Gamma}{2}n. \tag{4}$$

Numerical solutions of Eq. (4) are obtained assuming an initial Maxwell-Boltzmann distribution with a temperature of the trapped atoms of 100 μK. The simulation results, shown as a solid curve in Fig. 3 for the parameters $\dot{Q}$=4.5 μK/s and Γ=0.002 s^{-1}, closely reproduce the observed trap population, and in particular, show the 20 s delay before the onset of appreciable trap loss.

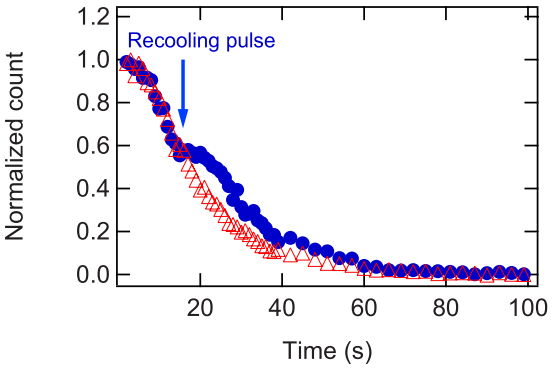

FIG. 6. (Color online) (●) Lattice population vs time showing the effect of a single 5-ms cooling pulse applied at $t=15$ s. (△) Similar data without the cooling pulse applied.

It is worth noting that this model is only strictly valid assuming a harmonic potential. In reality, the effective trap frequency becomes smaller as an atom approaches the top of the trap. However, due to the partially exponential nature of the heating, the atoms are expected to spend relatively less time near the top of the trap, which should minimize the resulting error. We would nevertheless expect the model to slightly overestimate the heating in the trap.

V. PULSED COOLING

The remarkable feature of our observation, which is supported by the simulation, is that it takes a finite amount of time for the atoms to heat up sufficiently to be ejected from the trap. It follows that it should be possible to extend the lifetime of the trapped atoms by occasionally recooling them to the bottom of the trap. In Fig. 6, we demonstrate the proof of principle of this idea by applying a short 5-ms pulse of laser-cooling light to the atoms at $t=15$ s. The cooling light is provided by the laser beams used to form the MOT. As is evident from the data, the loss of atoms is halted for a time comparable to the delay in atom loss following initial loading. Note for these data, the overall lifetime is shorter than in Fig. 3. This is due to the fact that for these data, a different Yb fiber laser with a much higher-intensity noise is used as the trapping laser.

The results in Fig. 6 suggest that it should be possible to minimize atom loss caused by heating almost entirely by providing cooling pulses at time intervals shorter than the initial heating time. In Fig. 7, we demonstrate that this is indeed possible and realize a dramatic increase in the lifetime by application of a periodic cooling pulse to the atoms. For these data (◇), the atoms are cooled with a 1-s cooling pulse applied every 19 s. The trap population for this cooling method shows a simple exponential decay with a 310-s lifetime. To our knowledge, this is the longest lifetime reported in an optical lattice by a factor of 5 [21].

We have compared the lifetime of the pulsed cooling method to the case where the atoms are continuously exposed to the cooling light. This is also shown in Fig. 7. The continuously cooled atoms exhibit an initial fast decay rate ($\Gamma_{initial}^{-1}=45$ s) in the first ~100 s followed by a slower decay

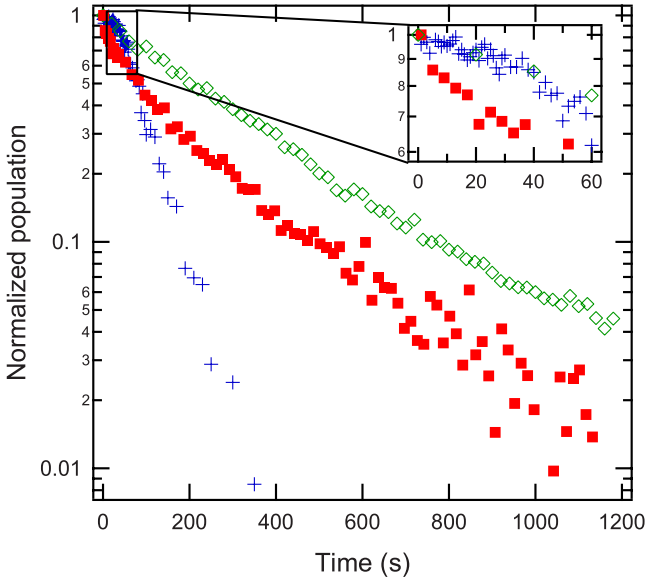

FIG. 7. (Color online) Number of atoms in the trap vs time, normalized to the initial loading for three difference cases: (◇) pulse-cooled atoms, (■) continuously cooled atoms, and (+) uncooled atoms. The inset shows the first 60 s of data.

at approximately the same rate as the pulsed cooling case and the rate inferred from the distinguishable trapped atom case shown in Fig. 2. We attribute this fast initial decay to light assisted collisions between two atoms trapped in the same antinode. For these data, the initial loading was ~700 atoms distributed over ~500 sites, and hence one expects >40% of the sites to have at least 2 atoms initially assuming Poissonian loading statistics. Two atoms per site corresponds to an effective density of $n=1.1\times10^{10}$ cm^{-3} at the Doppler temperature. The loss rate due to light assisted collisions at this density for the intensity and detuning of our cooling beams is $\Gamma_{\text{light}}=0.02$ s^{-1} [27,28], which is consistent with the fast initial loss rate for the continuous cooling data in Fig. 7. Once the multiply occupied sites are vacated, the decay rate reduces to the pulsed cooling case, which is likely limited by the background vacuum. Note that the pulsed cooling data also has a similar number of sites with multiple atoms. In this case, however, the light is on for only 1/20 of the time, thus the effective Γ_{light} is correspondingly reduced.

The trap lifetime in the absence of cooling is limited by fluctuations in the axial trap position due to vibrations in the mount for the mirror used to form the lattice standing wave. Although the measured fluctuations of the lattice standing wave are very small ($\Delta x_{\text{rms}}\sim10^{-4}$ λ in the frequency range from 10 kHz to 2 MHz), they provide the dominant heating source. In the current setup, it is necessary to have an adjustable mirror mount to achieve the required alignment of the lattice. It should be straightforward to reduce these vibrations by moving to a fixed mount in the future. The heating due to the laser intensity noise will limit the lifetime to ~1000 s, which is much longer than the background-limited lifetime.

VI. CONCLUSION

In conclusion, we have examined lifetime limitations due to heating in a long-lived 1D optical lattice. We have been

able to identify the dominant heating mechanism in the trap by comparing our results with measured fluctuations of the trap parameters. Furthermore, we have demonstrated that it is possible to greatly extend the trap lifetime in our optical lattice through judicious application of laser cooling to counteract the heating. With this, we were able to extend the lifetime beyond 300 s.

More generally, the results of this study can be employed in designing optical lattices with very long lifetimes. While the cooling pulses described in this paper do not preserve the quantum state of the atoms, they can be used to maintain the structure of a quantum register between operations. Future experiments requiring precise positioning of the atoms in the lattice to allow controlled interactions and addressing of specific atoms would benefit greatly from longer trap lifetime.

ACKNOWLEDGMENTS

We would like to acknowledge valuable discussions with Paul Griffin. This work is supported by the National Science Foundation, Grants No. PHYS-0605049 and No. PHYS-0703030.

[1] S. Chu, J. E. Bjorkholm, A. Ashkin, and A. Cable, Phys. Rev. Lett. **57**, 314 (1986).
[2] M. Takamoto, F. L. Hong, R. Higashi, and H. Katori, Nature (London) **435**, 321 (2005).
[3] C. Chin, V. Leiber, V. Vuletic, A. J. Kerman, and S. Chu, Phys. Rev. A **63**, 033401 (2001).
[4] M. D. Barrett, J. A. Sauer, and M. S. Chapman, Phys. Rev. Lett. **87**, 010404 (2001).
[5] D. M. Stamper-Kurn, M. R. Andrews, A. P. Chikkatur, S. Inouye, H.-J. Miesner, J. Stenger, and W. Ketterle, Phys. Rev. Lett. **80**, 2027 (1998).
[6] D. Frese, B. Ueberholz, S. Kuhr, W. Alt, D. Schrader, V. Gomer, and D. Meschede, Phys. Rev. Lett. **85**, 3777 (2000).
[7] N. Schlosser, G. Reymond, I. Protsenko, and P. Grangier, Nature (London) **411**, 1024 (2001).
[8] N. Schlosser, G. Reymond, and P. Grangier, Phys. Rev. Lett. **89**, 023005 (2002).
[9] K. M. Fortier, S. Y. Kim, M. J. Gibbons, P. Ahmadi, and M. S. Chapman, Phys. Rev. Lett. **98**, 233601 (2007).
[10] D. Schrader, I. Dotsenko, M. Khudaverdyan, Y. Miroshnychenko, A. Rauschenbeutel, and D. Meschede, Phys. Rev. Lett. **93**, 150501 (2004).
[11] P. J. Lee, M. Anderlini, B. L. Brown, J. Sebby-Strabley, W. D. Phillips, and J. V. Porto, Phys. Rev. Lett. **99**, 020402 (2007).
[12] K. Murr, S. Nuszmann, T. Puppe, M. Hijlkema, B. Weber, S. C. Webster, A. Kuhn, and G. Rempe, Phys. Rev. A **73**, 063415 (2006).
[13] A. D. Boozer, A. Boca, R. Miller, T. E. Northup, and H. J. Kimble, Phys. Rev. Lett. **97**, 083602 (2006).
[14] M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, Nature (London) **415**, 39 (2002).
[15] J. D. Miller, R. A. Cline, and D. J. Heinzen, Phys. Rev. A **47**, R4567 (1993).
[16] T. A. Savard, K. M. O'Hara, and J. E. Thomas, Phys. Rev. A **56**, R1095 (1997).
[17] C. W. Gardiner, J. Ye, H. C. Nagerl, and H. J. Kimble, Phys. Rev. A **61**, 045801 (2000).
[18] H. Engler, T. Weber, M. Mudrich, R. Grimm, and M. Weidemuller, Phys. Rev. A **62**, 031402(R) (2000).
[19] K. M. O'Hara, S. R. Granade, M. E. Gehm, T. A. Savard, S. Bali, C. Freed, and J. E. Thomas, Phys. Rev. Lett. **82**, 4204 (1999).
[20] W. Alt, D. Schrader, S. Kuhr, M. Muller, V. Gomer, and D. Meschede, Phys. Rev. A **67**, 033403 (2003).
[21] Y. Miroshnychenko, W. Alt, I. Dotsenko, L. Forster, M. Khudaverdyan, D. Meschede, D. Schrader, and A. Rauschenbeutel, Nature (London) **442**, 151 (2006).
[22] Y. Miroshnychenko, D. Schrader, S. Kuhr, W. Alt, I. Dotsenko, M. Khudaverdyan, A. Rauschenbeutel, and D. Meschede, Opt. Express **11**, 3498 (2003).
[23] J. E. Bjorkholm, Phys. Rev. A **38**, 1599 (1988).
[24] A. M. Bacon, H. Z. Zhao, L. J. Wang, and J. E. Thomas, Appl. Opt. **34**, 5326 (1995).
[25] S. Friebel, C. D'Andrea, J. Walz, M. Weitz, and T. W. Hansch, Phys. Rev. A **57**, R20 (1998).
[26] M. E. Gehm, K. M. O'Hara, T. A. Savard, and J. E. Thomas, Phys. Rev. A **58**, 3914 (1998).
[27] C. D. Wallace, T. P. Dinneen, Kit-Yan N. Tan, T. T. Grove, and P. L. Gould, Phys. Rev. Lett. **69**, 897 (1992).
[28] D. Hoffmann, P. Feng, and T. Walker, J. Opt. Soc. Am. B **11**, 712 (1994).