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ABSTRACT

We present experimental and theoretical results on the measurements of the oscillation frequency in a dipole trap based on the spin current in a sodium spinor Bose–Einstein condensate. The spin current is induced under different magnetic field intensities. The oscillation of the spin components in the dipole trap is strongly enhanced by a radio frequency pulse. Both theoretical analysis and experimental results demonstrate that this method can be used to efficiently measure the trap frequencies. Since this mechanism is independent of atomic species, this study is promising to be extended to rubidium and other optical-trappable quantum gases.

Optical dipole trap (ODT)[1] has been extensively studied for various applications in the cold atom experiments.[2] The spinor Bose–Einstein condensate (BEC) has been prepared in a tight ODT.[3] Since then, quantum gas is acquired via evaporation in different forms of trap potentials constructed using an ODT.[3–5] Recently, quantum gas has been prepared via direct laser cooling in a crossed dipole trap.[6,7] A dipole trap with a narrow waist (near diffraction limit) has been established as a standard technique for the manipulation of neutral atoms.[8] Previous reports have shown coherent assembly of atoms into a single weakly bound NaCs molecule in an optical tweezer formed by an ODT.[9] Thereafter, various studies have been performed with different dimensions of an optical trap such as the research of artificial lattice[10–12] and observation of Faraday waves,[13] solitons,[14,15] and domains.[16,17] Moreover, the ODT has the advantage over magnetic traps that leave the magnetic field as a degree of freedom.[18] As a consequence, they are crucial to the formation of ultracold molecules utilizing magnetically tuned Feshbach resonances.[19] In general, it is necessary to precisely know the strength of the dipole trap to accurately use it in such quantitative studies.

It is well known that there are two methods to experimentally measure the trap frequency, namely, the kick and parametric heating methods.[20] These methods have been widely employed to measure the trap frequency for thermal gas in an optical trap. However, the particles in a tight trap constitute a strongly damped system, which is hard to be kicked. Hence, the excitation method is more suitable for the system with a higher trap frequency. The trap frequency for the optical trap that confines the quantum gas is usually very low,[6,7] often at several hundred hertz. Therefore, low frequency noise will inevitably interfere with the measurement during the parametric heating process. Although the oscillation frequency in an optical-tweezer has been measured using parametric excitation,[21] other reports have stated that the observed resonance cannot originate in the system's dynamics.[22,23] Thus, it is possible to calculate the trap strength theoretically;[2] however, the experimental measurement is affected by several parameters such as the optical alignment, absorption along the optical path, and aberrations in the lenses. It is, therefore, desirable to have a direct and precise calibration of the trap strength.

In this study, we demonstrate a standard method to measure the oscillation trap frequency of a damped system. Such a method is

achieved by combining the magnetic force kick and the radio frequency (RF) pulse, which has been applied to the Na spinor BEC in a highly focused ODT. As a result, the amplitude of the oscillation is significantly enhanced. Therefore, this method is highly promising and can be used for the measurement of the optical-trapped quantum gas and other confined spaces such as in a dimple trap or optical tweezers.

The sodium spinor BEC in the $F=1$ state confined in a crossed ODT was created using two red-detuned laser beams along the axes, as demonstrated in Fig. 1(a). The two dipole trap beams were in the horizontal direction. The trapping beam 1 was guided to propagate along the x-direction by maintaining the angle between beams 1 and 2 at 45°. The beam waists were ∼31 and ∼39 μm, respectively, which were measured using the parametric heating method under a high dipole trap laser power of 14 W. The gradient magnetic field along the z-direction, as shown in Fig. 1(a), would kick the atoms and separate the spin components. The time sequence to control the magnetic field and the RF field is shown in Fig. 1(b). Forced evaporation was performed in a dipole trap with an initial trap depth of 700 μK for 4 s, and a gradient field was also provided in the first 1 s; the typical number of atoms in the BEC was 8×10^4 in the $|F=1, m_F=-1\rangle$ state. The potential depth, by considering the effect of gravity, was typically 2.6 μK. For the well-known kick experiments, the magnetic field was switched on for several milliseconds. After holding in the ODT for different time intervals, the atoms were released from the crossed far-off optical trap. The position of each spin component was measured using the Stern–Gerlach method, which was followed by time of flight absorption imaging studies. The image beam propagation was along the y-direction. To measure the trap frequency, an RF pulse was employed. The RF pulse was switched on for hundreds of microseconds in the presence of a magnetic field gradient. The atoms were transferred to other states by the RF pulse.

In Fig. 2(a), the plot in the lower region reveals the conventional well-established method to measure trap frequency wherein, first, the force induced by the magnetic field gradient (10 G/cm) removes the atoms. Subsequently, the positions of atoms held in the ODT for a variable duration of time were recorded. The atoms appear to show a spin current phenomenon[24] with indistinguishable oscillation. An increase in the field gradient up to 35 G/cm and extending the duration fail to show a considerable influence on the amplitude of oscillation. As the momentum of the atoms in the BEC is nearly zero, the atoms could show a large oscillation only when their momentum is significantly increased by the application of a high magnetic force. However, it is usually difficult to experimentally obtain a very high magnetic field gradient in a short time. Additionally, the narrow beam waist severely dampens the movement of the atom cloud. However, it is noticed from the upper panel in Fig. 2(a) that an application of the π pulse transfers the atoms from the $m_F=-1$ state to the $m_F=+1$ state over a period with a standard duration of 138 μs. When the atoms move to the maximum position, as indicated by the vertical dotted line in Fig. 2(a), the time is 8 ms. The atoms in the $m_F=+1$ state show an oscillation with high amplitude in the trap after being subjected to the RF pulse. The trap frequency cannot be deduced from the trivial movement indicated in the bottom panel of Fig. 2(a), whereas it can be easily interpreted from the upper panel of Fig. 2(a).

The schematic diagram in Fig. 2(b) clarifies the reason for the increment in amplitude of the oscillation, which is induced by the π pulse. At the end of evaporation, when the atoms are positioned at the bottom-most point of the dipole trap, a force induced by the magnetic field knocks the atom. However, the atoms are damped to a large extent and reveal nearly invisible oscillations, as depicted by the red curves in Fig. 2(a). A π pulse transfers the atoms from the $m_F=-1$ state to the $m_F=+1$ state in the presence of a magnetic field gradient, as represented by the arrow in Fig. 2(b). The atoms now exhibit an increased potential, which is induced by the magnetic field gradient. This causes a drift of the lowest potential position for the atoms as depicted by the blue curve in Fig. 2(b). Hence, it is noticed that the $m_F=+1$ state has an obvious oscillation.

To further study the trap frequency and verify the above explanation on the enhanced oscillation amplitude, the duration of the RF pulse has been set at 78 μs. Each data point is derived from three measurements with same experimental conditions. The average of the position for three components is acquired as shown in Fig. 3. After the exposure to the RF pulse, a part of the atoms on the $m_F=-1$ state has been transferred to the $m_F=+1$ and $m_F=0$ states. The three

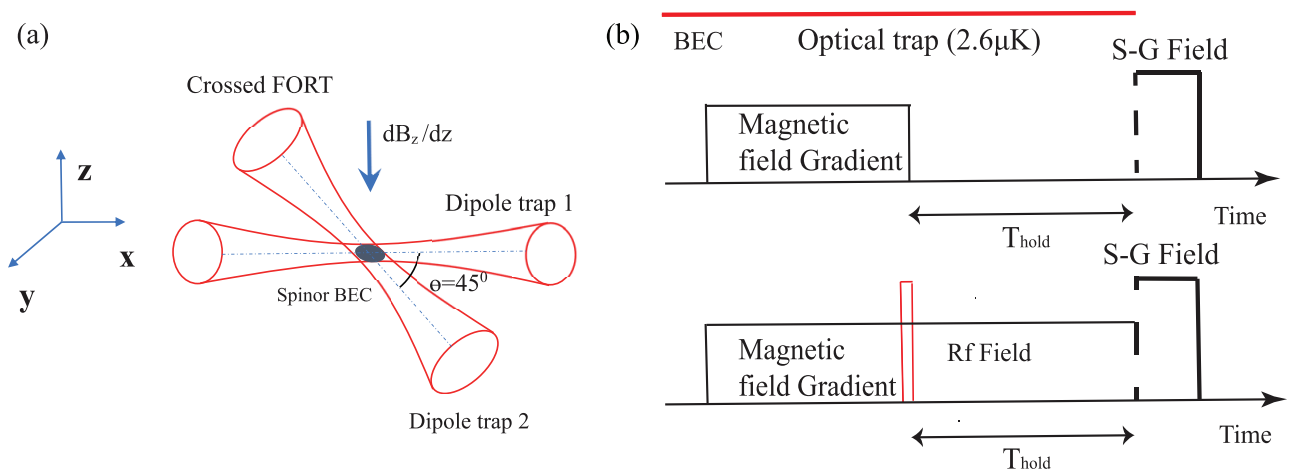

FIG. 1. (a) Scheme of the experimental setup. Sodium BECs were trapped in the dipole trap. (b) Time sequence for controlling the magnetic field and the radio frequency pulse. The red line is the sequence of the optical dipole trap. S–G field—Stern–Glach field.

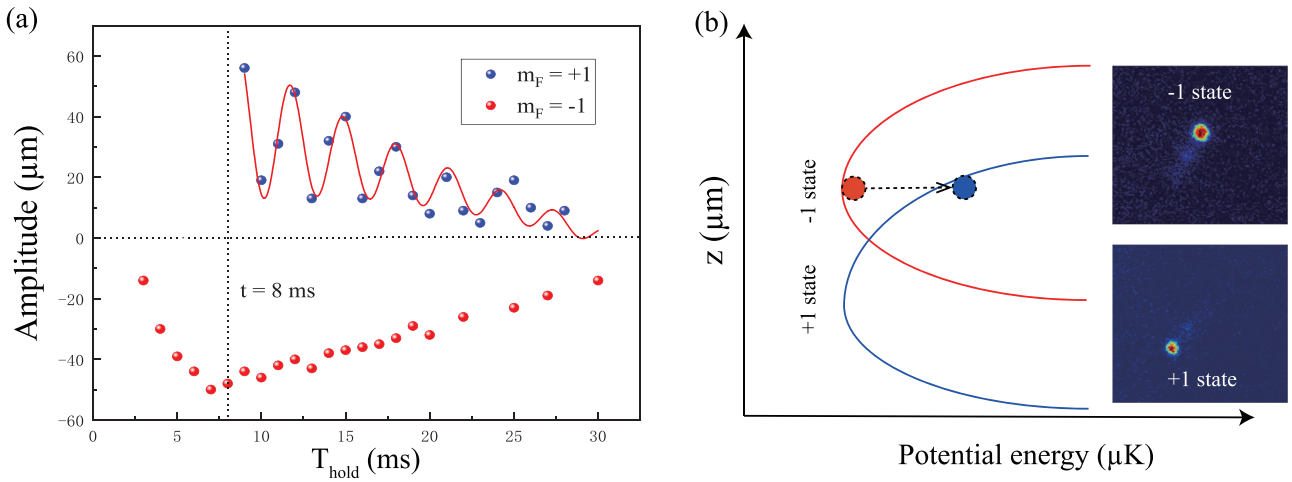

FIG. 2. (a) (Bottom panel) the movement of atoms in the $m_F = -1$ state induced by the magnetic field. (Top panel) the movement of atoms in the $m_F = +1$ state induced by the radio frequency (RF) pulse combined with the magnetic field gradient. The red curve is a fit with a damped sinusoid. (b) Scheme of the potentials for different atomic states after action of the magnetic field and the RF pulse. The images of atoms transferred by the π pulse from the $m_F = -1$ state to the $m_F = +1$ state are shown in the inset.

components contribute toward the oscillation in the potential. From Fig. 3, it is noticed that the atoms in the $m_F = +1$ state have a high amplitude, and those in the $m_F = -1$ state show the least movement. This experimental result is concurrent with the analysis shown in Fig. 2(b). The potential for the $m_F = +1$ state is observed to be far from the potential of the $m_F = -1$ state, and the potential for the zero state is in between them. The movement of the $m_F = -1$ component is enhanced compared with the results shown in the bottom panel of Fig. 2(a). This observation shall be attributed to the spin current excitation, as opposed to decay.[25,26] The movement of the $m_F = +1$ and $m_F = 0$ components shows a larger enhancement, which is mainly due to the influence of the RF pulse. The $m_F = +1$ and $m_F = -1$ components are sensitive to the magnetic field gradient,[27,28] causing their oscillation to decay faster than the $m_F = 0$ component. To obtain the frequency from the movement of the atoms in the trap, the data for the zero state have been fitted using the function of $P = D + A\sin(x\omega + \phi)e^{(-x/b)}$. The trap frequencies for the $m_F = +1$ and $m_F = 0$ states are independently measured as 377.3 and 356.7 Hz, respectively.

The trap frequency measured using the $m_F = 0$ state component atoms is not influenced by the magnetic field gradient, as there is zero interaction between the atoms and magnetic fields. The oscillation of the $m_F = 0$ state has been measured under different values of the magnetic field gradient. The oscillation amplitude is noticed to increase with the magnetic field gradient because of the shift of the potential. The trap frequency as a function of varying magnetic field gradients measured using the $m_F = 0$ state atoms is demonstrated in Fig. 4.

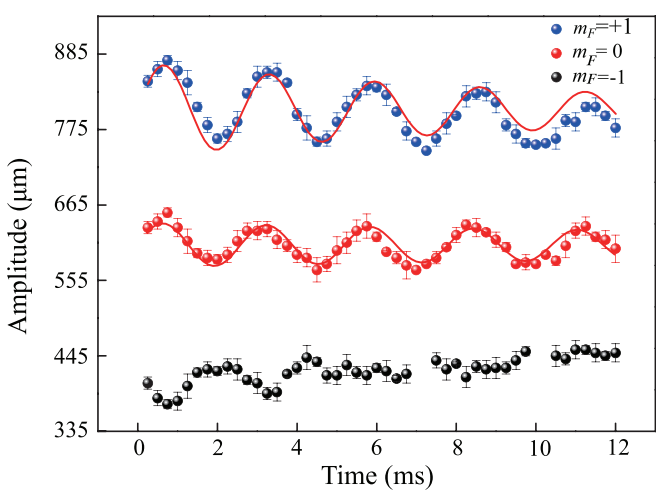

FIG. 3. The oscillation for the three components of the atoms after the effect of the radio frequency pulse. The red solid lines are fits with a damped sinusoid.

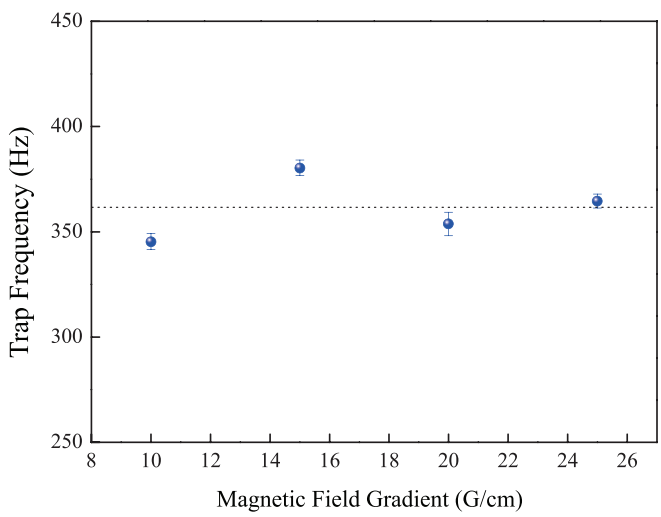

FIG. 4. The trap frequency under different magnetic field gradients measured with the $m_F = 0$ spin component. The horizontal line is a linear fit.

The average frequency is obtained as 361(15) Hz. The trap frequency can be measured precisely by this method. The powers of the laser beams at the end of evaporation are computed to be nearly 70 and 65 mW, according to the theoretical calculation,[24] and the ideal radial frequency is approximately 341 Hz.

In summary, we have developed a standard method to measure the trap frequency in a dipole trap by combining the influence of the magnetic field gradient and a RF pulse. The axial (z-direction) frequency has been measured using the application of a magnetic field. The radial frequency can also be measured using this method. The atoms have been transferred to other states due to the RF pulse, and a new position in their potential, shifted by the magnetic field gradient, is experienced. The effect of the magnetic field gradient in this method mainly shifts the potential of the atoms in different Zeeman states, rather than knocking them out. This method can be applied to measure the frequency of strongly damped optical systems, such as the Bose or Fermi quantum gas, in a narrow beam waist dipole trap.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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