A novel controllable double-layer magnetic lattice with cold atoms

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Received March 31, 2004

We propose a novel array of controllable double-well magnetic microtraps for cold atoms by using an array of square current-carrying wires and two additional bias magnetic fields. Arrays of double layer magneto-optical traps (MOTs) and Ioffe traps can be constructed by using same wire configurations and different currents and bias fields. Furthermore, the array of double-well magnetic microtraps can be continuously evolved as an array of single-well magnetic microtraps by reducing the currents in the wires. Our study shows that our scheme can be used to realize a controllable double-layer magnetic lattice with cold atoms, to form array of Bose-Einstein condensations (BECs), or to study atom interference, and so on.

OCIS codes: 020.7010, 140.7010, 140.3320, 020.2070.

In recent years, the investigation of atomic optical lattices (AOLs)[1−3], atomic magneto-optical lattices (AMOLs), and atomic magnetic lattices (AMLs)[4,5] has become a hot research subject in atomic physics and atomic optics. AOL has been widely applied in the studies of ferromagnetic and antiferromagnetic properties[6], Sisyphus cooling and trapping dynamics[7−9], and tunneling dynamics[10,11], atomic interference[12], properties of Bose-Einstein condensation (BEC)[13,14], and so on. Since Hänsch's group first demonstrated surface magneto-optical trapping (MOT) and BEC in a microtrap formed by nanofrabricated current-carrying wires on a sapphire substrate[15], the research on "atom chip" has become a new focus in atom and quantum physics research. Such atom chip has many robust and wide applications in the fields of ultracold atomic physics, atom and quantum optics, even in the studies of the fundamental physics questions and quantum information processing[16]. In 2003, the lattice of surface microtraps for cold atoms was demonstrated experimentally[17].

In this letter, we propose a new scheme to form a lattice of controllable double-well magnetic microtraps for cold atoms by using an array of square current-carrying wires and two bias magnetic fields, as shown in Fig. 1. In our scheme, all of the wires on the xoy plane carry the same current I, and the size of each square wire is $2a \times 2a$, the distance between the adjacent two square wires is c. The size e of the gap between two wires in each square one is very small (30 μm as the wire diameter $d = 20$ μm). The unit cell of the array of the square wires is shown in Fig. 1(b). To realize the manipulation and control of cold atoms along the z-direction, square holes ($2b \times 2b$) at the center of each square wire are excavated on the substrate. Of course, without the square holes, our scheme can also be used to form an array of single-well surface magnetic microtraps. In Fig. 1, the used parameters are respectively: $2a = 200$ μm, $2b = 150$ μm, $c = 250$ μm. In this case, we can obtain 1×10^4 square-wire cells (i.e., 100×100 microtraps) in an area of 2.5×2.5 cm^2.

The spatial distribution of the magnetic field $\mathbf{B}$ from our array of square current-carrying wires combined with two bias fields B_{z0} and B_{x0} can be calculated by

$$\mathbf{B}_x = \frac{\mu_0 I \hat{\mathbf{x}}}{4\pi} \sum_{m=-N}^{N} \sum_{n=-N}^{N} \left(\int_{a+mc}^{-a+mc} \frac{z}{\left((x+a-nc)^2+(y-y')^2+z^2\right)^{3/2}} \mathrm{d}y' + \int_{-a+mc}^{a+mc} \frac{z}{\left((x-a-nc)^2+(y-y')^2+z^2\right)^{3/2}} \mathrm{d}y' \right) - B_{x0}\hat{\mathbf{x}}, \quad (1)$$

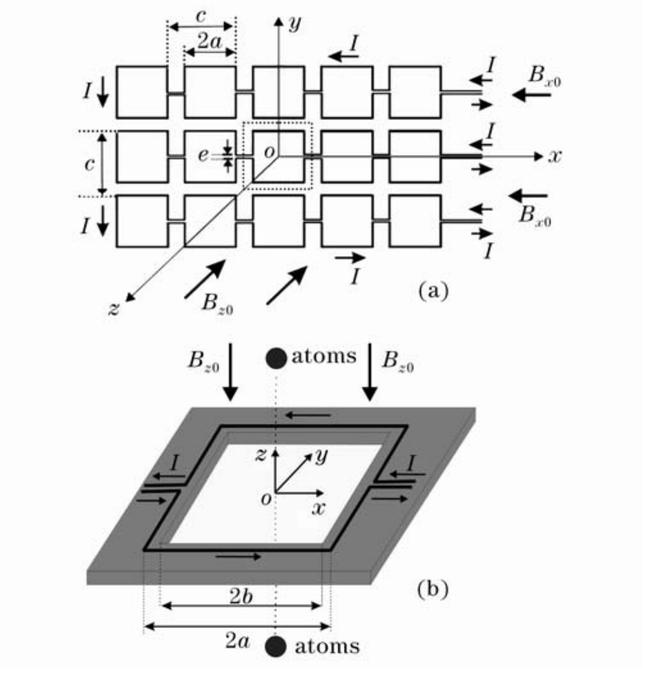

Fig. 1. (a) Schematic diagram of our two-dimensional (2D) arrays of controllable double-well magnetic microtraps. (b) Scheme of unit cell in our square-wire layout fabricated on a substrate with a square hole at each cell center.

$$\mathbf{B}_y = \frac{\mu_0 I \hat{\mathbf{y}}}{4\pi} \sum_{m=-N}^{N} \sum_{n=-N}^{N} \left(\int_{a+nc}^{-a+nc} \frac{-z}{\left((x-x')^2 + (y-a-mc)^2 + z^2\right)^{3/2}} \mathrm{d}x' + \int_{-a+nc}^{a+nc} \frac{z}{\left((x-x')^2 + (y+a-mc)^2 + z^2\right)^{3/2}} \mathrm{d}x' \right), \quad (2)$$

$$\mathbf{B}_z = \frac{\mu_0 I \hat{\mathbf{z}}}{4\pi} \sum_{m=-N}^{N} \sum_{n=-N}^{N} \left(\int_{a+mc}^{-a+mc} \frac{-(x+a-nc)}{\left((x+a-nc)^2 + (y-y')^2 + z^2\right)^{3/2}} \mathrm{d}y' + \int_{-a+mc}^{a+mc} \frac{-(x-a-nc)}{\left((x-a-nc)^2 + (y-y')^2 + z^2\right)^{3/2}} \mathrm{d}y' + \int_{a+nc}^{-a+nc} \frac{y-a-mc}{\left((x-x')^2 + (y-a-mc)^2 + z^2\right)^{3/2}} \mathrm{d}x' + \int_{-a+nc}^{a+nc} \frac{y+a-mc}{\left((x-x')^2 + (y+a-mc)^2 + z^2\right)^{3/2}} \mathrm{d}x' \right) - B_{z0}\hat{\mathbf{z}}, \quad (3)$$

where $2N$ is the number of square-wire cells in the x- and y-directions.

From Eqs. (1)—(3), the contours of the magnetic field $B = \sqrt{B_x^2 + B_y^2 + B_z^2}$ at the vertical and horizontal planes are calculated, and the results are shown in Fig. 2. When $I = 0.01$ A, $B_{z0} = 0.25$ G, and $B_{x0} = 0$, there are two arrays of quadrupole magnetic traps with a $B = 0$ value at each well center, which are located at $x_0 = y_0 = \pm 250k$ μm, and $z_0 = \pm 93$ μm (here k is the integer number, i.e., $k = 0, 1, 2, 3, \cdots$). If another horizontal bias field B_{x0} is added, the above two arrays of quadrupole traps will become two arrays of Ioffe traps with nonzero-B well centers. When $I = 1$ A, $B_{z0} = 22$ G, and $B_{x0} = 6$ G, we obtain $B_{\min} = 1.4$ G at each trap center, which are located at $x_0 = \pm 36 + 250k$ μm, $y_0 = \pm 250k$ μm, and $z_0 = \pm 83$ μm. It is clear from Fig. 2 that the distance between two well centers can be controlled by adjusting the current I in the wires (or by changing the added bias field B_{z0}), which can be used to prepare a controllable double-layer magnetic lattice.

To know the characteristics of each magnetic micro-well of our traps, we calculate the spatial distributions of the magnetic fields, gradients and curvatures in the x-, y-, and z-directions. When $I = 0.01$ A, $B_{z0} = 0.25$ G, $B_{x0} = 0$, the gradients of each quadrupole trap are $\left|(\frac{\partial B}{\partial x})\right| = \left|(\frac{\partial B}{\partial y})\right| \approx 13$ G/cm, $\left|(\frac{\partial B}{\partial z})\right| \approx 26$ G/cm, which are suitable to construct a standard MOT. While $I = 1$ A, $B_{z0} = 22$ G, and $B_{x0} = 6$ G, we obtain

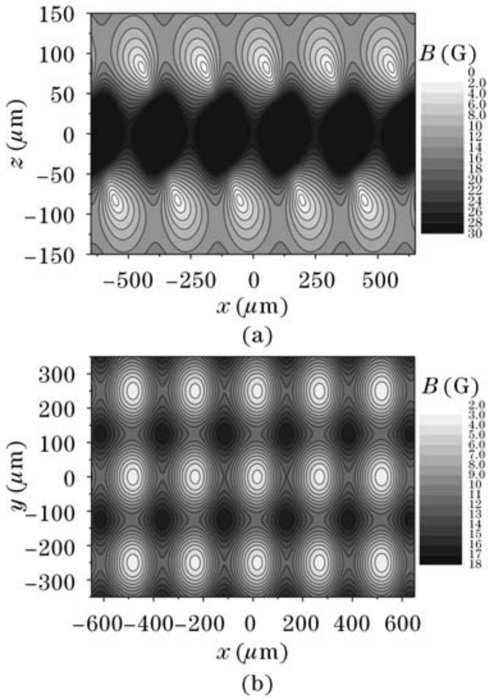

Fig. 2. Magnetic field contours from our scheme of magnetic microtrap array on the xoz plane (a) and xoy plane (b). The white zone shows the minimum B-value field, and the interval of contours is 2 G in (a) and 1 G in (b). $I = 1$ A, $a = 100$ μm, $c = 250$ μm, $B_{z0} = 22$ G, $B_{x0} = 6$ G. (a) $y = 0$; (b) $z = 83.6$ μm.

$\Delta B(x)_{\max} \geq 11$ G within $\Delta x = x - x_0 = \pm 50$ μm, $\Delta B(y)_{\max} \geq 9.5$ G within $\Delta y = y - y_0 = \pm 50$ μm, and $\Delta B(z)_{\max} \geq 6.5$ G within $\Delta z = z - z_0 = 50$ μm, where (x_0, y_0, z_0) are the position coordinates of each trap center. The maximal magnetic-field gradients are $\left|(\frac{\partial B}{\partial x})_{\max}\right| \approx 1.46 \times 10^3$ G/cm, $\left|(\frac{\partial B}{\partial y})_{\max}\right| \approx 1.73 \times 10^3$ G/cm, and $\left|(\frac{\partial B}{\partial z})_{\max}\right| \approx 2.85 \times 10^3$ G/cm, respectively, and we have the curvatures $(\frac{\partial^2 B}{\partial x^2}) \approx 2.04 \times 10^6$ G/cm^2, $(\frac{\partial^2 B}{\partial y^2}) \approx 1.48 \times 10^6$ G/cm^2, and $(\frac{\partial^2 B}{\partial z^2}) \approx 2.71 \times 10^7$ G/cm^2 at each well center. The results are shown in Figs. 3(a)—(c). These results are far greater than normal BEC magnetic traps (usually the corresponding maximal gradient and curvature are ~ 200 G/cm and 300 G/cm^2 respectively, whereas the used typical currents I are about 25—200 A). So each microscopic magnetic trap of our scheme is deep and tight enough to realize an array of controllable double-layer BECs. After preparing a MOT with a number of $\sim 10^9$ atoms in a low vacuum vapor cell, we can load the cold atoms into our arrays of MOTs (in the case of $I = 0.01$ A, $B_{z0} = 0.25$ G, and $B_{x0} = 0$) in a high vacuum cell by using the low-velocity intense atomic beam with a larger divergent angle. When the conditions of $I = 0.01$ A, $B_{z0} = 0.25$ G, and $B_{x0} = 0$ are changed as $I = 1$ A, $B_{z0} = 22$ G, $B_{x0} = 6$ G, the cold atoms in two MOT arrays can be loaded adiabatically into our arrays of Ioffe traps, and then the trapped atoms are further cooled to around recoil temperature, realizing BECs in each magnetic trap by using the forced rf evaporation[18,19].

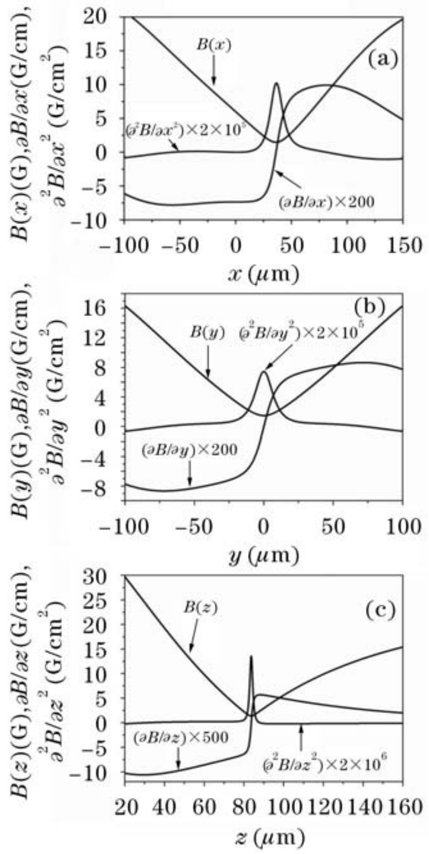

Fig. 3. Distributions of magnetic fields, gradients and curvatures in (a) x-, (b) y-, and (c) z-direction for our magnetic microtrap array. $I = 1$ A, $a = 100$ μm, $B_{z0} = 22$ G, $B_{x0} = 6$ G.

In consideration of the interaction between a neutral atom with a magnetic dipole moment μ and an inhomogeneous magnetic field B, the trapping potential for cold atoms depends on the position, and is given by

$$U_{\text{mag}} = -\boldsymbol{\mu} \cdot \mathbf{B} = g_F m_F \mu_{\text{B}} B, \quad (4)$$

where m_F is the magnetic quantum number, g_F is the Lande G-factor, and μ_{B} is the Bohr magneton. When $\boldsymbol{\mu} \cdot \mathbf{B} < 0$, the potential is repulsive, and the atom in the weak-field-seeking state will be repulsed to the minimum of magnetic field. For ^{87}Rb atoms in the $|F = 2, m_F = 3\rangle$ state, the trapping potential is $U^{\text{Rb}} = 67.2|B|$ (μK), here the magnetic field B is in unit of Gauss. When $I = 1$ A, we obtain $\Delta B(z)_{\max} \geq 6.5$ G and $U^{\text{Rb}} \geq 436.8$ μK, which is far higher than the temperature T_{OM} of cold atoms in a 2D optical molasses (such as $T_{\text{OM}} \approx 20$ μK for ^{87}Rb atoms). So our lattice of magnetic traps is deep enough to collect and trap nearly all of cold atoms from a standard 2D optical molasses, and can be used to realize an array of controllable double-layer BECs by using rf evaporative cooling.

Our wire configuration can be fabricated on the sapphire substrate by using standard microfabrication techniques (such as photolithography and electroplating). In 1998, the experiment of Pretiss's group showed that, for Au wire at room temperature with the temperature difference $\Delta T = 100$ K between the wire and substrate, the maximum linear-current density was 1×10^4 A/cm. They also investigated the heating effect of Au, Cu, and Ag wires on sapphire substrate and the best results were obtained with Au, for which the area-current density and power dissipation are $\sim 10^8$ A/cm^2 and ~ 10 kW/cm^2, respectively[20,21]. For our microtraps, we chose the wire diameter $d = 20$ μm and current $I \leq 1$ A, the current density in the wire is ≤ 500 A/cm, which is far lower than 10^4 A/cm. So the heating problem of our current-carrying wires on the substrate can be solved well only by cooling water.

Our array of double-layer magnetic microtraps can be controlled adiabatically by adjusting the current I in the square wire. It can be used not only to realize 2D array of controllable double-well BECs, but also to study atom interference. The interferometer can be realized via a dynamic splitting potential that transforms cold atoms from a single well into two separate wells and then back into a single well, which is similar to the scheme of Hänsch's group[22]. Furthermore, the scheme can be used to study cold atoms' nonlinear effect and wave-packet dynamics, quantum transport and tunneling, quantum entanglement, even to prepare cold homonuclear or heteronuclear diatomic molecules.

In conclusion, we have proposed a scheme to form a 2D array of controllable double-well magnetic traps for cold atoms by using an array of square current-carrying wires and two bias magnetic fields. The scheme can be used to construct 2D double-layer MOTs associated with horizontal bias field, as well as 2D double-layer Ioffe traps using horizontal and vertical bias fields. It brings us a new way to realize 2D arrays of BECs in surface microtraps. Furthermore, the proposed 2D double-well magnetic microtraps can be continually changed into an array of single-well microtraps by reducing the current I in the wire and *vice versa*, which can be used to form a 2D controllable double-layer magnetic lattice, to study cold atom interference, quantum entanglement, even to prepare cold homonuclear or heteronuclear molecules, and so on.

This work was supported by the National Natural Science Foundation of China (No. 10174050, 10374029, and 10434060), Shanghai Priority Academic Discipline, and the 211 Foundation of the Educational Ministry of China. J. Yin is the author to whom the correspondence should be addressed, his e-mail address is jpyin@phy.ecnu.edu.cn.

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