PHYSICAL REVIEW A **78**, 033415 (2008)

Optically induced fictitious magnetic trap on an atom chip

G. Q. Yang (杨国卿),[1,2,3] H. Yan (颜辉),[1,2,3] T. Shi (石涛),[1,2,3] J. Wang (王谨),[1,2] and M. S. Zhan (詹明生)[1,2,*]

[1]*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China*

[2]*Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China*

[3]*Graduate School, Chinese Academy of Sciences, Beijing 100080, China*

(Received 29 May 2008; published 15 September 2008)

We propose a microtrap realized with a fictitious magnetic field by applying a circularly polarized laser beam. We calculate the potentials and demonstrate that various atom traps, such as the Ioffe-Pritchard trap, double traps, and ring trap, can easily be built by varying the intensity and the position of the laser beams. We show that even an optical lattice can be realized by adding more laser beams properly. Our trap has the advantage as compared to a general atom lattice that the properties of the traps can be manipulated individually.

DOI: 10.1103/PhysRevA.78.033415 PACS number(s): 37.10.Gh, 32.80.Qk, 32.60.+i

With the development of integrated and miniaturized technology, the atom chip has emerged recently as a powerful and attractive tool for handling microscopic ultracold atoms [1–9]. An intriguing feature of miniature atom optical elements is the possibility of constructing various complicated forms of potentials utilizing magnetic [9], electrostatic [10], optical [11–13], and even hybrid fields [14] to create microstructures on a chip surface. The most successful application of atom chips is to realize Bose-Einstein condensates (BEC) [4] and to manipulate coherent ensembles of ultracold atoms [7]. Although current microfabrication techniques allow the production of high quality electromagnetic fields which can be controlled spatially and temporally, there are still some latent disadvantages including spin-flip losses near metallic surfaces, strong atom-surface interactions, and the geometrical imperfections of microstructures, which have been shown recently to limit the development of the atom chip [15–18]. Besides the intrinsic points mentioned above, some limitations due to imperfect design may also be severe. Usually, near the chip surface there needs to be a uniform bias field [9], and inconsistent designs are deleterious to integration and to parallel operation. So it is necessary to limit the bias field locally.

Here, we demonstrate a new hybrid atom chip based on an optically induced fictitious magnetic trap (OFMT). Atoms in the circularly polarized laser beam can act as though they were in a real magnetic field [19–21]. When a laser beam replaces the uniform bias magnetic field, the resulting optically induced fictitious magnetic traps have distinguishing characteristics: (a) The interaction between atoms and the chip surface can be highly depressed since OFMTs are higher from a chip with strong confinement; (b) the fictitious magnetic field really works locally since the intensity of the laser decreases rapidly along the radius, which is meaningful for integration and for parallel operation. It will be shown that precise measurement and quantum-information processing both benefit from these advantages.

We first introduce the simple concept of a fictitious magnetic field. If an alkali-metal atom in ground state is considered, when irradiated by a laser field tuned near the transitions of D lines, the ac Stark shift of an alkali metal can be approximated as [21]

$$U=\frac{|\langle nS_{1/2}|er|nP_{1/2}\rangle|^2}{9}\left[\left(\frac{1}{\Delta_{1/2}}+\frac{2}{\Delta_{3/2}}\right)+\left(\frac{1}{\Delta_{3/2}}-\frac{1}{\Delta_{1/2}}\right)\varepsilon^{*}g_F m_F\right]I(x,y,z), \tag{1}$$

where g_F is the Lande g factor, m_F is the magnetic quantum number, ε^{*} here characterizes the laser polarization, and $I(x,y,z)$ is the laser field intensity. When the laser is right circularly polarized and the detuning, $\Delta_{1/2}=\hbar\omega-(E_{nP_{1/2}}-E_{nS_{1/2}})$ and $\Delta_{3/2}=\hbar\omega-(E_{nP_{3/2}}-E_{nS_{1/2}})$, satisfy $\Delta_{3/2}=-2\Delta_{1/2}$, then

$$U=\mu_B B^{*} g_F m_F, \tag{2}$$

where $B^{*}=\frac{|\langle nS_{1/2}|er|nP_{1/2}\rangle|^2}{3\mu_B\Delta_{3/2}}I(x,y,z)$ and μ_B is the Bohr magneton.

The direction of B^{*} is normal to equiphase surface. The curvature radius of the equiphase surface R is determined by the Rayleigh length z_R. When $z\ll z_R$, $R\sim z^2_R/z$, the equiphase surface can be well approximated as a plane. Since the expansion of the trapped atoms is smaller than the beam waist, and since z_R is usually many times the beam waist, the direction of the fictitious field is approximately along the z axis. In this case, the field can be written as

$$\vec{B}^{*}=\frac{\beta}{\mu_B}\exp\left(-2\frac{x^2+y^2}{\omega_0^2}\right)\begin{pmatrix}0\\0\\1\end{pmatrix}, \tag{3}$$

where $\beta=\frac{|\langle nS_{1/2}|er|nP_{1/2}\rangle|^2}{3\Delta_{3/2}}I_0$ is the intensity of the laser waist which determines the depth and type of traps.

Before calculating the potentials, we must demonstrate one key point which is the fundamental of our scheme, although fully studied in theory and experiment from the 1960s [19–24]. According to [19,23], the efficient Hamil-

*Author to whom correspondence should be addressed; mszhan@wipm.ac.cn

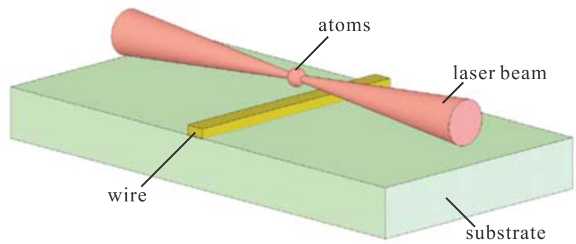

FIG. 1. (Color online) Scheme of OFMT. The real magnetic field is produced by the current in the wire on the substrate. The atoms feel a fictitious magnetic field if they are in the laser field above the chip. The real and the fictitious magnetic field will create a three-dimensional field minimum above the wire, and the atoms are trapped there.

tonian describing interaction between atom and circularly polarized laser has the same form of atom in a real magnetic field when the laser has a special wavelength. The magnetic dipole will feel no difference between the real and the fictitious field. When the atoms are in a fictitious field, the field will offer a quantization axis along the light propagating direction [20,21,24]. When atoms are in the hybrid real-fictitious field, the total amplitude and direction of field is under the rule of vector operation. The related experiment was carried out [24].

We consider the usual traditional two-dimensional quadrupole potential which is formed in the vicinity of a current-carrying wire [9]. The minimum is created by adding an external homogeneous field with a pair of large Helmholtz coils. When this inconsistent part is replaced by a Gaussian laser beam, the corresponding OFMT becomes a versatile tool for atom optics.

The basic structure of the OFMT is shown in Fig. 1. A Gaussian laser beam above the atom-chip results in fictitious magnetic field along the z axis, and a current wire also creates a real magnetic field. As shown above, we can consider the total field directly. When the laser is tuned to the critical frequency [22], the total equivalent magnetic field for atoms is

$$\vec{B}=\begin{pmatrix}0\\0\\B^*\end{pmatrix}+\frac{I\mu_0}{2\pi(x^2+z^2)}\begin{pmatrix}z\\0\\-x\end{pmatrix}, \tag{4}$$

where μ_0 is the permeability of free space. Because of the Gaussian profile of the fictitious field, there will be a minimum in the total field in the x-y plane ($z=0$). It is amazing that atoms will also be confined in the y direction. So we have a three-dimensional potential with the simplest potential structure as compared with its traditional counterpart. This is one of its most important characteristics. The position can be adjusted by moving the light and the depth dependent on I_0, but the current on the chip determines the maximum depth and also the type of the trap.

According to the localization of the fictitious field, the minimum value of the total field may be nonzero. Then the OFMT can be considered as an Ioffe-Pritchard trap. It is possible to create BEC with the simplest miniature structure in place of a Z trap. The distribution of the field in the x-z plane is shown in Fig. 2. The vector graph is shown here. It is obviously not a quadrupole potential but an Ioffe-Pritchard one. The total magnetic field outside the laser beam is the same as the field created by the wire. This means that the fictitious field only exists around the trap which is quite different from a homogeneous bias field. Any cooling method [25] for ground-state atoms in traditional static magnetic traps can conveniently be applied in an OFMT, because atoms in the hybrid potential behave as in a real magnetic field. Although the tensor component of light shift also affects the Zeeman substructure, however the corresponding frequency shift is much smaller [23]. It should be considered only when the light is near resonance [23,26]. If the detuning of light is much larger than the hyperfine structure, the frequency shift is generally negligible, which was comfirmed by experiment [27]. Still, under some conditions, such as clock transition [28], we should consider this term. In the present case, frequency shift with order of Hz will not affect the structure of traps nor evaporative cooling. Moreover, with the Gaussian laser beam, the atom cloud in an OFMT can be compressed without having to move towards the wire, which really can depress the heating and the losses from atom-surface interactions efficiently [15]. The center of the OFMT can be shifted flexibly by modulating the parameters of the laser beam, which allows the loading rate to be improved. All of these properties, in fact, meet the requirement of high efficiency BEC creation [29].

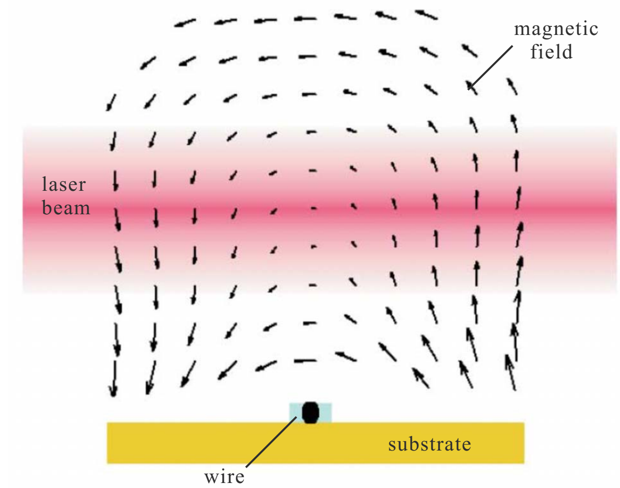

FIG. 2. (Color online) The Ioffe-Pritchard trap based on an optically induced magnetic trap. The real magnetic field is produced by the current in the wire on the substrate. The red part represents the laser beam. The arrows show the direction and strength that the total field atoms feel.

In order to analyze the OFMT quantitatively, we calculated the depth with the following parameters: $I=2$ A, $\omega_0=100$ μm, $\lambda=790$ nm, and the axis of laser beam 0.2 mm over the chip surface. If we adjust the power P of laser beam, the trap depth will change simultaneously (Fig. 3). When $P=4.1$ W, the depths are about 0.21 mK in the x direction and 0.67 mK in the y direction. When $P=7.9$ W, the depths are about 0.8 mK in the x direction and 1.28 mK in the y direction. The difference arises because the real magnetic field

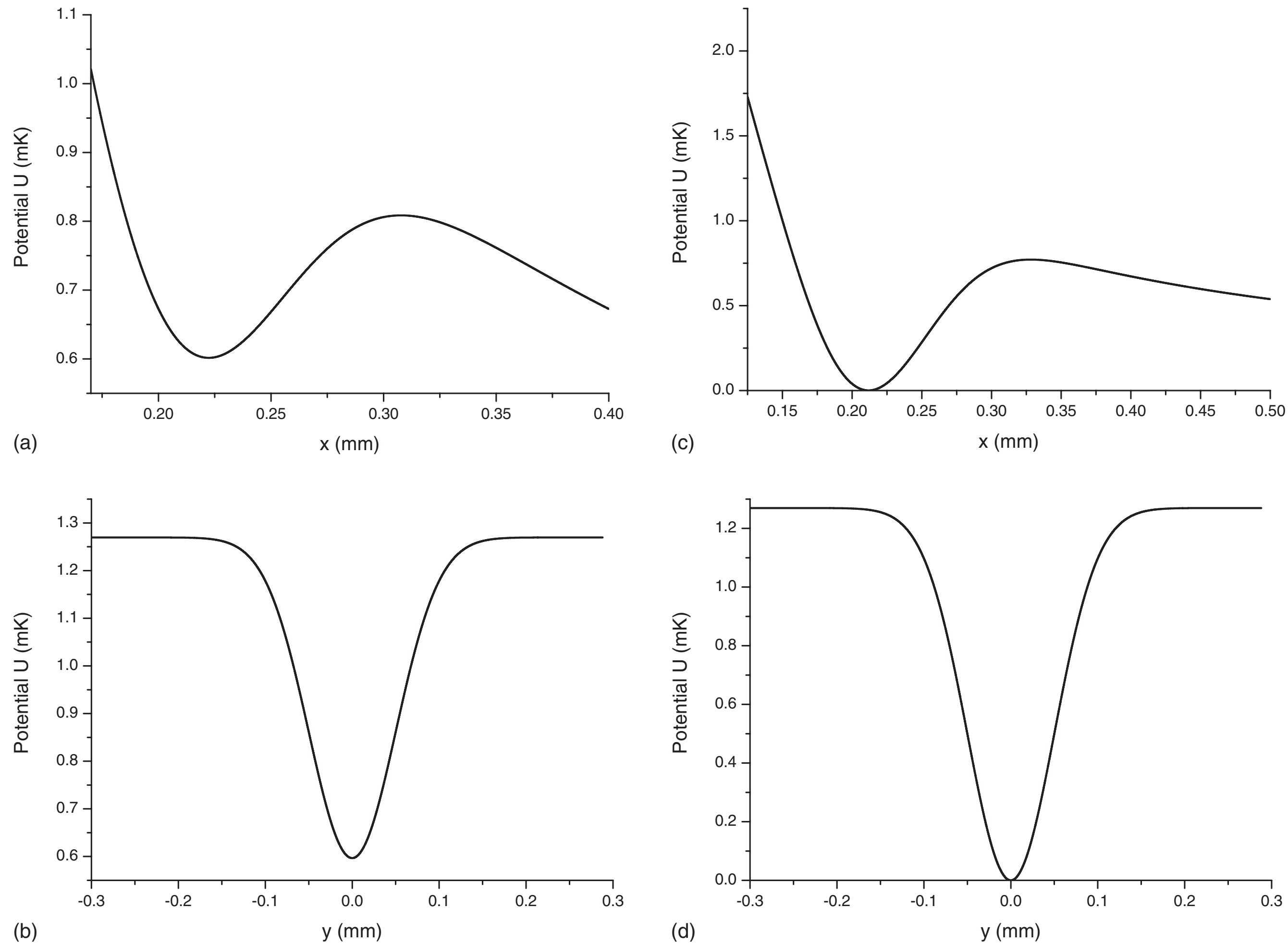

FIG. 3. The potentials with different laser power P: (a) x direction and (b) y direction with $P=4.1$ W; (c) x direction and (d) y direction with $P=7.9$ W.

decreases in the x direction and stays constant in the y direction. But OFMTs have much larger spring constant in these two directions as compared with U or Z traps [9]. This means that OFMTs are much deeper at the same height. So OFMTs can trap many more atoms. This is very important in atom-chip experiments, for sometimes the number of atoms in the trap limits the practicability of an experiment. As to the z direction, since the gradient of field is mainly determined by the real magnetic field, the situation is the same as for traditional traps.

If the power of the laser is very large, the fictitious magnetic field may exceed the real field also because of localization of the laser beam. In this case, the minimum points of the total field are zero, forming a ring in the x-y plane. Two or more beams can be partially superposed to create larger ring traps (Fig. 4). The OFMT may be a good candidate for the incoherent atom-chip interferometer proposed in [30]. For the traditional atom chip, creating a ring waveguide with one or more traps as ports will sacrifice some wire and chip area [9], and also, the technique will be complex. For the OFMT, all we need are one single wire and several laser beams. A single wire creates the real magnetic field. Some laser beams create a large radius loop, while another laser forms the port. All parameters of the interferometer can easily be modified using the laser. Moreover, the example in [30] required the ring to be 10 μm above the chip surface to have a large magnetic field gradient. In fact, at this distant, atoms in the waveguide hardly exist for 10 s because of strong atom-surface interactions. This directly limits the sensitivity of the interferometer. This difficulty can easily be solved by using an OFMT. As shown above, OFMTs have a high field gradient even much higher above the chip surface. So the atoms can have larger velocity while preserving a longer trap lifetime. The higher sensitivity and easy realization are also benefits of the OFMT.

Another advantage of the OFMT is that it is convenient to manipulate atoms by adjusting the laser beams. When two laser beams with the same waist radius overlap partially, one can modify the relative intensity of two beams to move atoms around. We show in Fig. 5 two Gaussian laser beams superposed along the y direction. The distance between their centers equals their waist radius 0.1 mm. We assume the power of one laser is P_1 and the other is P_2. First, $P_1=P_0$, $P_2=0$, the trap is at $y=-0.05$ mm. Then turning on P_2 and tuning to P_0 adiabatically, the position of the trap moves to $y=0$ mm. But the total power is not big enough to form a ring trap. Then we turn off P_1. The atoms are at $y=0.05$. It is clear that the potential depth becomes larger in this process,

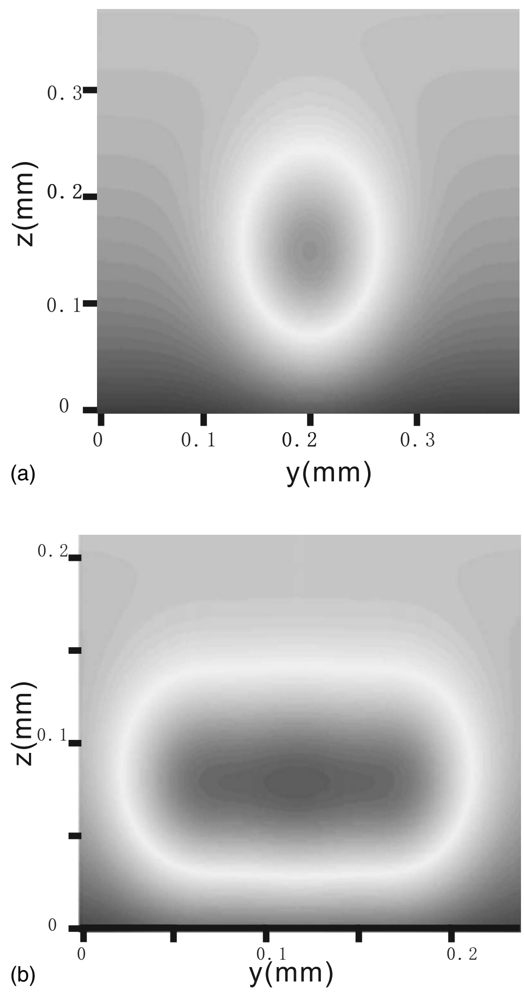

FIG. 4. Ring traps with (a) single laser beam and (b) two laser beams which superpose along the y direction. The brightest parts are the traps.

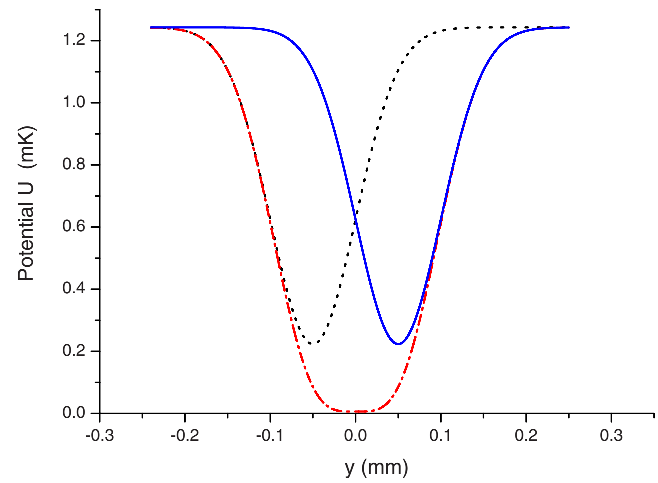

FIG. 5. (Color online) The process of transferring atoms. At the beginning, when $P_1=P_0$, $P_2=0$, the trap is at $y=-0.05$ mm (dotted curve); then turning on the second laser slowly while holding the first one, the trap position will move along the y direction and the potential becomes deeper, when $P_1=P_2=P_0$, the trap is at $y=0$ mm (dashed-dotted curve); keeping the second laser and turning off the first one, the trap continues moving along the y direction, when $P_1=0$, $P_2=P_0$, the trap is at $y=0.05$ mm and the depth returns back (solid curve).

which should depress the loss rate during the transfer. Similar to the process above, we can realize atom splitting with three beams. We first superpose three beams to build an Ioffe-Pritchard trap. Decreasing the power of laser in the middle, whereas increasing others, the single trap is then transformed into a double trap. This splits the atoms into two groups. Of course, the converse process is a beam combiner. The angle of splitter can be modified from 0 to π.

Now we demonstrate that the OFMT is also an ideal candidate for quantum computation. Several schemes for the realization of a quantum logic gate with an atom chip have recently been proposed [31,32]. However, because of the weak spring constant, the trap is very close to the chip surface for tight confinement and for certain shapes with special vibrational states. Since the bias magnetic field influences the distribution in one direction only, a single atom is weakly confined in another dimension which makes operation difficult. At the same time, the structure is very complex for suppressing the Majorana loss [15]. In this case, the single atom experiences a complicated surface environment and the loss rate becomes very large, so it is not a practical design and is hard to achieve. Extension is another problem. Parallel operation is impossible, if the bias field for one gate affects all the gates.

These problems can be solved successfully with the OFMTs. With a microlens array, a tightly confined OFMT lattice can be created on an atom chip (Fig. 6). Each laser beam only creates one site and does not disturb other sites. The lattice constant is determined by the microlens and each site can be operated individually with a vertical-cavity surface-emitting laser (VCSEL) array [11]. The sites positions are set arbitrarily which avoids decoherence from the surface.

In order to estimate the properties of the system, we choose parameters similar to Ref. [33]. For a trap depth of $U=1$ mK, a beam waist of $\omega_0=3.5$ μm, far-off resonant trap (FORT) [33] at $\lambda=850$ nm needs $P=44$ mW, while OFMT needs $P=7.6$ mW. At a large waist, several BEC ensembles can be obtained at the same time, which is very useful to study a large BEC reservoir or create a quantum register. Also, the lattice constant can be modified by the distance between the laser beams, which is impossible in other schemes.

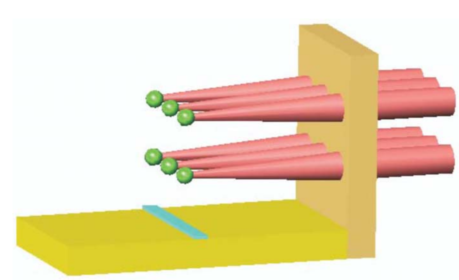

FIG. 6. (Color online) Laser beam is modified by microlens. The lattice constant is the same as that of the microlens array.

Only one problem we should consider is heating due to photon scattering. In our scheme, we use a special light with wavelength between the $D1$ and $D2$ line of alkali-metal atoms. The photon scattering rate of all the alkali-metal atom had been shown in [22]. According to the data, our scheme will work well for rubidium and cesium atoms. In [33], the photon scattering rate is 24 Hz. In our scheme the rates for the two species atoms are 154 Hz and 30 Hz. The lifetime of atoms in a trap with similar parameters in [33] is about several minutes or longer [34]. Obviously, the lifetime of atoms in our scheme is long enough for most experiments.

In summary, an optically induced fictitious magnetic trap is proposed. We have shown that various traps can be created by modifying the "bias" laser beam. This provides a simple atom-chip system which can be applied in precise measurements and in quantum-information processing.

We acknowledge the financial support of National Basic Research Program of China under Grants No. 2006CB921203 and No. 2005CB724505/1 and of the National Natural Science Foundation of China under Grant No. 10774160, and of funds from the Chinese Academy of Sciences.

[1] J. D. Weinstein and K. G. Libbrecht, Phys. Rev. A **52**, 4004 (1995).
[2] J. Fortágh, A. Grossman, C. Zimmermann, and T. W. Hänsch, Phys. Rev. Lett. **81**, 5310 (1998).
[3] J. Denschlag, D. Cassettari, and J. Schmiedmayer, Phys. Rev. Lett. **82**, 2014 (1999).
[4] W. Hänsel, P. Hommelhoff, T. W. Hänsch, and J. Reichel, Nature (London) **413**, 498 (2001).
[5] D.-W. Wang, M. D. Lukin, and E. Demler, Phys. Rev. Lett. **92**, 076802 (2004).
[6] Y.-J. Wang, D. Z. Anderson, V. M. Bright, E. A. Cornell, Q. Diot, T. Kishimoto, M. Prentiss, R. A. Saravanan, S. R. Segal, and S. Wu, Phys. Rev. Lett. **94**, 090405 (2005).
[7] A. Günther, S. Kraft, M. Kemmler, D. Koelle, R. Kleiner, C. Zimmermann, and J. Fortágh, Phys. Rev. Lett. **95**, 170405 (2005).
[8] S. Aubin, S. Myrskog, M. H. T. Extavour, L. J. LeBlanc, D. McKay, A. Stummer, and J. H. Thywissen, Nat. Phys. **2**, 384 (2006).
[9] J. Fortágh and C. Zimmermann, Rev. Mod. Phys. **79**, 235 (2007).
[10] T. Kishimoto, H. Hachisu, J. Fujiki, K. Nagato, M. Yasuda, and H. Katori, Phys. Rev. Lett. **96**, 123001 (2006).
[11] R. Dumke, M. Volk, T. Müther, F. B. J. Buchkremer, G. Birkl, and W. Ertmer, Phys. Rev. Lett. **89**, 097903 (2002).
[12] M. Hammes, D. Rychtarik, H.-C. Nägerl, and R. Grimm, Phys. Rev. A **66**, 051401(R) (2002).
[13] K. Christandl, G. P. Lafyatis, S.-C. Lee, and J.-F. Lee, Phys. Rev. A **70**, 032302 (2004).
[14] C. García-Segundo, H. Yan, and M. S. Zhan, Phys. Rev. A **75**, 030902(R) (2007).
[15] C. Henkel, S. Pötting, and M. Wilkens, Appl. Phys. B: Lasers Opt. **69**, 379 (1999).
[16] M. P. A. Jones, C. J. Vale, D. Sahagun, B. V. Hall, and E. A. Hinds, Phys. Rev. Lett. **91**, 080401 (2003).
[17] D. M. Harber, J. M. McGuirk, J. M. Obrecht, and E. A. Cornell, J. Low Temp. Phys. **133**, 229 (2003).
[18] P. K. Rekdal, S. Scheel, P. L. Knight, and E. A. Hinds, Phys. Rev. A **70**, 013811 (2004).
[19] C. Cohen-Tannoudji and J. Dupont-Roc, Phys. Rev. A **5**, 968 (1972).
[20] K. L. Corwin, S. J. M. Kuppens, D. Cho, and C. E. Wieman, Phys. Rev. Lett. **83**, 1311 (1999).
[21] C. Y. Park, J. Y. Kim, J. M. Song, and D. Cho, Phys. Rev. A **65**, 033410 (2002).
[22] D. Cho, J. Korean Phys. Soc. **30**, 373 (1997).
[23] B. S. Mathur, H. Tang, and W. Happer, Phys. Rev. **171**, 11 (1968).
[24] M. Zielonkowski, J. Steiger, U. Schunemann, M. DeKieviet, and R. Grimm, Phys. Rev. A **58**, 3993 (1998).
[25] W. D. Phillips, Rev. Mod. Phys. **70**, 721 (1998).
[26] J. Y. Kim, J. S. Lee, J. H. Han, and D. Cho, J. Korean Phys. Soc. **42**, 483 (2003).
[27] C. Y. Park, H. Noh, C. M. Lee, and D. Cho, Phys. Rev. A **63**, 032512 (2001).
[28] J. Y. Kim and D. Cho, J. Korean Phys. Soc. **37**, 744 (2000).
[29] E. A. Cornell and C. E. Wieman, Rev. Mod. Phys. **74**, 875 (2002).
[30] Y. Japha, O. Arzouan, Y. Avishai, and R. Folman, Phys. Rev. Lett. **99**, 060402 (2007).
[31] P. Treutlein, T. W. Hänsch, J. Reichel, A. Negretti, M. A. Cirone, and T. Calarco, Phys. Rev. A **74**, 022312 (2006).
[32] E. Charron, M. A. Cirone, A. Negretti, J. Schmiedmayer, and T. Calarco, Phys. Rev. A **74**, 012308 (2006).
[33] M. Weber, J. Volz, K. Saucke, C. Kurtsiefer, and H. Weinfurter, Phys. Rev. A **73**, 043406 (2006).
[34] M. Saffman and T. G. Walker, Phys. Rev. A **72**, 022347 (2005).