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Interference properties of a trapped atom interferometer in two asymmetric optical dipole traps*

Li-Yong Wang(王立勇)[1,2,3,†], Xiao Li(李潇)[3,4], Kun-Peng Wang(王坤鹏)[3,4], Yin-Xue Zhao(赵吟雪)[5], Ke Di(邸克)[6], Jia-Jia Du(杜佳佳)[6], and Jian-Gong Hu(胡建功)[7]

[1] *Center for Optics Research and Engineering (CORE), Shandong University, Qingdao 266237, China*
[2] *School of Information Science and Engineering, Shandong University, Qingdao 266237, China*
[3] *State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, APM, Chinese Academy of Sciences, Wuhan 430071, China*
[4] *Center for Cold Atom Physics, Chinese Academy of Sciences, Wuhan 430071, China*
[5] *Wuhan Social Work Polytechnic, Wuhan 430079, China*
[6] *Chongqing University of Post and Telecommunications, Chongqing 400065, China*
[7] *School of Information Engineering, Nanchang University, Nanchang 330031, China*

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We investigate interference properties of a trapped atom interferometer where two symmetric optical dipole traps (ODTs) act as the atomic wave-packets splitter and combiner with internal state labelling. After the preparation of initial superposition states, the atomic wave-packet is adiabatically split and moves into two spatially separate asymmetric ODTs. The atomic wave-packets in two ODTs are then adiabatically recombined after a duration of free evolving in traps, completing the interference cycle of this atom interferometer. We show that the interferogram exhibits a series of periodic revivals in interference visibility. Furthermore, the revival period decreases as the asymmetry of two dipole potentials increases. By introducing an echo sequence to the interferometer, we show that while the echo effect is not influenced by the asymmetry of the two ODTs, the onset of periodic revivals changes by the echo sequence. Our study provides an effective method to cancel or compensate the phase shift caused by position and time correlated force.

Keywords: atom interferometer, optical dipole traps, revival, echo sequence

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1. Introduction

Nowadays, atom interferometer has become one of the most powerful techniques with applications in precision measurements,[1–3] inertial sensing and navigation,[4] gravitational-wave observatory,[5–7] testing fundamental laws of physics,[8–13] etc. It is capable of measuring acceleration, rotation,[14] inclination, time-dependent or gradient distributed force with a high precision. Compared with atom interferometers in free space,[15–17] trapped-atom interferometers (TAIs)[18–20] have some advantages such as interrogation time independent of the atom's flight[21] and prospect of compactness and portability.[22] It is especially promising for applications because of its compactness and portability.[23,24] Integrated on a chip, waveguide or other micro-fabricated structures, it can be used to study atom-surface interactions,[25] two-body collision[26] and Josephson phenomena,[27] etc.

In a typical atom interference process, matter waves are first coherently split followed by free flight phase where the influence of the external field is imprinted to the flying atom clouds. The atom clouds are then recombined and information on external environment is extracted. In the past few decades, techniques of precise manipulation of trapped atoms have experienced a remarkable progress.[28] The dynamical evolution of a quantum system in a double-well potential has been studied extensively.[29–32] Atoms can be transported or guided adiabatically.[33–36] For example, the Bloch vector evolution of a single atom interferometry (SAI) in asymmetric double-well potential has been investigated.[29] An SAI based on 2D spatial adiabatic passage process using a system consisting of three identical harmonic traps in a triangular geometry is studied theoretically.[37] A digital SAI on a discretized space-time geometry is also experimentally performed in optical lattice to measure potential gradients[32] with a precision of 5×10^{-4} in units of gravitational acceleration g. Now the coherent controlled splitting and spin-state-dependent transportation of atomic wave-packets have been experimentally demonstrated in many physical systems such as diploe trap,[30] trapped-ions in a linear Paul trap,[38] BEC,[19,39–42] neutral atoms in 1D optical lattice[43–45] and atom chip.[46–49] At the same time, some techniques utilized to split and combine atomic wave-packets like spin-dependent light force,[50,51] guiding potential,[52,53] stimulated Raman adiabatic passage (STIRAP),[34] ramping

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†Corresponding author. E-mail: wangliyong@sdu.edu.cn

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up of a radio-frequency field,[46] shortcut to adiabaticity (STA),[54–57] internal state labelling (ISL),[30,31] etc, have been developed. The splitting and recombining process of a double-well TAI using a thermal ensemble is investigated theoretically, and it shows that the contrast and phase shift of the TAI with ISL and STA methods have the same form.[30] In a recent experiment, two wave-packets split from a single atom is separated to create a very large Schrödinger-cat states.[58] Later, a driven trapped-ion interferometer in one-dimensional harmonic trap is used to measure time-dependent and spin-dependent weak forces.[59] Most recently, two heteronuclear atoms are precisely transferred and combined with two ODTs to form a single molecule.[60] All of the above imply the important development and application prospects of the TAIs.

In this paper, we propose a TAI scheme in which splitting and recombination of atomic wave-packets are adiabatically accomplished using two spatial transport symmetric optical dipole traps (ODTs) with ISL. The wave-functions of two wave-packets in each of two potential wells evolve independently once two asymmetric optical dipole traps are separated far enough and their phases ϕ are sensitive to their individual local environments. As a result, these two wave-functions acquire a relative accumulated phase difference $\Delta\phi$, resulting in an interferogram from which information about local environments, i.e., asymmetric wells and others can be extracted. The visibility of the Ramsey interference process reflects the coherence of the atom interferometer. After the initial collapse, a series of periodic revivals of the interference visibility reappear when the accumulated phase difference satisfies $\Delta\phi = 2n\pi$ (n is an integer). The revival period decreases as the asymmetry of two dipole potentials increases. Furthermore, we introduce an echo sequence to the TAI with two asymmetric ODTs and show a full recovery of the interference visibility followed by the echo sequence. This indicates that the accumulated phase difference $\Delta\phi$ caused by asymmetric ODTs can be totally reversed by the echo effect. In addition, we show that the inherent behavior of periodic revivals can be significantly influenced by the echo sequence.

Specifically, two components of wave-packets created from the dynamic splitting of the 1D system are in a phase coherent state. The phase shift observed from the interference patterns after the recombination of two wave-packets reveals the time evolution of coherence properties of TAI in two spatially separate asymmetric ODTs. It provides a versatile method for studying precision measurement,[22,61] phase dynamics,[46,62] squeezed and entangled states,[49,63,64] ultracold chemistry,[60] and superfluidity,[65] etc. Moreover, the controllability of the asymmetry between two wells will be a useful tool for atom interferometry since it can be used to compensate for any position/time-dependent asymmetry like the tilting potentials,[66] the gradient due to gravity and other inhomogeneous coupling strength in a matter-wave beam splitter,[61,67] or act as a phase shifter.[68,69]

2. Ramsey atom interferometer

A typical Ramsey atom interferometric operation requires a well-known $\pi/2$–$\pi/2$ optical pulses sequence. In this sequence, the first $\pi/2$–pulse prepares the atom into a coherent superposition state and the second $\pi/2$-pulse then acts as a detector to extract the interference signal after a duration of dynamic evolving time.

In this study, an ensemble of two-level cold atoms is initially trapped and prepared in an ODT. The wavelength of trap laser beam is 830 nm, and it has a waist radius of 2.1 μm and a Rayleigh length of 16.7 μm. We consider an one-dimension case of a TAI in two asymmetric ODTs. The Hamiltonian of a TAI in two asymmetric ODTs has the form[70,71]

$$\begin{aligned} H &= H_{\downarrow}|a\rangle\langle a| + (H_{\uparrow} + E_{\mathrm{HF}})|b\rangle\langle b| \\ &= \left[\frac{P^2}{2m} + V_1(\boldsymbol{x}_1) + \mathrm{i}\lambda\right]|a\rangle\langle a| \\ &\quad + \left[\frac{P^2}{2m} + V_2(\boldsymbol{x}_2) + E_{\mathrm{HF}} + \mathrm{i}\lambda\right]|b\rangle\langle b|, \end{aligned} \tag{1}$$

where $|a\rangle$ (spin down) and $|b\rangle$ (spin up) represent two hyperfine spin states of atom. $E_{\mathrm{HF}} = \hbar\omega_0$ is the energy level splitting of two hyperfine spin states. Two asymmetric dipole potentials are represented by $V_1(\boldsymbol{x}_1)$ and $V_2(\boldsymbol{x}_2)$, $V_i(\boldsymbol{x}_i) = U_i \mathrm{e}^{-\frac{(\boldsymbol{x}-\boldsymbol{x}_i)^2}{\beta^2}}$ ($i = 1, 2$), and we assume a trap depth relation of $U_2 = \eta U_1$ with η indicating the extent of asymmetry between the two spatially separate potential wells and β being the dipole trap width. Dissipative mechanisms such as spontaneous photons scattering of atom due to dipole laser, heating of atoms, changes of dipole potentials, etc., affect coherence of cold atoms in the interference process,[72] and all these factors can be summarized as a dissipative item $\mathrm{i}\lambda$ in Hamiltonian.[70] The dissipative value λ is set via simulating with the experimental results. Compared with the asymmetry of two dipole potentials, the effects of interactions of atoms[73] and vibration excitation are so small that can be neglected.

Figure 1 shows the schematic diagram for operating a TAI with two asymmetric ODTs. Initially, an atom ensemble in a symmetric ODT is prepared in state $|\Psi\rangle = |a\rangle \otimes |\psi\rangle = |a, \psi\rangle$, where $|\psi\rangle$ represents the center-of-mass part of the atomic wave-function and can be written as

$$|\psi\rangle = \frac{1}{\pi^{1/4}\alpha^{1/2}} \mathrm{e}^{\left[-\frac{(\boldsymbol{x}-\boldsymbol{x}_0)^2}{2\alpha^2} - \mathrm{i}\boldsymbol{k}_0\cdot(\boldsymbol{x}-\boldsymbol{x}_0)\right]}, \tag{2}$$

where α is the statistical-averaged width of atomic wave-packet having a Gauss distribution and $\boldsymbol{k}_0$ is the averaged wave vector of the initial atomic momentum. The initial position of the atom wave-packet is assumed as $x_0 = 0$.

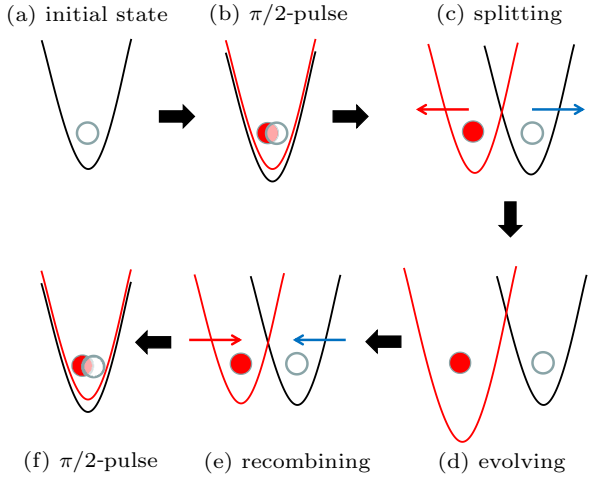


Fig. 1. Schematic diagram of a Ramsey interferometer with a trapped atom ensemble in two asymmetric ODTs. Time increases from (a) to (f). White circle: atom in state $|a\rangle$; red circle: atom in state $|b\rangle$. Blue and red arrows indicate directions of the displacements of transportation traps respectively. (a) A trapped atom ensemble is initially prepared in internal state $|a\rangle$; (b) a $\pi/2$-pulse puts the atoms in a coherent superposition of two internal states $|a\rangle$ and $|b\rangle$; (c) wave-packets for two internal states are removed adiabatically with two spatially separate trapping potentials; (d) wave-packets evolve in two asymmetric ODTs separated with a distance Δd; (e) wave-packets are adiabatically recombined into one trap; (f) a second $\pi/2$-pulse is applied to measure the probability of atoms in state $|b\rangle$.

The Raman light scheme has been described in detail before.[74,75] First, a $\pi/2$ Raman pulse excites the atom into a coherent superposition state $|\Psi\rangle = \frac{1}{\sqrt{2}}|a,\psi\rangle + \frac{\mathrm{i}}{\sqrt{2}}|b,\psi\rangle$. Then the state-selective transport operation is performed to move the spin state $|a\rangle$ of atom adiabatically to the right (whereas state $|b\rangle$ of atom moves to the left along an opposite direction). The adiabatic spatial separated directions of wave-packets depend on their internal spin states. Then two symmetric transport wells are switched off simultaneously and two asymmetric wells $V_1(\boldsymbol{x}_1)$ and $V_2(\boldsymbol{x}_2)$ are turned on. Wave-packets evolve independently under different dipole potentials. After a duration of holding time τ, the atom state evolves as $|\Psi\rangle = \frac{1}{\sqrt{2}}\mathrm{e}^{\mathrm{i}H_\uparrow\tau/\hbar}|a,\psi\rangle + \frac{\mathrm{i}}{\sqrt{2}}\mathrm{e}^{\mathrm{i}H_\downarrow\tau/\hbar}|b,\psi\rangle$, then two asymmetric wells are switched off and two symmetric transportation wells are turned on again. Lastly, wave-packets are recombined into the original potential well and a detecting $\pi/2$-pulse is applied instantly to obtain the population probabilities of atom in different spin states. In this process, wave-packets are split and recombined using transportation potentials that change from a single well into two separate symmetric wells and then come back. Both the splitting and recombination processes are adiabatic, and the time is neglected since it is so short as compared to the coherence time of the TAI.[30] The population probability of atom lastly in state $|b\rangle$ can be expressed as

$$P_\uparrow = \tfrac{1}{2}[1+\mathrm{Re}(\langle\psi|\mathrm{e}^{\mathrm{i}H_\downarrow\tau/\hbar}\cdot\mathrm{e}^{-\mathrm{i}H_\uparrow\tau/\hbar}|\psi\rangle)]. \tag{3}$$

The above process is similar to the Mach–Zehnder interferometer where the evolution of wave-packets in two separated asymmetric wells is analogous to the propagation of an optical field via two pathways. The wave-packets evolve in different paces under two asymmetric dipole potentials, thus it gives rise to an inhomogeneous dephasing to the TAI. The interference visibility reduces slowly due to different evolving paths of two wave-packets. Solving the nonlinear Schrödinger equation in a time-dependent interaction picture with Eqs. (1) and (2), we can obtain the simulated interference visibility of the TAI in this process. As shown in Fig. 2, the visibility decays totally when the accumulated phase difference $\Delta\phi$ of two wave-packets is large enough, but later there are some periodic revivals in the interference visibility. The interference visibility could be fully recovered at the integer multiples of the revival period T. For $U_1/k_\mathrm{B} = 6$ mK and $\eta = 1.1$, the revival period T is 2.84 ms. We note that the collapse and revival of the interference visibility is attributed to the phase difference $\Delta\phi$ of the wave-packets evolving in double asymmetric ODTs. It reflects the potential gradient versus time for the evolution of TAI in a phase space diagram. The interference visibility can also be expressed simply as

$$P_\uparrow = \frac{(1-\gamma)}{2}\cdot[1+C\cdot\cos(\Delta\phi)], \tag{4}$$

where γ represents the dissipation due to the anharmonic of dipole potentials $V_1(\boldsymbol{x}_1)$ and $V_2(\boldsymbol{x}_2)$, and C is the Ramsey fringe visibility. The visibility recovers and the revival appears when the relative phase meets $\Delta\phi = 2n\pi$.

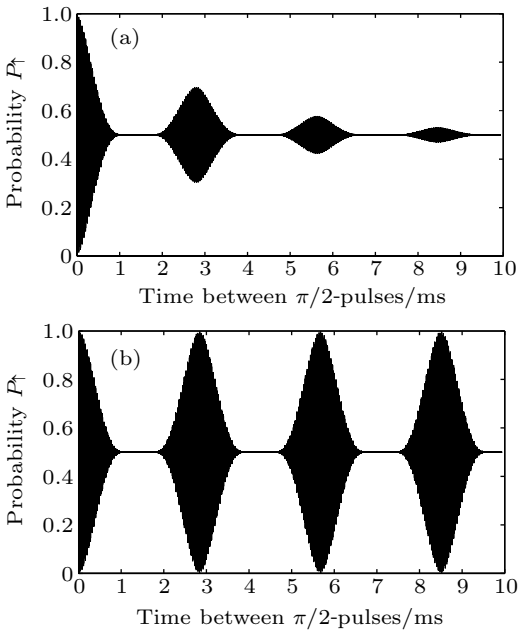


Fig. 2. Interference visibilities of a TAI in two asymmetric ODTs. The revival of the interference visibility is periodic: (a) $\lambda = 3\times10^{-7}U_1$, (b) $\lambda = 0$. Other parameters are trap depth $U_1/k_\mathrm{B} = 6$ mK, $\eta = 1.1$ and the initial atom temperature $T_0 = 2$ μK.

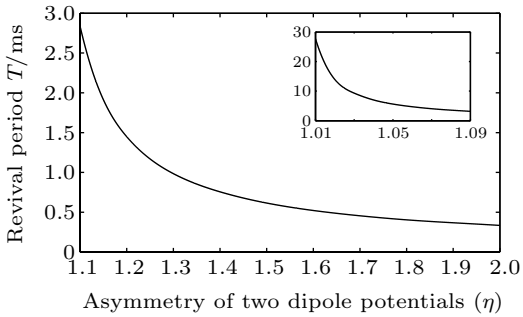


Fig. 3. The revival period T of the TAI influenced by the asymmetry of two ODTs. T decreases sharply as the asymmetry of the dipole potentials η increases. Other parameters are trap depth $U_1/k_B = 6$ mK, $\lambda = 3\times10^{-7}U_1$ and the initial atom temperature $T_0 = 2$ μK. Inset: the relation between T and η when η increases from 1.01 to 1.09.

In order to clearly investigate the interference properties of the TAI influenced by the asymmetry of two ODTs, next we neglect other dissipative effects except asymmetric trap potentials. Figure 2(b) shows the Ramsey visibility of the TAI without the dissipative effects. The dephasing induced by the asymmetry of two ODTs is reversible, and this is the result from the wave functions separation and periodic evolution of wave functions in the ODTs. Figure 3 shows the relation between the revival period T of the interference visibility and the asymmetry of two dipole potentials, η. The result is obtained by solving the nonlinear Schrödinger equation (3). As shown in Fig. 3, the revival period decreases as the asymmetry of two dipole potentials increases. The parabolic behavior indicates the phase of wave-packet changing quickly under the left deep trap. The revival period decreases sharply when η increases from an initially little value, which means that the phase shift is very sensitive to the asymmetry of two potentials, thus our scheme can be used as a sensitive way to detect the small changes of external potential. It can also be used as an effective method to cancel or compensate position/time-dependent asymmetric gradients which cause inhomogeneous dephasing like the tilting potentials, light shift, etc. Here we also note the initial atom temperature T_0 affects the statistical-averaged width α of the initial atomic wave-packet. The dissipation effect of the TAI increases as T_0 increases, but the revival period T does not changes with T_0.

3. Atom interferometer with echo sequence

In order to enhance the controllability of the interference process and attempt to reverse the inhomogeneous dephasing of the TAI caused by two asymmetric ODTs, we applied an echo sequence to the interference process mentioned above.

Figure 4 shows our schematic diagram for an echo sequence applied to a TAI in two asymmetric ODTs. An ensemble of atoms in ODT is initially in state $|\Psi\rangle = |a,\psi\rangle$. Firstly, a $\pi/2$-pulse excites the atom into a coherent superposition state $|\Psi\rangle = \frac{1}{\sqrt{2}}|a,\psi\rangle + \frac{\mathrm{i}}{\sqrt{2}}|b,\psi\rangle$. After two steps of the quantum interference loop as similarly shown in Fig. 1 but with an echo sequence inserted at time τ, i.e., the end of the first loop, two parts of the wave-functions are then recombined in a common optical dipole well. The second loop accumulates a phase opposite to the first loop. Lastly, the detecting $\pi/2$-pulse at $t = 2\tau$ is used to obtain the population probabilities of atoms in different spin states. The population probability of atoms lastly in $|b\rangle$ is given as follows:

$$P_\uparrow = \frac{1}{2}[1 - \mathrm{Re}(\langle\psi|\,\mathrm{e}^{\mathrm{i}H_\downarrow\tau/\hbar}\,\mathrm{e}^{\mathrm{i}H_\uparrow\tau/\hbar}\,\mathrm{e}^{-\mathrm{i}H_\downarrow\tau/\hbar}\,\mathrm{e}^{-\mathrm{i}H_\uparrow\tau/\hbar}|\psi\rangle)]. \quad (5)$$

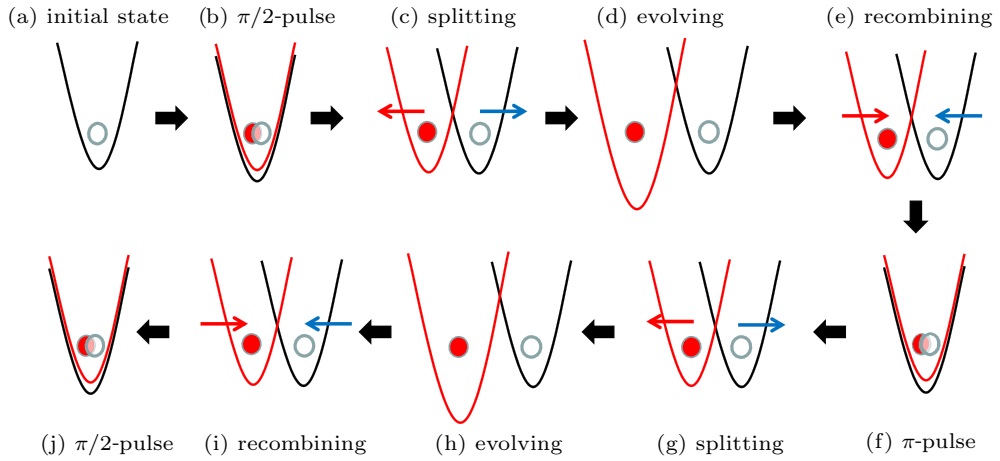


Fig. 4. Schematic diagram of an echo sequence applied to a TAI in two asymmetric ODTs. Time increases from (a) to (j). White circle: atom in state $|a\rangle$; red circle: atom in state $|b\rangle$. Blue and red arrows indicate directions of the displacements of traps respectively. (a)–(e) The same as those in Fig. 1. (f) A π-pulse is applied to reverse the atom state; (g) wave-packets for two internal spin states are removed adiabatically with two spatially separate symmetric transportation potentials; (h) wave-packets evolve independently in two asymmetric ODTs separated with a distance Δd; (i) wave-packets are adiabatically recombined again; (j) a $\pi/2$-pulse is used to probe the probability of atoms in state $|b\rangle$.

Figure 5 shows the interference visibility for a TAI in two asymmetric ODTs with echo sequence. In order to show the dynamical changes of the visibilities with time, here the adding time of the detecting $\pi/2$-pulse is varied and not fixed at 2τ. In Fig. 5(a), the echo sequence is added at time $\tau = 0.9$ ms, in which the interference visibility does not totally collapse. The following echo revival appears at time $2\tau = 1.8$ ms. In Fig. 5(b), the echo sequence is added at time $\tau = 1.6$ ms,

in which the interference visibility totally collapses. The following echo revival appears at time $2\tau = 3.2$ ms. This means that the atomic wave-packets totally coincide under the echo operation at the time of the echo revival. After that, the interference visibility starts its periodic revival which is only linked to the asymmetry of two spatially separated dipole potentials.

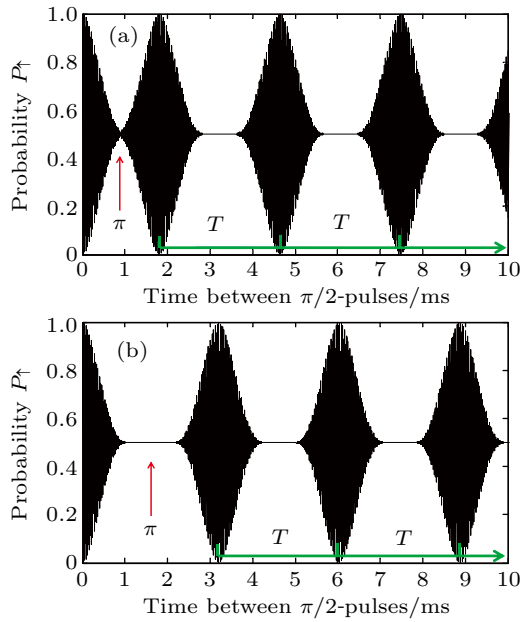


Fig. 5. The echo interference visibilities of a TAI in two asymmetric ODTs. (a) A π-pulse is added at the time of $\tau = 0.9$ ms, the echo revival appears at 1.8 ms, i.e., double time of the π-pulse time. After the echo revival, the periodic revivals recover in the interference visibility of the interferometer. (b) A π-pulse is added at the time of $\tau = 1.6$ ms, the echo revival appears at 3.2 ms. Other parameters are trap depth $U_1/k_B = 6$ mK, $\eta = 1.1$, $\lambda = 0$ and the initial atom temperature $T_0 = 2$ μK.

In this echo interference process, atoms travel fully symmetric paths and the inhomogeneous dephasing caused by the dipole potentials can be totally reversed by the echo sequence. This makes the double well interferometer scheme suitable to measure time-controllable gradients in differential situations.[32] Furthermore, the echo sequence can also be used to cancel the inhomogeneous phase shift caused by the background gradient and study of discrete-time quantum walks (DTQWs) which is hopeful to provide an universal computational primitive and the basic building blocks of a series of quantum algorithms.[76]

4. Conclusion

In summary, we have investigated the interference properties of a TAI influenced by the asymmetry of two spatial separated ODTs. The interference visibility of the TAI presents periodic revivals which are directly linked to the potential difference of two dipole traps. An echo sequence is introduced to the TAI in two asymmetric ODTs. We find that the inhomogeneous dephasing caused by the asymmetric ODTs can be totally reversed by the echo sequence. Moreover, the echo sequence influences the beginning time of the periodic revivals. Based on this, one can choose the best detection time of the atom interferometer in order to maximize the output signal. It could be beneficial to future manufacturing of quantum computer,[77] precision measurement, and also useful to help us to determine the best position/time, to conduct the measurement process and to obtain an optimizing signal in many fields like atom waveguides,[78,79] optical lattice, atom chips, etc., since the interference visibility presents a periodic revival behavior in this case. The asymmetric potential wells can also be used to cancel or compensate the phase shift caused by position and time correlated force of a TAI significantly, thus it can be used as a matter-wave beam splitter or act as a phase shifter.

The TAI in two asymmetric ODTs will be useful in applications such as quantum cellular automata,[80–82] atomic point sources and spatially resolved detection,[4,83] measuring gravity and magnetic field varying gradients,[84,85] measurement of the spatially distributed force and time-dependent potential,[86–88] controlling collisions between neighbouring atoms,[26,89] etc. We propose our design scheme is promising to be integrated onto many experimental systems like the atom chip,[90–92] 1D optical lattice,[43–45] waveguides,[93] magnetic microtrap [94] and trapped ions in a linear Paul trap.[38]

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