Single layer atom chip for magnetically trapping one-dimensional array of ultracold atoms*

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We propose a wire configuration to create a one-dimensional (1D) array of magnetic microtraps for trapping ultracold atoms. The configuration is formed by replacing the central part of the Z-wire pattern with a zigzag wire. We simulate the performance of this pattern by the finite element method which can take both the width and depth of the wire into consideration. The result of simulation shows that this configuration can create magnetic microtraps which can be separated and combined by changing the bias magnetic field. We manage to split the Z-wire trap and prove that a similar result can occur for the new wire configuration. The fabrication processes of the atom chip are also introduced. Finally we discuss the loading method.

Keywords: atom chip, magnetic micro-trap array, magnetic lattices

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1. Introduction

Bose–Einstein condensation (BEC) is considered as a carrier of qubits and source of atom laser. Before the realisation of quantum computation and continuous wave atom laser,[1] BECs should be trapped separately so that they can be addressed solely. One way to approach this goal is to use optical lattice which is based on the interference of intersecting laser beams. In optical lattice, due to the interactions of ultracold atoms with the spatially modulated light field, traps are created at the potential maxima of red detuned lattices and minima of blue detuned lattices. However, the distance between neighbouring lattice sites is half the wavelength of the laser, which brings difficulty to the addressing and manipulating of traps. An alternative way proposed by Yin *et al.*[2,3] is to use the magnetic lattice. Unlike the optical lattice, purely magnetic traps suffer no spontaneous emission and no photon scattering, and are well isolated from their external environment resulting in a higher atomic density. Moreover, it is convenient to use radio frequency (rf) evaporative cooling in the magnetic lattice.

It has been pointed out that[4] the gradients and curvatures of magnetic fields created by current-carrying wires scale as I/s^2 and I/s^3, where I is the wire current and s is the characteristic size of the system. It is indicated that a smaller wire layout can generate a tighter magnetic trap. Atom chip[5] offers physicists a platform to realize a variety of electromagnetic designs in a micrometer scale. One way to create magnetic lattice on atom chip is to use permanent magnetic film. Compared with current-carrying wires, traps generated by permanent magnetic film have lower current noise and heating rates, resulting in a longer lifetime. However, once the permanent magnet configuration is decided, its magnetic field can never be changed. That is why they need one more layer for current-carrying wires to capture and load atoms to the magnetic lattice.[6] Unlike the case of the permanent magnet, the magnetic field generated by current-carrying wires can be controlled by changing the current in the wires. Three configurations[7] for two-dimensional magnetic lattice of this kind have been proposed. Still, they use two layers of parallel wires, where any two wires in the two layers are perpendicular to each other. The layers must be insulated, or the currents in the wires will be difficult to control, making the fabrication of atom chip complicated. In this paper, we propose a single layer design

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of wire pattern to create one-dimensional (1D) array of magnetic microtraps for cold neutral atoms.

2. Configurations

The magnetic trap (MT) can be realized due to interaction between particles and the magnetic field. In a static magnetic field $\boldsymbol{B}$, a particle with total spin $\boldsymbol{F}$ and magnetic moment $\boldsymbol{\mu} = g_{\rm F}\mu_{\rm B}F$ experiences the potential

$$V_{\rm mag} = -\boldsymbol{\mu}\cdot\boldsymbol{B} = g_{\rm F}m_{\rm F}\mu_{\rm B}B, \tag{1}$$

when $\boldsymbol{B}$ is not too much strong, where $\boldsymbol{\mu}$ is the magnetic dipole moment, $g_{\rm F}$ is the Landé factor, $m_{\rm F}$ is the magnetic quantum number, and $\mu_{\rm B}$ is the Bohr magneton. For ultracold atoms, the Larmor precession is much faster than the change of the direction of the magnetic field, which means atoms always follow the direction of the local magnetic field and the adiabatic approximation can be applied. So we can take $B = |\boldsymbol{B}|$ which is proportional to the potential. If $g_{\rm F} \times m_{\rm F} < 0$, atoms are in the weak-field-seeking state, which means that they will be attracted towards the minimum of magnetic field. In this way, the key point of using he tmagnetic lattice is to create a series of magnetic field minima. There are two basic wire structures on atom chip which has been well studied[8] and demonstrated,[9] i.e., the U-shaped wire magnetic trap (UMT) and Z-shaped wire magnetic trap (ZMT). UMT is a kind of quadrupole trap whose magnetic field minimum is zero. It can be used to form a U-shaped wire magneto-optical trap (U-MOT). But it is not convenient to be used as a trap since there is atom loss due to the Majorana transition. Instead, ZMT is a kind of Ioffe–Prichard trap which can be used to magnetically trap ultracold atoms and realize BEC.[10] Furthermore, ZMT can be split by changing the direction of homogeneous bias field. Hence, ZMT is an ideal unit cell to construct 1D magnetic lattice.

We connect several Z-shaped wires head to tail and obtain a new wire which looks like steps of a stair or a zigzag wire (Fig. 1(a)). We use it to replace the central part of Z-shaped wire, and Zz-shaped wire is formed (Fig. 1(b)), where a is the distance between two adjacent inflexions of the zigzag wire, b is the width of the wire and I is the current flow though the wire. The lowercase z represents the zigzag wire in the centre of a Z-shaped wire. We plan to use this single current-carrying wire to realize 1D array of magnetic traps. To create magnetic trap, we also need a homogenous bias field B_y along the $\boldsymbol{y}$-direction to shift the trap centres. Another homogenous bias field B_x along the $-\boldsymbol{x}$-direction can be used to move and combine adjacent traps which will be shown later.

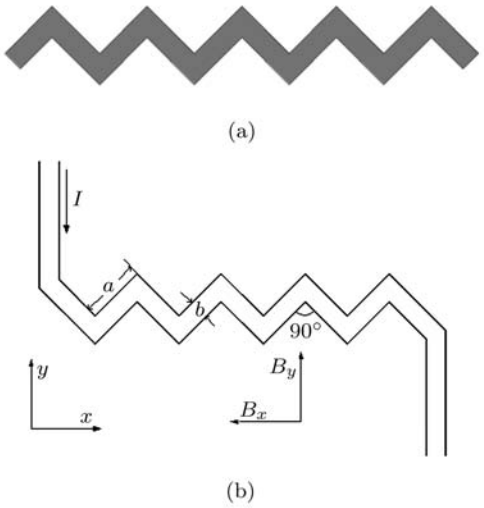


Fig. 1. Configuration of Zz–wire: (a) zigzag wire; (b) Zz–wire.

3. Analysis of magnetic traps

The magnetic field generated by current-carrying wires can be calculated by the following formula:

$$\boldsymbol{A} = \frac{\mu_0}{4\pi}\int \boldsymbol{J}\,{\rm d}V/r, \tag{2}$$

$$\boldsymbol{B} = \boldsymbol{\nabla}\times\boldsymbol{A}, \tag{3}$$

where $\boldsymbol{A}$ is the vector potential, $\boldsymbol{J}$ is the current density in free space, and the integral is taken over elements of the wires. We use the finite element method to analyse the space distribution of magnitude of the magnetic field. By using this method, both the width and height of the wire should be taken into consideration, which is important when traps are close to the surface of the chip. Figure 2(a) shows the spatial distribution of magnitude of the magnetic field in the plane 80 μm above the chip surface as shown in Fig. 1(b) when B_y is 5 mT, I = 3 A, a = 300 μm, b = 100 μm and the depth of the wires is 500 nm (not shown). It is clear that there are 8 micro-traps in two rows 80 mm above the 8 inflexions of the zigzag wire. And all of the traps are contained in a bigger external trap of which the depth is equal to B_y.

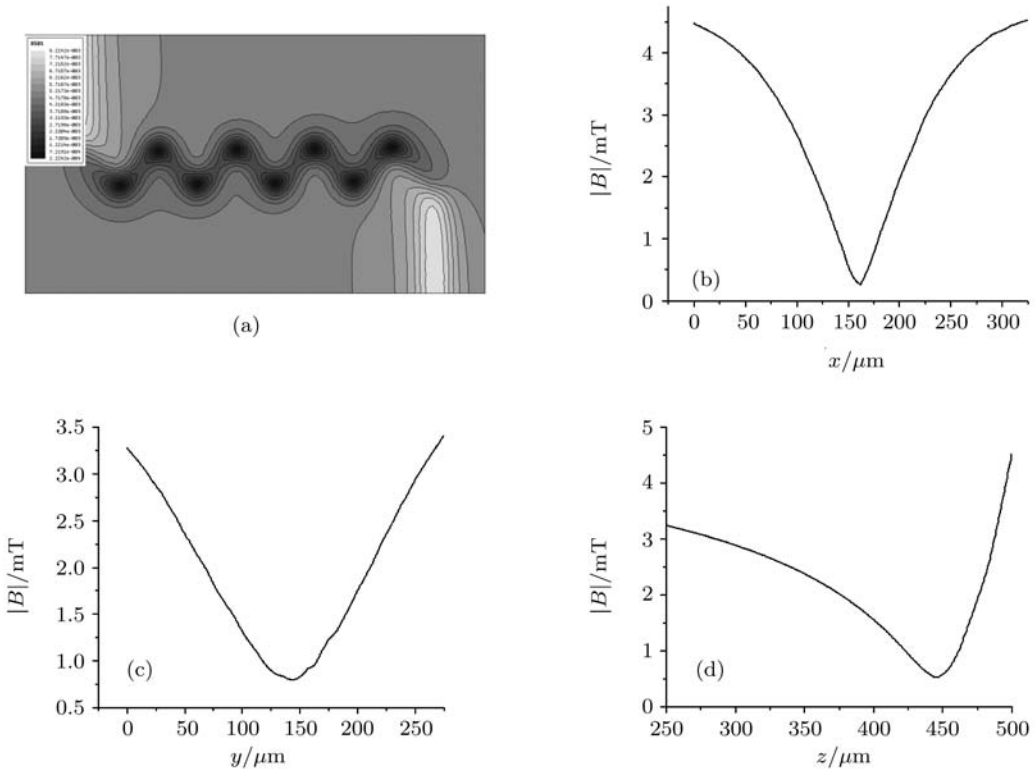


Fig. 2. Abruption of Zz–MT: (a) magnetic field contours of Zz–MT in the plane 80 μm above the layout of Fig. 1(b) when $B_y = 5$ mT; (b), (c) and (d) are the spatial distribution of magnetic field of a single well along x, y and z direction.

To analyse the characteristic of a single well of Zz–MT, we choose one of the micro-traps in Fig. 2(a) and focus on its shape and depth. The distribution of the magnetic field around its bottom along x, y, and z axes is shown in Figs. 2(b), 2(c), and 2(d). It is clear that the magnetic field changes linearly along $\boldsymbol{x}$ direction, and harmoniously along $\boldsymbol{y}$ and $\boldsymbol{z}$ directions. The results of curve fitting shows that at the trap centre $\partial B/\partial x \approx 50$ T/m, $\partial^2 B/\partial y^2 = 2.5 \times 10^5$ T/m^2 and $\partial^2 B/\partial z^2 = 5.1 \times 10^5$ T/m^2. The depth of the trap is also calculated. But we need to define it first. In a single magnetic trap, the contour points of the same value of $|B|$ will form a closed surface. For a bigger $|B|$, its corresponding contour surface will be larger. For two adjacent micro-wells of Zz–MT, one value of $|B|$ corresponds to two closed surfaces. If its value is larger than the potential barrier between them, the two surfaces will be so large that they merge into each other. We plot the contour surfaces of the two neighbouring traps in 3D view and change their corresponding $|B|$. B_0 is defined as the $|B|$ value when the two surfaces merge. B_1 and B_2 is $|B|$ of the bottom of the two traps. According to Eq. (1), we define the depth of the two adjacent wells as

$$V_1 = g_{\rm F} m_{\rm F} \mu_{\rm B} (B_0 - B_1), \tag{4}$$

$$V_2 = g_{\rm F} m_{\rm F} \mu_{\rm B} (B_0 - B_2). \tag{5}$$

Finally, we obtain that the depth of the single well is almost 1.7 mT. For ^{87}Rb atoms in the state of $|F = 2, m_{\rm F} = 2\rangle$ the trapping potential is $67.2B$ (μK), where the magnetic field B is in units of Gauss. In this way, for the single well we have $V_{\rm mag}^{\rm Rb} = 1.142$ mK. For other traps the value may deviate from this.

Figure 2(a) can be considered as a series of ZMT which has been split. We can add another homogenous bias field B_x to combine them to a series of ZMT. Figure 3 shows the movement of two neighbouring wells when we keep $B_y = 5$ mT and $I = 3$ A and increase B_x from 0 to 2.3 mT. It is clear that the two traps move together and the potential barrier between them decreases. When B_x reaches 2.3 mT, the eight micro-traps merge into 4 bigger traps due to the combination of the neighbouring micro-traps, as shown in Fig. 3(d). Further increasing B_x will rotate the new traps and raise the bottom of the traps. The new traps are almost the same

as ZMT, which have a shape of ellipsoid. For a single trap, it is harmonic along the slow axis with a curvature of 1.3×10^5 T/m^2 and linear in the transverse plane with gradients of 50 T/m and 40 T/m. The depth of the trap is almost 4 mT, which means 2.6 mK for Rb atoms in the state of $|F=2, m_{\rm F}=2\rangle$.

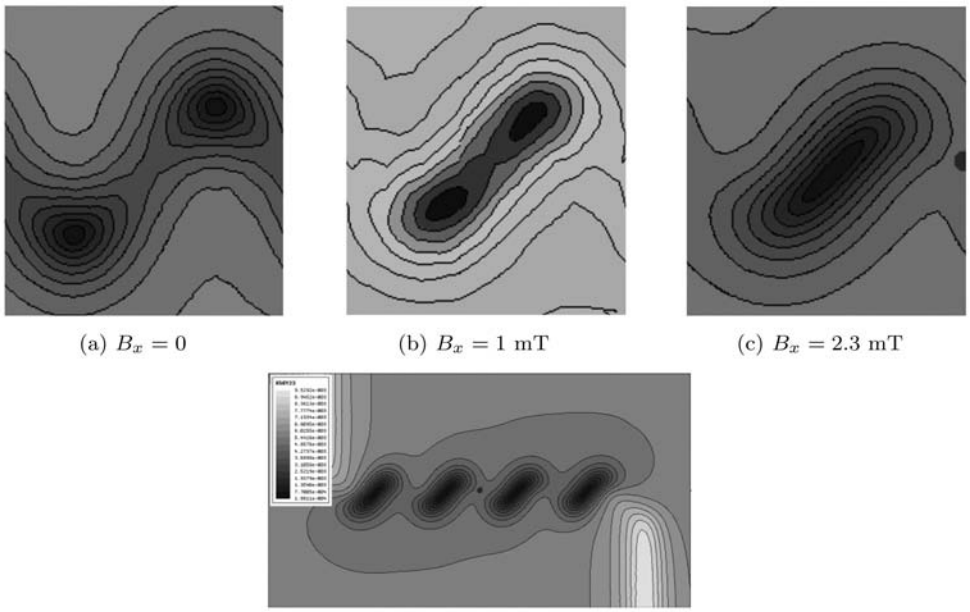


Fig. 3. Combination of neighbouring traps: (a), (b) and (c) are magnetic field contours of two microtraps when B_x is 0, 1 mT, and 2.3 mT, respectively; (d) magnetic field contours in xoy plane 90 μm above the wire surface when B_y is 2.3 mT.

4. Abruption of ZMT

Since ZMT can be considered as a unit of Zz–MT, we tried to verify the feasibility of Section 3 by splitting a single ZMT. To create a ZMT, we applied both a current of 3.6 A to the Z-shaped wire of our atom chip and a bias magnetic field B_x of 1 mT in x direction. The ZMT was loaded by a cloud of 2×10^6 atoms with a temperature of 60 μK. We compressed the trap by increasing the bias magnetic field to 2.2 mT to make it close enough to the wire. In the following 100 ms, we apply another bias magnetic field B_y in y direction adiabatically to split the trap.

Figure 4 shows absorption images taken for traps with different B_y without time of flight, for which only a part of atoms are illuminated. And the stripes in the images are due to the diffraction of our imaging system.[11] From the figures it can be seen that the ZMT is split into two traps when B_y is bigger than 1 mT. From the contrast of brightness we can see that the new traps are tighter than the ZMT. The result of our experiment shows that single ZMT can be split by changing bias magnetic field, which is consistent with the analysis of Section 3.

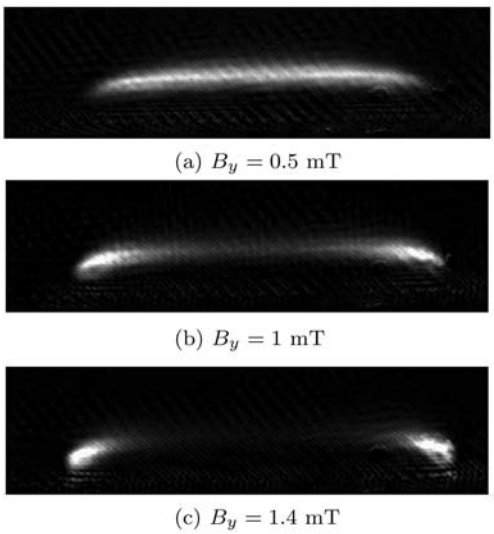


Fig. 4. Abruption of single ZMT: (a), (b) and (c) are images of atom clouds for $B_y = 0.5$ mT, 1 mT and 1.4 mT, respectively when the current of Z-wire is 3.6 A and $B_x = 2.2$ mT.

To expand the result of single ZMT to Zz–MT, we still need to consider the difference between ZMT and Zz–MT. We calculate magnetic field distribution in two vacuum boxes 50 μm above Z–wire and Zz–wire (Fig. 5), respectively. The two boxes have a volume of 100 μm×400 μm×100 μm, which is big enough to cover the area where there are traps. The current of Z–wire is 4.12 A and that of Zz–wire is 4 A. The result of calculation shows that the magnitudes of magnetic field $|B|$ in the two boxes have a difference of 6% in maximum and 1.5% on average and the angles of direction of magnetic field have a difference of 10.9° in maximum and 4.5° on average. The results show that the neighbours of single ZMT in Zz–MT have a little influence on it, which can be considered as a negligible perturbation. So Zz–MT can be taken as a series of isolated ZMT which have no interaction between each other. Then we can predict that the result of Fig. 4(c) will occur periodically when we change Z–wire to Zz–wire.

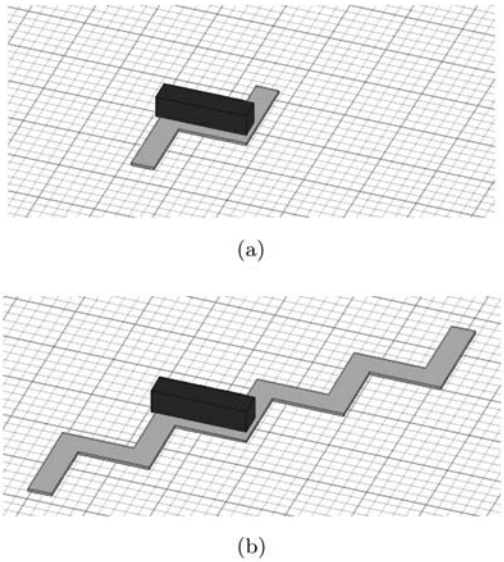


Fig. 5. The dark boxes covering the areas of our interest. The magnetic field contribution to the areas created by Z–wire (a) and Zz–wire (b) has been calculated.

5. Discussion and outlook

Since Zz-shaped wire is a plane structure, it can be fabricated on the surface of an atom chip. Limited by the scale of our glass cell, the zigzag wire cannot be too long. So it is hard to create too many magnetic traps. We try to reduce 'a' in Fig. 1(b) and find that if the rate of a to b is smaller than 2 it will be very hard to split the traps because they are too close to their neighbours. If we reduce both a and b, we can keep the rate and make more inflexions for a finite length of zigzag wire. But the resistance of the wire which is inversely proportional to b will increase as well. With the same current, more heat will be generated and cause the gold wire to melt. Increasing the depth of the wire reduces the resistance, but reduces the smoothness of the chip surface too, which may influence the performance of mirror magneto–optical trap (MOT). Besides, for our setup, the chip is mounted up side down in a vacuum chamber. If the wire is too thick, it will be too heavy to be held on the chip. As a result, we have to reduce the current. According to the experiment of Pretiss's group, a gold wire on a sapphire substrate can support a power dissipation of ∼10 kW/cm^2 at liquid nitrogen or helium temperatures in vacuum. For a square wire with a transverse plane of 100 μm×0.5 μm, 20-A is the limit. In our setup, we use Si instead of sapphire as the material of substrate. Usually, we keep the current lower than 4 A for safety.

The chip fabrication is described in the following. First, with thermal oxidation at about 1100 °C, a thin SiO_2 layer covered on the surface of Si wafer. Then a thin gold film was deposited on the SiO_2 layer by magnetron sputtering. The magnetron sputtered gold film showed excellent smoothness (AFM rms roughness of about 4.67 nm) and high reflectance (93% at 780 nm in wavelength and 45° of incident angle). Finally, gold wires were microfabricated with photolithograthy and wet etching method.[12]

We can use techniques similar to those of Schmiedmayer's group to collect Rb atoms and transfer them to ZMT. First, we collect more than 2×10^7 atoms in mirror-MOT (magneto–optical trap). We increase the current of external coil wires to compress the mirror-MOT when it is almost saturated. Then the U-shaped wire near the Zz-shaped wire is turned to load the atoms in mirror-MOT into U-MOT. With our setup in which the chip is mounted upside down in vacuum chamber, the gravity must be taken into consideration. For Rb atoms in the state of $|F=2, m_{\rm F}=2\rangle$, the gravity that the atoms experience equals 0.15 T/m. This means that without dipole force of laser beam, a pure magnetic well generated by a 4-A current-carrying wire can hardly trap atoms 2 mm away from the wire. So U-MOT must be well compressed before further processes. During compres-

sion, atoms near the surface of atom chip will be lost for surface-induced evaporation. We need to make a balance to optimize the number of atoms. According to our experience of making BEC,[13] keeping the bias external field and lowering down the current in the U-wire is a better choice to compress the U-MOT. After polarized gradient cooling and optical pumping, millions of atoms can be trapped in Zz–MT.

As shown in Fig. 6, Zz–MT is almost the same as ZMT when their centres are 700 μm above the wire surface. Because at this height, the microstructure of the zigzag wire is so small that it can be considered to be straight. When we compress the trap to 300 μm above the wire surface, it is wrinkled due to the zigzag wire. Finally, the trap is completely split up at the height of 100 μm. Since we can obtain two arrays of clouds of ultra cold atoms and the traps are deep and tight enough, the atoms can be further cooled by rf evaporative cooling. So we can make two arrays of BEC separately. And the two neighbouring BECs can be combined together as shown in Fig. 3.

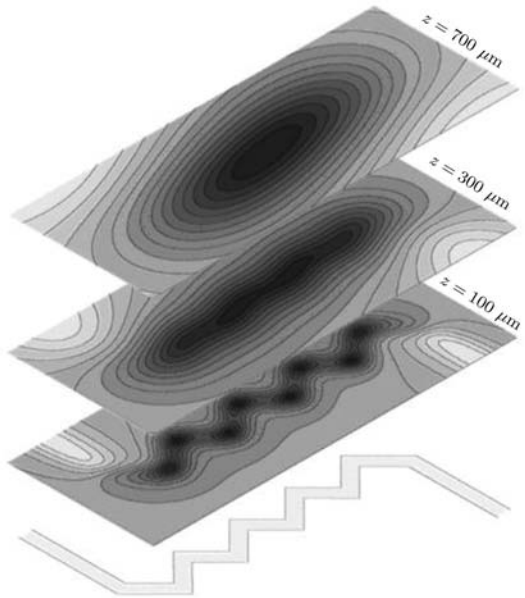


Fig. 6. Change of shape of magnetic traps in different stages of compression: when the trap is compressed to 700 μm above the wire surface, its shape is similar to ZMT; when the trap is 300 μm above the wire surface, it shrinks due to the zigzag wire; when B_y is 5 mT and its height is 100 μm, it is completely split up.

6. Conclusions

In conclusion, we have presented a simple atom chip structure for magnetically trapping an array of neutron atoms. We have calculated the spatial distribution of the magnetic field. The gradient, curvature and depth of the traps are also calculated. Results of both experiment and calculation prove that a series of ZMT can be realized. The result demonstrates that the traps are deep and tight enough to encage ultra cold atoms and BEC. And the atoms can be loaded into the trap smoothly by adiabatic compression. By changing the bias magnetic field, two arrays of microtraps can be realized and any two neighbouring traps can combine together to form a bigger trap. They are deep and tight enough to realise 1D array of BECs.

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