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Chip-Based Square Wave Dynamic Micro Atom Trap *

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We propose a scheme for a chip-based dynamic micro atom trap where the trap potentials are created by square wave radiation and an inhomogeneous static magnetic field. The parameters of this kind of trap array can be modulated dynamically. Both one-dimensional (1-D) and two-dimensional (2-D) trap array potentials for ^{6}Li atoms are discussed. The 1-D trap is combined by a square wave radiation (6 kHz) and a gradient magnetic field (300 G/cm), the array constant of 1-D trap is 0.85 μm. Since the trap array does not require any laser field, it can be easily integrated on a chip and it is useful in applications of scalable quantum information processing.

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Recently, the research of the atom chip has attracted much attention.[1,2] Similar to dc and rf radiation, it can be applied to chip wires to form atom traps.[3−5] In order to control the atoms more flexibly, researchers have adopted rf mixing[6−8] and rf combs[9] in atom traps. Chip-based neutral atom traps are suitable for quantum information processing (QIP).[10−13] However, it is difficult to realize analog frequency mixing and frequency combs. Since the control of the square wave is more versatile than that of sine wave, the digital signal is more suitable for chip-based rf atom traps.[14] In this Letter, we propose a dynamic micro trap scheme. A square wave radiation and an inhomogeneous static magnetic field are used to generate dynamic micro trap, and the trap is very easy to integrate with other systems. The trap array generated by the square wave and magnetic field can be modulated dynamically. It is different from the ordinary static magnetic trap array. The feature of the one-dimensional trap array is mainly studied, and the scheme of the two-dimensional trap array is briefly discussed.

The analog rf signals cannot be directly generated by a digital signal generator without a digital-to-analog converter (DAC). A sine signal provides only single frequency, and frequency comb or multi-frequency are usually generated by analog frequency mixing. In contrast, square wave can be considered as a mixture of a serial of multi-frequency sine waves and described as[14]

$$B(t) = B_0\Big[\sin(\omega t) + \frac{1}{3}\sin(3\omega t) + \cdots \frac{1}{n}\sin(n\omega t) + \cdots\Big], \quad n = 1, 3, 5, \cdots, \qquad (1)$$

where $\omega = 2\pi/T$, and $T$is the period of the square wave, $\pi B_0/4$ is its amplitude. According to Eq. (1), the combined field of a square wave and others is equal to multi-frequency sine wave fields, that is, a square wave could be considered as a series of analog rf signals.

In a homogeneous static magnetic field, if we apply a square wave field with the frequency being nearly resonant with the Zeeman sublevel transition of atom, then the far higher-order detuned frequencies of square wave can be treated as small perturbations. This square wave is similar to monochromatic analog frequency radiation and can be used to build micro rf traps.[14]

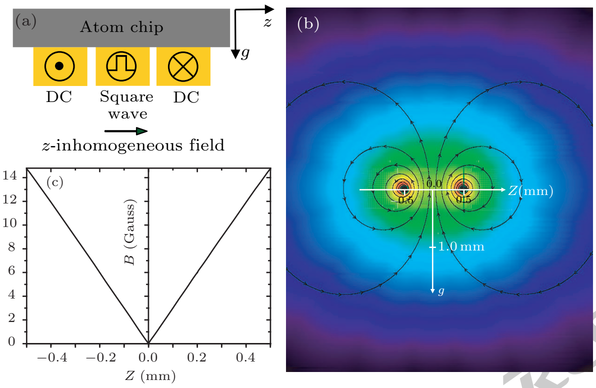

Fig. 1. (a) Setup of square wave on an atom chip, which is perpendicular to the gravity field. (b) The flux density of the inhomogeneous static magnetic field. (c) Intensity distribution of the inhomogeneous magnetic field.

If the external bias magnetic field is inhomogeneous, the trap will be more complex and more in-

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teresting. A simple setup for the usage of a square wave on an atom chip is shown in Fig. 1(a). The two contra-propagated dc currents can be used to form a linear magnetic field between the two side wires; the square wave will propagate via the central wire. The space of two side wires is 1.0 mm; two dc currents are set to be 37.5 mA. Thus an atom trap can be formed near the chip surface. At a height of 1.0 mm from the atom chip, the orientation of inhomogeneous magnetic field is along the z axis and parallel to the surface of atom chip; the intensity of magnetic field B is exactly proportional to the distance $|z|$ (as shown in Figs. 1(b) and 1(c)), the gradient of the linear field is approximately 300 G/cm.

In inhomogeneous static magnetic field, different subsets of square wave will resonate with the Zeeman sublevels of neutral atoms at proper positions. For example, if we assume a one-dimensional (1-D) linear static magnetic field in the z direction, as shown in Fig. 1, and $B(z) = bz$, where b is the gradient, then all the components could be resonant with certain energy states at some positions. In Fig. 2, the frequency of the square wave is supposed to be $f = 6$ kHz, and $b = 300$ G/cm, according to $z = \hbar\omega_n/b\mu_B g_F \Delta m_F$, where $\Delta m_F = 1$, $g_F = -2/3$ in the case of ^{6}Li, then frequency components $\omega = 2\pi\times 6$ kHz, $3\omega = 2\pi\times 18$ kHz, and $5\omega = 2\pi\times 30$ kHz will resonate with Zeeman sublevels at positions $z = \pm 0.215\,\mu$m, $\pm 0.644\,\mu$m, and $\pm 1.07\mu$m, respectively.

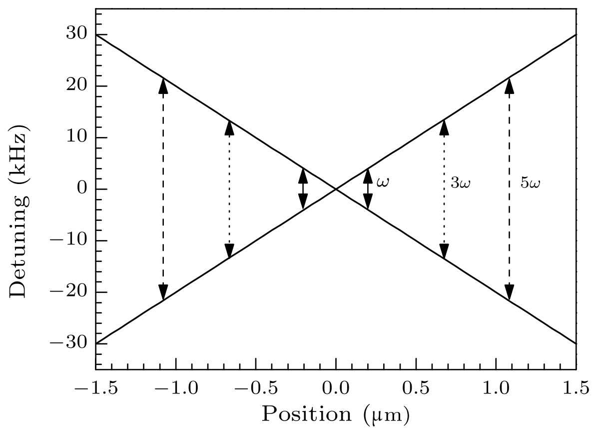

Fig. 2. Square wave resonate with ^{6}Li atom levels in 1-D linear magnetic field, $B(z) = bz$, $b = 300$ G/cm. The frequency of the square wave is 6 kHz.

When an analog rf field (ω) interactes with a two-sublevel (m_F, m'_F) atom system (^{6}Li), the coupling strength between $|F, m_F\rangle$ and $|F, m'_F\rangle$ is[15]

$$\mu = \frac{1}{4} g_F \mu_B (\boldsymbol{B}_{\rm rf} \times \hat{e}_z)\sqrt{F(F+1) - m_F m'_F}, \quad (2)$$

where g_F is the g factor, and $\hat{e}_z$ is the direction of the 1-D linear static magnetic field ($B(z)$). As discussed in Ref. [14], the eigenvalues of this coupling system read

$$E_{\pm}(z) = \pm\frac{1}{2}\sqrt{\left[\mu_B g_F B(z) - \hbar\omega\right]^2 + \hbar^2\Omega_R^2}, \quad (3)$$

where Ω_R is the Rabi frequency,[16] $\Omega_R = \mu/\hbar$.

The case of a square wave field is different from that of an analog rf filed. For the frequency components, when Rabi frequency ($\Omega_R < \omega$) is sufficiently low and frequency separation (2ω) is large enough, the coupling positions can be separated as shown in Fig. 3. In a special range, only one nearly resonant component should be considered, while others can be considered as the dynamic Stark shift.[17] For example, from 0 to 0.5 μm, the resonant frequency is ω as shown in Fig. 3, the adiabatic potential is determined by ω, and other frequency components (3ω, 5ω, $7\omega, \cdots$) only cause dynamic Stark shifts.

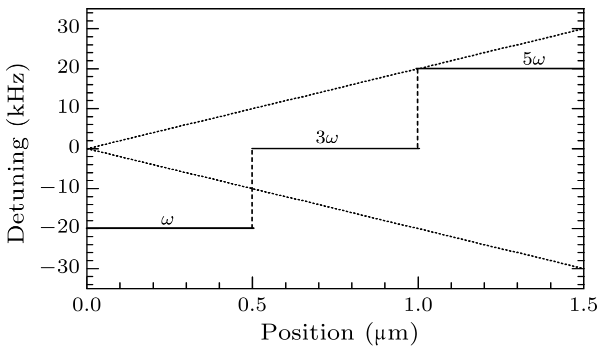

Fig. 3. Separation of the coupling frequency in space. The dotted lines represent the Zeeman sublevels in a 1-D linear magnetic field, $B(z) = bz$, $b = 300$ G/cm; the solid lines define the local coupling frequency.

According to Eq. (3), we could determine the dynamic Stark shift by

$$\Delta = \frac{\hbar^2\Omega_R^2}{4[\mu_B g_F B(z) - \hbar\omega]}.$$

Considering the square wave field, a series of non-resonant frequencies components contribute to the dynamic Stark shift, which should be modified as

$$\Delta_n = \sum_{j\neq n}\frac{\hbar^2\Omega_R^2}{4[\mu_B g_F B - \hbar\omega_j]}.$$

The consequent Hamiltonian is

$$H(z) = \begin{pmatrix} \frac{\mu_B g_F B(z)}{2} - \frac{\hbar\omega}{2} - \Delta_n & \frac{\hbar\Omega_R}{2} \\ \frac{\hbar\Omega_R}{2} & \mathcal{H}_{22} \end{pmatrix}, \quad (4)$$

$$\mathcal{H}_{22} = -\frac{\mu_B g_F B(z)}{2} + \frac{\hbar\omega}{2} + \Delta_n$$

and the eigenvalues read

$$E_{\pm}(z) = \pm\frac{1}{2}\sqrt{\left[\mu_B g_F B(z) - \hbar\omega + 2\Delta_n\right]^2 + \hbar^2\Omega_R^2}. \quad (5)$$

The near resonant frequencies are strongly coupled with the sublevels at certain positions and the far detuning components also weakly affect the potential energies. According to the Landau-Zener effect,[18] the atoms are transferred from initial state to another adiabatically. The corresponding adiabatic potentials are described as[7,9]

$$V_{ad,\pm}(z) = (-1)^{n(z)}\left[E_\pm(z) \mp \frac{\hbar\omega_{n(z)}}{2}\right] \mp \sum_{k=1}^{n(z)-1}(-1)^k\hbar\omega_k, \quad (6)$$

where $n = 1, 2, 3, \cdots$, $\omega_1 = \omega$, $\omega_2 = 3\omega$, $\omega_3 = 5\omega, \cdots$. As shown in Fig. 4, a periodic potential which is similar to the potential of a standing wave can be realized. This potential is a 1-D trap array, and cold atoms can be trapped at the potential minima. The array constant which is defined as the distance between two adjacent potential minima is

$$d = 2\hbar\Delta\omega/(\mu_B g_F b), \quad (7)$$

where $\Delta\omega$ is the frequency difference between two adjacent components. The potential depth is $\hbar\omega - \hbar\Omega_R$, for $b = 300$ G/cm, $\Delta\omega = 12$ kHz, the array constant is 0.85 µm. According to Eq. (7), the array constant can be adjusted either by altering the frequency difference or by changing the bias magnetic field gradient. As shown in Fig. 5, the array constant is proportional to the frequency difference and inversely proportional to the gradient of bias magnetic field.

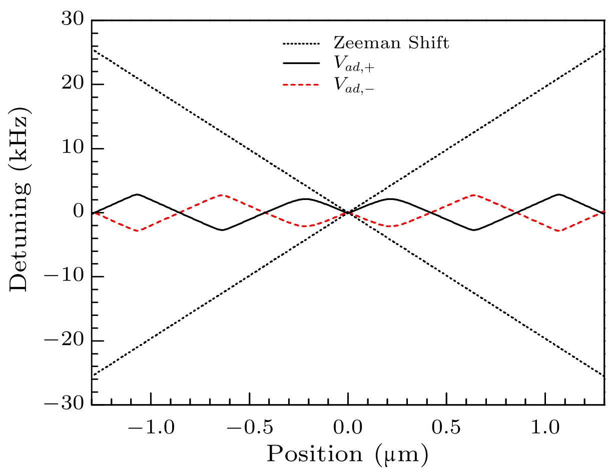

Fig. 4. Periodic adiabatic potential of a square wave in 1-D linear magnetic field. The Rabi frequency Ω_R is set to 1 kHz, b is 300 G/cm, and the array constant is 0.85 µm.

In contrast to optical trap arrays, this hybrid trap array does not require any laser field, and there is no spontaneous emission involved in the trapping process. Compared with static magnetic array, this trap array can be dynamically tuned. Since this trap array is generated by coupling a square wave field with a static inhomogeneous magnetic field, it can be easily integrated on an atom chip. This kind of dynamic array can be used for atom optics and atom lithography, it is also a potential candidate for realization of a scalable QIP.[10−13,19−22] The 1-D trap array can also be used as grating for matter waves and can be modulated dynamically.

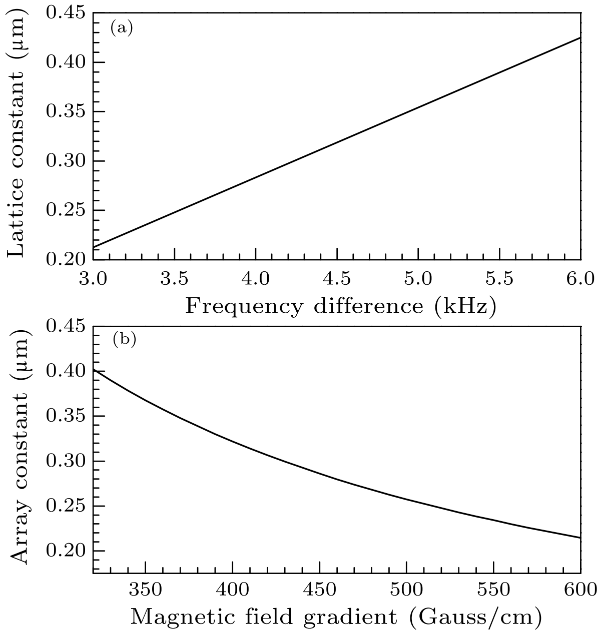

Fig. 5. Dependence of array constant on frequency difference (a) and on the gradient of bias magnetic field (b).

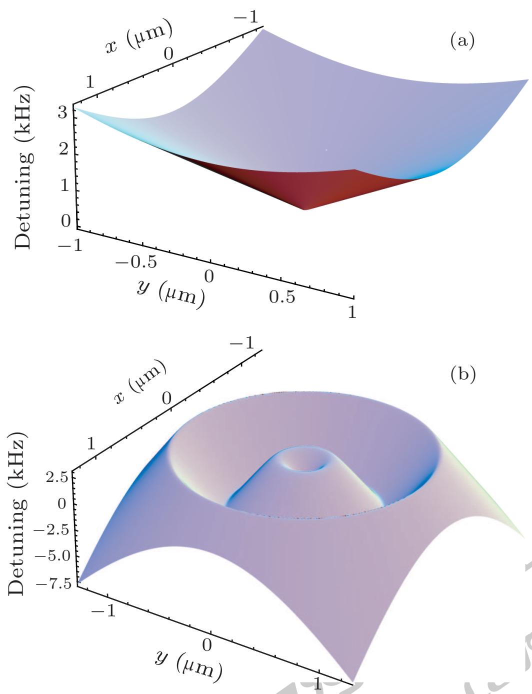

Fig. 6. (a) Two-dimensional magnetic field with gradient $b_r = 300$ G/cm. (b) Two-dimensional ring trap potential array for ^{6}Li atoms.

The 1-D trap array can be easily extended to 2-D by perpendicularly applying a homogeneous magnetic field to the atom chip. The 2-D magnetic trap array is defined by a cylindrical field $B(r) =$

$b_r r (r = \sqrt{x^2+y^2})$, where forms the guide potential for weak-field seeking atoms.[23] The configuration of the 2-D magnetic field and a 2-D hybrid trap array (ring trap potential) are shown in Figs. 6(a) and 6(b). The distance between two adjacent ring potentials is also deterimined by Eq. (7) and the potential depth is $\hbar\omega - \hbar\Omega_R$. If we ignore the far detuning sine wave components, we can change the number of the ring traps by selecting position of the 2-D magnetic field. This novel ring traps can be applied in atom interferometers.[24,25]

The above analysis is based on a simple two-level ^{6}Li atom system, it is also suitable for multi-sublevel systems, such as Rb and Cs.[7,9,26–28]

In conclusion, we have demonstrated a scheme for a chip-based dynamic micro atom trap, which is combined by a square wave and a static inhomogeneous magnetic field. We calculate the 1-D and 2-D periodic trap arrays for ^{6}Li atoms. The trap array constant can be modulated dynamically. The 1-D periodic trap array has important applications in dynamic atom gratings, atomic optics and implementing QIP; the 2-D periodic trap array can be used in atom interferometers.

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