Journal of the Optical Society of America B
OPTICAL PHYSICS

Storage time of cold Rb atoms in an optical dipole trap formed by a multimode fiber laser

Weilun Hung,[1] Panpan Huang,[1] Feng-Chuan Wu,[1] M. Bruvelis,[1,2] Hau-Yl Xiao,[1] A. Ekers,[1,2,3] and Ite A. Yu[1,*]

[1]Department of Physics and Frontier Research Center on Fundamental and Applied Sciences of Matters, National Tsing Hua University, Hsinchu 30013, Taiwan
[2]University of Latvia, 19 Raina Blvd., Riga LV 1586, Latvia
[3]King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia
*Corresponding author: yu@phys.nthu.edu.tw

Received 9 January 2015; revised 12 February 2015; accepted 12 February 2015; posted 12 February 2015 (Doc. ID 231992); published 9 April 2015

We systematically studied the storage time of ^{87}Rb atoms in an optical dipole trap (ODT) formed by a multimode fiber laser. Storage time is an important parameter in cold atom experiments. If atoms are prepared in the hyperfine state $|F = 2\rangle$, hyperfine-state-changing collisions can transfer these atoms from $|F = 2\rangle$ to $|F = 1\rangle$, whereby the released kinetic energy leads to considerable trap loss. In most ODT experiments, atoms are prepared in the hyperfine state $|F = 1\rangle$. However, two-photon Raman transitions induced by high-power multimode fiber lasers can optically pump these atoms from $|F = 1\rangle$ to $|F = 2\rangle$, and the following hyperfine-state-changing collision results in the trap loss. In this work, our experimental data indicate that both the two-photon Raman transition and the hyperfine-state-changing collision can be inhibited if the atoms are prepared in the single Zeeman sublevel of $|F = 2, m = 2\rangle$ (or $|F = 2, m = -2\rangle$) and an auxiliary magnetic field is applied.

OCIS codes: (020.7010) Laser trapping; (190.5650) Raman effect; (020.2070) Effects of collisions.

http://dx.doi.org/10.1364/JOSAB.32.000B32

Development of the far off-resonant optical dipole traps (ODTs) has become an important tool in ultra-cold atomic and molecular physics. ODTs are often used to achieve a high-density confinement of atoms with minimal perturbation from the trapping field [1–5]. It has been shown that the extension of atom storage time in ODTs can be above 130 s [6]. Because atoms in the higher-energy hyperfine state suffer the hyperfine-state-changing collisional loss [7,8], one often loads the atoms prepared in the lower-energy hyperfine state to the ODT. However, the achievement of high atomic densities at long storage times can still pose experimental challenges when the cost-efficient multimode fiber lasers are used for trapping [9–11].

The use of multimode fiber lasers, with availability of suitable frequency combinations within the broad bandwidth of the laser emission profile with small mode separation, can drive the two-photon Raman transition that optically pumps the population out of the lower-energy hyperfine state, and leads to a significantly increased population of atoms in the higher-energy hyperfine state [10]. This process is followed by the hyperfine-state-changing collision back to the lower hyperfine state, whereby the excess energy is converted into translational motion of atoms that results in an increased trap loss. In this paper, we present an optimized strategy toward the achievement of longer storage times by preparing Rb atoms in the higher-energy hyperfine state $|F = 2\rangle$ of the electronic ground state. Under the conditions of our experiment, the storage time of Rb atoms prepared in the single Zeeman sublevel of $|F = 2, m = 2\rangle$ is better than that of the lower-energy hyperfine state $|F = 1\rangle$. With the atoms only populating in $|F = 2, m = 2\rangle$, we also demonstrated that the two-photon Raman transition induced by the multimode fiber laser can be eliminated.

We used a double magneto-optical trap (MOT) setup for producing cold ^{87}Rb atoms from the background gas. The experimental setup consists of a collection MOT and an experimental MOT. The collection MOT can trap about 1.3×10^9 atoms with a lifetime of about 1 s. The vacuum chamber of the collection MOT is connected to that of the experimental MOT by a stainless steel transfer tube with an inner diameter of 10 mm and a length of 340 mm, allowing for differential pumping of both MOTs. We transferred the atoms trapped in the collection MOT to the experimental MOT by about 200 pulses of a pushing laser beam. After the transfer sequence, we can trap about 8×10^8 atoms in the experimental MOT at a temperature of about 300 μK. The lifetime of the trapped

atoms in the experimental MOT is about 25 s. The atom number quoted in this paper was calibrated by the optical pumping measurement [12,13]. Other details of our double MOT setup can be found in Ref. [12]. The trapping field of our single-beam ODT is provided by a 10.7 W multimode 1064 nm fiber laser (IPG YLR-10-1064-LP). The laser is linearly polarized with a polarization extinction ratio better than 17 dB. We used the method of parametric resonance to measure the beam waist and trap depth [14,15]. The waist of the focused laser beam is approximately 27 μm, and the ODT trap depth of up to 850 μK can be achieved. The cold atoms were loaded into the ODT with two different approaches which will be described in the following two paragraphs.

In the first approach, the cold atoms in the MOT were loaded into the ODT through the procedure of transient dark MOT [16], which can significantly enhance the atomic density as compared with the ordinary MOT shown by our previous work in Ref. [17]. Immediately after the ODT was switched on, we reduced the intensity of the repumping field from 115 to 2.4 $\mu W/cm^2$ at $t = 0$. This reduction of the repumping field intensity makes most of the atoms distributed in $|F = 1\rangle$. In the next 90 ms, the MOT magnetic field gradient was linearly ramped down to zero, and the MOT trapping field detuning was linearly shifted from −18 to −35 MHz. When intending to make the atoms distributed in $|F = 1\rangle$, we completely switched off the repumping field at $t = 92$ ms and turned off the trapping field 4 ms later, allowing the atoms in $|F = 2\rangle$ to be optically pumped to $|F = 1\rangle$ by the trapping field. When intending to make the atoms distributed in $|F = 2\rangle$, we reversed the above timing sequence of switching off the repumping and trapping fields. During the next 40 ms, all the laser and magnetic fields except the ODT field were switched off. We released the atoms in the ODT after different storage time and measured the atom number and temperature with the time-of-flight absorption image. Note that no magnetic field was present during the storage time, and the atoms should uniformly distribute among the degenerate Zeeman states. A representative image of cold atom cloud released from the ODT is shown in Fig. 1(a). Typically, we can trap about 3.4×10^6 (3.0×10^6) atoms with a temperature of 340 μK (170 μK) in the 10.7 W (5.2 W) ODT.

In the second approach, the cold atoms in the MOT were loaded into the ODT through the procedure of evaporating cooling with a time-averaged orbiting potential (TOP) magnetic trap [18]. We optically pumped all the atoms into a single Zeeman state of $|F = 2, m = 2\rangle$ which can be confined in the minimum of the magnetic field. Details of the atom loading from the MOT to the TOP trap and the evaporative cooling procedure with the TOP can be found in Ref. [12]. At the end of the evaporative cooling process, there were 1.3×10^8 atoms at a temperature of 60 μK in the TOP trap. The atoms were then transferred from the TOP to the ODT. To maintain the population in $|F = 2, m = 2\rangle$, we added a homogeneous magnetic field before switching off the TOP. The homogeneous magnetic field was increased from 0 to 4.8 G in 100 ms and kept on during the ODT storage of cold atoms. A representative image of a cold atom cloud released from the ODT is shown in Fig. 1(b). Typically, we can trap about 2.0×10^6 atoms with a temperature of 60 μK in the 5.2 W ODT.

The atoms prepared in all Zeeman states of $|F = 2\rangle$ were loaded to the ODT from the transient dark MOT. They decayed fast as shown by the blue diamonds in Fig. 2. The storage time in the figure is defined as the time that the atom number is decreased by a factor of e^{-1}. Hyperfine-state-changing collisions can transfer atoms from $|F = 2\rangle$ to $|F = 1\rangle$ [7,8]. Because the energy difference of the two hyperfine levels of Rb is about 0.3 K, the released kinetic energy after the collisions is much larger than the trap depth and makes the atoms escape from the ODT, leading to the trap loss. The hyperfine-state-changing collision is a two-body process, and its rate depends on the product of atomic density and speed. In the experiment, a higher ODT laser power captured atoms with a slightly larger collision rate. This may explain a shorter storage time at a larger ODT laser power.

The atoms prepared in all Zeeman states of $|F = 1\rangle$ were also loaded to the ODT from the transient dark MOT. As compared with the $|F = 2\rangle$ atoms, they decayed much more slowly as shown by the black circles in Fig. 2. However, two-photon Raman transitions induced by the multimode fiber laser can optically pump these atoms from $|F = 1\rangle$ to $|F = 2\rangle$.

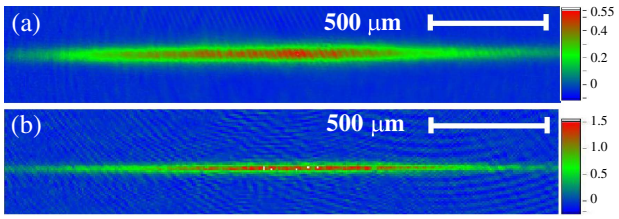

Fig. 1. Absorption images of atom clouds released from the 5.2 W ODT after a time-of-flight of 0.1 ms. The color indicates the absorption depth. (a) The atoms at a temperature of 170 μK loaded into the ODT from the transient dark MOT and (b) atoms at a temperature of 60 μK loaded into the ODT from the TOP trap. The two images were taken by different cameras and have separate legends for the calibration of their signals.

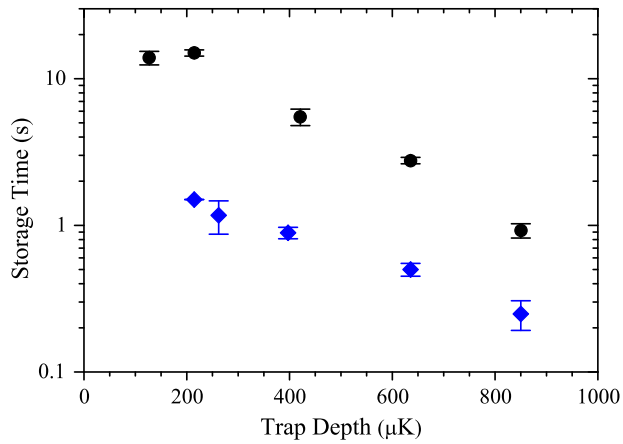

Fig. 2. Storage time of Rb atoms in different hyperfine states as a function of dipole trap depth. The trap depth is linearly proportional to the ODT laser power, and a depth of 850 μk is equivalent to a laser power of 10.7 W. The circular and diamond data points represent storage times of the atoms prepared in the $|F = 1\rangle$ and $|F = 2\rangle$ states, respectively.

These Raman transitions are one-photon far-off-resonant with respect to the $D1$ or $D2$ transition (from $|5S_{1/2}\rangle$ to $|5P_{1/2}\rangle$ or $|5P_{3/2}\rangle$) of the wavelength of 795 or 780 nm, where the natural linewidth of the excited state $|5P_{1/2}\rangle$ or $|5P_{3/2}\rangle$ is about 6 MHz, but can be two-photon resonant with respect to the ground-state hyperfine splitting of 6.835 GHz. To see whether our 1064 nm multimode fiber laser with a linewidth of about 0.7 nm or 190 GHz is able to drive the transition, we measured the mode spacing of the laser. A photodetector (Thorlabs DET410 with a bandwidth of 70 MHz) was employed to directly detect a small fraction of the laser power. We sent the output signal of the detector to a signal/spectrum analyzer (Agilent N9010A with a bandwidth of 7 GHz). Figure 3 shows the power spectrum of the fiber laser. In the spectrum, two adjacent peaks are separated by 3.2 MHz indicating the mode spacing of the laser. The two-photon Raman transition from $|F = 1\rangle$ to $|F = 2\rangle$ can be induced by pairs of two laser modes with a frequency difference equal to the hyperfine splitting of about 6.835 GHz. Because of the ratio of 6.835 GHz to 3.2 MHz, a change of 1.5 kHz in the mode spacing corresponds to a change of about 3.2 MHz in the frequency difference of these two modes. As long as the mode spacing can fluctuate more than 1.5 kHz [19], it is likely that the multimode fiber laser constantly drove the transition from $|F = 1\rangle$ to $|F = 2\rangle$.

The data of black circles in Fig. 2 show that the storage time of these $|F = 1\rangle$ atoms in the 2.7 W ODT is about 16 times longer than that in the 10.7 W ODT. Following the two-photon Raman transition, the hyperfine-state-changing collision of the atoms being pumped to $|F = 2\rangle$ results in the trap loss. Because the ODT field is far detuned such that the Raman transition rate is much smaller than the hyperfine-state-changing collision rate, the trap loss rate of these $|F = 1\rangle$ atoms is determined mainly by the two-photon Raman process. Thus, the storage time depends on the laser intensity or power of the ODT significantly, explaining this large difference.

To ensure atoms only populated in the single Zeeman state of $|F = 2, m = 2\rangle$, we loaded the atoms to the ODT from the TOP trap. A homogeneous magnetic field of 4.8 G was applied during the trapping of the ODT to maintain the magnetic-dipole polarization of the atomic ensemble. When two atoms all come from the outermost Zeeman sublevel $|F = 2, m = 2\rangle$ (or $|F = 2, m = -2\rangle$), their hyperfine-state-changing collision is not possible because of conservation of total angular momentum of the quasi-molecular complex formed by the two colliding atoms. The black squares in Fig. 4 show the atom number in the 5.2 W ODT as a function of time, indicating the storage time is 6.8 s. The storage time of the atoms in the lower-energy hyperfine state $|F = 1\rangle$ under the same ODT depth shown in Fig. 2 is 5.5 s. Note that the density of the atoms in Fig. 4 is higher and the collision rate is larger as compared to those under the same ODT depth in Fig. 2, estimated from the atom number and temperature. In consideration of storage time, preparing atoms in the single Zeeman state $|F = 2, m = 2\rangle$ is better than or comparable to preparing them in the hyperfine state $|F = 1\rangle$. As a reference, we also performed the same measurement, except that the magnetic field was absent during the ODT trapping time. The data from this measurement have the storage time of 0.3 s as shown by the blue diamonds in Fig. 4. Without the magnetic field the atoms were distributed among all degenerate Zeeman states of $|F = 2\rangle$ in the ODT, and they quickly decayed because of the hyperfine-state-changing collision.

With the atoms only populating in $|F = 2, m = 2\rangle$, we performed the following measurement to directly verify whether the multimode spectral profile of our fiber laser can affect the storage time. We first set the direction of the ODT laser polarization parallel to that of the magnetic field. In this configuration, the laser field only drove the π (or $\Delta m = 0$) transition and was not able to pump the population out of $|F = 2, m = 2\rangle$. The storage time measured in such experimental condition is denoted as $\tau_{\|}$. We then set the direction of the ODT laser polarization perpendicular to that of the magnetic field. In this configuration, the laser field drove

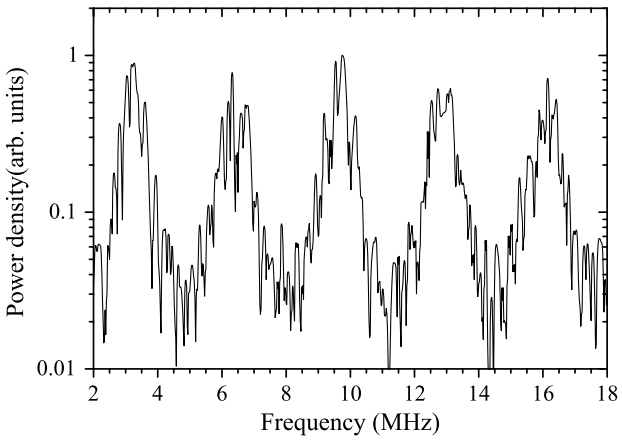

Fig. 3. Power spectrum of our multimode fiber laser. Each peak in the spectrum has a linewidth of about 1.8 MHz. The two adjacent peaks are separated by 3.2 MHz, indicating the mode spacing of the laser.

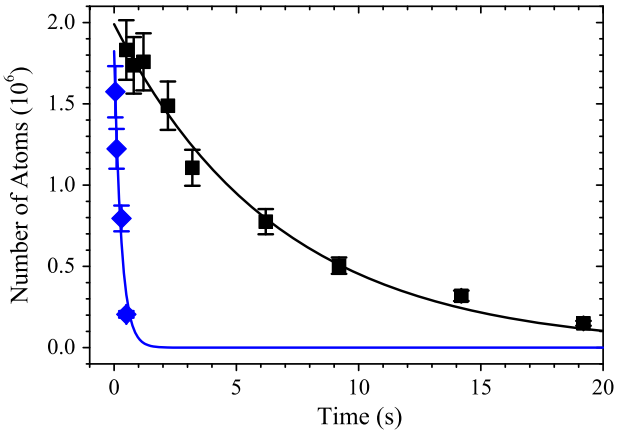

Fig. 4. Atom number in the 5.2 W ODT as a function of time. The atoms were prepared in the single Zeeman state of $|F = 2, m = 2\rangle$ and loaded to the ODT from the TOP trap. The square and diamond data points are the experimental data with and without the presence of homogeneous magnetic field of 4.8 G during the ODT trapping time, respectively. The solid lines are the best fit of exponential decay function. The decay time constants or storage times of the blue and black lines are 0.3 and 6.8 s.

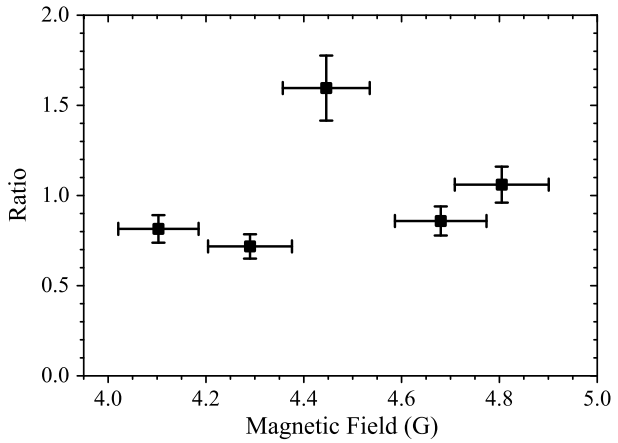

Fig. 5. Ratio of $\tau_{\|}$ to $\tau_{\perp}$ as a function of the magnetic field magnitude, where $\tau_{\|}$ ($\tau_{\perp}$) is the storage time under the condition that the direction of the ODT laser polarization is parallel (normal) to that of the magnetic field. The ODT power was set to 5.2 W. The horizontal error bars result from the fluctuation of magnetic field magnitude.

the $\sigma+$ and $\sigma-$ (or $\Delta m = \pm 1$) transitions and optically pumped the population from $|F=2, m=2\rangle$ to $|F = 2, m = 0\rangle$ when the two-photon resonance was satisfied. The atoms in $|F = 2, m = 0\rangle$ enabled the hyperfine-state-changing collision which caused an additional loss. The storage time measured in such experimental condition is denoted as $\tau_{\perp}$. Figure 5 shows the ratio of $\tau_{\|}$ to $\tau_{\perp}$ as a function of the magnetic field magnitude B. The frequency difference between the energy levels of $|F=2, m=2\rangle$ and $|F=2, m=0\rangle$, induced by a magnetic field of 2.3 G, is equal to the mode spacing of the fiber laser. At $B = 4.6$ G, this frequency difference matches twice the mode spacing. As the match occurs, the two-photon Raman transitions driven by pairs of the Nth and $(N + 2)$th laser modes become resonant and, hence, shorten $\tau_{\perp}$. Experimentally, the ratio of $\tau_{\|}$ to $\tau_{\perp}$ significantly increased at $B = 4.45$ G. Considering the uncertainty in the absolute value of magnetic field magnitude, the difference between the theoretical and experimental values is acceptable. In the measurement of $\tau_{\perp}$, the loss of atoms follows the process of first two-photon Raman transition and then the hyperfine-state-changing collision. Being much smaller than the collision rate, the two-photon Raman transition rate determines the maximum ratio shown in Fig. 5. On the other hand, the hyperfine-state-changing collision rate determines the ratio of two storage times shown in Fig. 4. At other values of B, the Raman transition was out of the resonance such that $\tau_{\|}$ and $\tau_{\perp}$ were approximately equal. The data in Fig. 5 are consistent with the expectation that the two-photon Raman transitions induced by the multimode fiber laser can shorten the storage time. As long as atoms are prepared in a single Zeeman state of $|F = 2, m = 2\rangle$ or $|F = 2, m = -2\rangle$ with a suitable magnetic field or a laser polarization, these Raman transitions can be eliminated.

In conclusion, we have experimentally studied the storage time of the single-beam ODT formed by the multimode fiber laser. Our results show that losses induced by the hyperfine-state-changing collisions can be inhibited by preparing atoms either non-selectively in all Zeeman sublevels $m = -1, 0, 1$ of $|F = 1\rangle$ or selectively in the outermost Zeeman sublevels $m = -2$ or $m = 2$ of $|F = 2\rangle$. Two-photon Raman transitions induced by multimode fiber lasers can still drive the atoms out of these states leading to the trap loss, but the associated loss rates are much smaller than those because of the collisional decay. Importantly, such trap losses can be eliminated altogether by utilizing the selection rules for two-photon Raman transitions when atoms are prepared in the $|F = 2, m = -2\rangle$ or $|F = 2, m = +2\rangle$ states, and the laser polarization is chosen linear and parallel to the magnetic field. Such an arrangement works regardless of the spectral profile of the multimode fiber lasers, and it could be used potentially in ODTs formed by multimode lasers to achieve storage times that are comparable to those achieved in ODTs formed by single-mode lasers.

Minstry of Science and Technology of Taiwan (102-2923-M-007-001, 103-2923-M-007-001, 103-2119-M-007-011); National Tsing Hua University (102N2711E1); US ONR (N000141210514).

Partial support by the trilateral grant of Latvian, Lithuanian, and Taiwanese Research Councils, the EU FP7 IRSES Project COLIMA, the EU FP7 Centre of Excellence FOTONIKA-LV, and US ONR grant N000141210514 is acknowledged. We thank Dr. Ming-Shien Chang, Prof. Nikolay Bezuglov, and Prof. Klaas Bergmann for helpful discussions.

REFERENCES

1. C. S. Adams, H. J. Lee, N. Davidson, M. Kasevich, and S. Chu, "Evaporative cooling in a crossed dipole trap," Phys. Rev. Lett. **74**, 3577–3580 (1995).
2. M. Barrett, J. Sauer, and M. S. Chapman, "All-optical formation of an atomic Bose–Einstein condensate," Phys. Rev. Lett. **87**, 010404 (2001).
3. S. R. Granade, M. E. Gehm, K. M. O'Hara, and J. E. Thomas, "All-optical production of a degenerate fermi gas," Phys. Rev. Lett. **88**, 120405 (2002).
4. T. Weber, J. Herbig, M. Mark, H.-C. Nägerl, and R. Grimm, "Bose–Einstein condensation of cesium," Science **299**, 232–235 (2003).
5. M. W. Zwierlein, C. A. Stan, C. H. Schunck, S. M. F. Raupach, S. Gupta, Z. Hadzibabic, and W. Ketterle, "Observation of Bose–Einstein condensation of molecules," Phys. Rev. Lett. **91**, 250401 (2003).
6. J. He, B.-d. Yang, Y.-j. Cheng, T.-c. Zhang, and J.-m. Wang, "Extending the trapping lifetime of single atom in a microscopic far-off-resonance optical dipole trap," Front. Phys. **6**, 262–270 (2011).
7. J. Weiner, V. S. Bagnato, S. Zilio, and P. S. Julienne, "Experiments and theory in cold and ultracold collisions," Rev. Mod. Phys. **71**, 1–85 (1999).
8. M. Mudrich, S. Kraft, J. Lange, A. Mosk, M. Weidemüller, and E. Tiesinga, "Hyperfine-changing collisions in an optically trapped gas of ultracold cesium and lithium," Phys. Rev. A **70**, 062712 (2004).
9. E. Mimoun, L. De Sarlo, D. Jacob, J. Dalibard, and F. Gerbier, "Fast production of ultracold sodium gases using light-induced desorption and optical trapping," Phys. Rev. A **81**, 023631 (2010).
10. T. Lauber, J. Küber, O. Wille, and G. Birkl, "Optimized Bose–Einstein-condensate production in a dipole trap based on a 1070-nm multifrequency laser: influence of enhanced two-body loss on the evaporation process," Phys. Rev. A **84**, 043641 (2011).
11. S. Kumar, S. Hirai, Y. Suzuki, M. Kachi, M. Sadgrove, and K. Nakagawa, "Simple and fast production of Bose–Einstein condensate in a 1 μm cross-beam dipole trap," J. Phys. Soc. Jpn. **81**, 084004 (2012).

12. H. W. Cho, Y. C. He, T. Peters, Y. H. Chen, H. C. Chen, S. C. Lin, Y. C. Lee, and I. A. Yu, "Direct measurement of the atom number in a Bose condensate," Opt. Express **15**, 12114–12122 (2007).
13. Y. C. Chen, Y. A. Liao, L. Hsu, and I. A. Yu, "Simple technique for directly and accurately measuring the number of atoms in a magneto-optical trap," Phys. Rev. A **64**, 031401(R) (2001).
14. R. Jáuregui, "Nonperturbative and perturbative treatments of parametric heating in atom traps," Phys. Rev. A **64**, 053408 (2001).
15. S. Balik, A. L. Win, and M. D. Havey, "Imaging-based parametric resonance in an optical dipole-atom trap," Phys. Rev. A **80**, 023404 (2009).
16. W. Ketterle, K. B. Davis, M. A. Joffe, A. Martin, and D. E. Pritchard, "High densities of cold atoms in a dark spontaneous-force optical trap," Phys. Rev. Lett. **70**, 2253–2256 (1993).
17. Y. H. Chen, M. J. Lee, W. Hung, Y. C. Chen, Y. F. Chen, and I. A. Yu, "Demonstration of the interaction between two stopped light pulses," Phys. Rev. Lett. **108**, 173603 (2012).
18. W. Petrich, M. H. Anderson, J. R. Ensher, and E. A. Cornell, "Stable, tightly confining magnetic trap for evaporative cooling of neutral atoms," Phys. Rev. Lett. **74**, 3352–3355 (1995).
19. L. Gao, L. Chen, L. Huang, and X. Chen, "Multimode fiber laser for simultaneous measurement of strain and temperature based on beat frequency demodulation," Opt. Express **20**, 22517–22522 (2012).