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Efficient two-dimensional atom localization in a four-level atomic system beyond weak-probe approximation

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ABSTRACT

We present a new scheme for high-efficiency two-dimensional (2D) atom localization in a four-level atomic system via measuring the populations in two excited states beyond weak-probe approximation. Owing to the space-dependent atom-field interaction, the position probability distribution of the atom passing through the standing waves can be directly determined by measuring the populations in two excited states. It is found that the phase-sensitive property of the atomic system significantly reduces the uncertainty in the position measurement of the atom. Especially the probability of finding the atom at a particular position can be almost 100% via properly varying the parameters of the system. The proposed scheme may open a promising way to achieve high-precision and high-efficiency 2D atom localization.

1. Introduction

In the past few decades, the precision position measurement of an atom has been the subject of many recent studies because of its potential applications in laser cooling and trapping of neutral atoms [1], atom nano-lithography [2], Bose–Einstein condensation [3], etc. In some pioneering work, Thomas and colleagues have suggested and experimentally demonstrated subwavelength position localization of atoms using spatially varying energy shifts [4,5]. Walls and coworkers have discussed subwavelength atom localization using the measurement of the phase shift [6] after the passage of the atom through an off-resonant standing-wave field. In addition, two schemes for position measurement were performed, using absorption light masks [7,8], in which the precision of measurement achieved was nearly tens of nanometers.

On the other hand, it is well understood that, atomic coherence and interference can give rise to some interesting phenomena [9–12]. Based on atomic coherence and interference, a variety of schemes for the precise localization of the atom in one dimension have been proposed. For example, Paspalakis and Knight proposed a quantum-interference-induced sub-wavelength atomic localization a three-level Λ-type atom, and they found that the atomic position with high precision can be achieved via the measurement of the upper-state population of the atom [13]. Zubairy and coworkers have discussed atom localization using resonance fluorescence and phase and amplitude control of the absorption spectrum [14–16], and Agarwal and Kapale presented a scheme [17] based on coherent population trapping (CPT). Also, one-dimensional (1D) atom localization can be realized via dual measurement of the field and the atomic internal state [18], double-dark resonance effects [19], phase and amplitude control of the driving field [20,21], or coherent manipulation of the Raman gain process [22]. Recently, atom localization has been demonstrated in a proof-of-principle experiment using the technique of electromagnetically induced transparency (EIT) [23].

Apart from the above-mentioned 1D atom localization, more recently, some schemes have been put forward for two-dimensional (2D) atom localization by applying two orthogonal standing-wave laser fields. For instance, a scheme for 2D atom localization was proposed by Ivanov and Rozhdestvensky using the measurement of the population in the upper state or in any ground state in a four-level tripod system [24]. Another related 2D localization schemes have been studied by Wan, Ding and their coworkers via controlled spontaneous emission [25], probe absorption and gain [26–28], and interacting double-dark resonances [29]. In addition, atom nano-lithography based on 2D atom localization has been achieved by Gong et al. in [30].

In this work, we investigate the 2D atom localization via the measurement of the populations in two excited states in a four-level atomic system. Owing to the space-dependent atom-field interaction, the position probability distribution of the atom passing through the standing waves can be directly determined by measuring the populations in two excited states. The study and system are mainly based on [24–30], however, our scheme show some intrinsical characteristics that these schemes do not have. First, we are interested in showing the 2D atom localization via measurement of the populations in two excited states beyond weak-probe approximation, the expression for filter function

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$F(x,y;t\to\infty)$ under steady state conditions including all orders of all fields. Second, the maximal probability of finding an atom at a certain position is 100%, which is increased by a factor of 2 or 4 compared with the previous schemes [24,25,29,30]. Third, population measurement is much easier to carry out in a laboratory compared with the measurement of spontaneous emission [23]. In our scheme, the atom is prepared in the ground state, which is very easy to implement in atomic physics experiments.

2. The model and dynamic equations

We consider a four-level atomic system as shown in Fig. 1(a), which has two stable ground states $|1\rangle$ and $|2\rangle$, and two excited states $|3\rangle$ and $|4\rangle$. The atom moves in the z direction and passes through the intersectant region of two orthogonal classical standing-wave fields, which are respectively aligned along the x- and the y-axes (see Fig. 1(b)). Four laser components $E_m e^- i(\omega_m t+\phi_m)+c.c.(m=1\sim4)$ are applied to the transitions $|1\rangle\leftrightarrow|3\rangle$, $|1\rangle\leftrightarrow|4\rangle$, $|2\rangle\leftrightarrow|3\rangle$ and $|2\rangle\leftrightarrow|4\rangle$, respectively, where E_m, ω_m, and ϕ_m are the amplitudes, the frequencies and the initial phases. The four fields have the frequency matching relation $\omega_1+\omega_3=\omega_2+\omega_4$. E_1 and E_2 are weak fields as the probe components, and E_3 and E_4 are strong fields as the driving components. E_3 is dependent on the position and is defined by $E_3=E_3^s\ [\sin(kx)+\sin(ky)]$ with wave vector k. We assume that the center-of-mass position of the atom is nearly constant along the directions of the laser waves and neglect the kinetic part of the atom from the Hamiltonian in the Raman-Nath approximation. Note that during the interaction the atomic position does not change

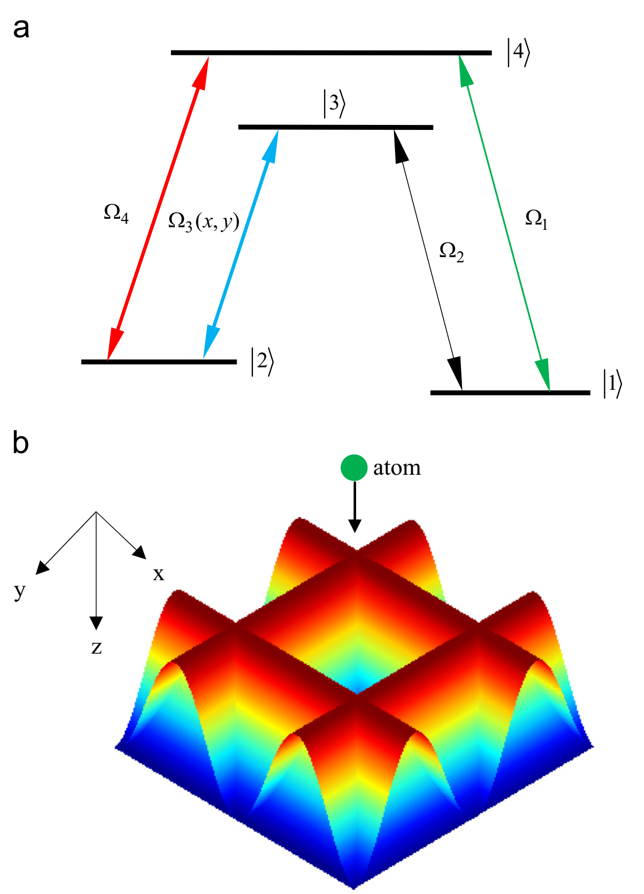

Fig. 1. Schematic diagrams: (a) A four-level atomic system and (b) an atom moves along the z-axis and interacting with two orthogonal standing-wave fields in the $x-y$ plane.

directly and our localization scheme only influences the internal states of the atom. Then, in the interaction picture and under the rotating-wave approximation, the Hamiltonian of this system is given as follows ($\hbar=1$) :

$$H_{int}=(\Delta_3-\Delta_2)|2\rangle\langle2|-\Delta_2|3\rangle\langle3|-\Delta_1|4\rangle\langle4| \\ -(\Omega_1|4\rangle\langle1|+\Omega_2|3\rangle\langle1|+\Omega_3|3\rangle\langle2|+\Omega_4 e^{-i\Phi}|4\rangle\langle2|+H.c.), \quad (1)$$

where $\Delta_1=\omega_1-\omega_{41}$, $\Delta_2=\omega_2-\omega_{31}$, $\Delta_3=\omega_3-\omega_{32}$, and $\Delta_4=\omega_4-\omega_{42}$ are the atom-field detunings, and ω_{41}, ω_{42}, ω_{32} and ω_{31} are resonant frequencies which associate with the corresponding transitions. These detunings satisfy the relation $\Delta_1+\Delta_3=\Delta_2+\Delta_4$. $2\Omega_3=\Omega[\sin(kx)+\sin(ky)]=E_3\mu_{32}/\hbar$, $2\Omega_1=E_1\mu_{41}/\hbar$, $2\Omega_2=E_2\mu_{31}/\hbar$ and $2\Omega_4=E_2\mu_{42}/\hbar$ are the Rabi frequencies of the optical fields with μ_{mn} (m=3,4; n=1, 2) are the dipole matrix elements. $\Phi=\phi_1+\phi_3-\phi_2-\phi_4$ is the collective phase of the four applied fields.

The dynamics of the system can be described using the density-matrix approach as

$$\frac{\partial\rho}{\partial t}=-\frac{i}{\hbar}[H,\rho]+L\rho, \quad (2)$$

and then we have

$$\frac{\partial\rho_{22}}{\partial t}=\gamma_3\rho_{33}+\gamma_4\rho_{44}+i\Omega_3\rho_{32}-i\Omega_3\rho_{23}+i\Omega_4\rho_{42}e^{i\Phi}-i\Omega_4\rho_{24}e^{-i\Phi}, \quad (3)$$

$$\frac{\partial\rho_{33}}{\partial t}=-(\gamma_2+\gamma_3)\rho_{33}-i\Omega_2\rho_{31}+i\Omega_2\rho_{13}-i\Omega_3\rho_{32}+i\Omega_3\rho_{23}, \quad (4)$$

$$\frac{\partial\rho_{44}}{\partial t}=-(\gamma_1+\gamma_4)\rho_{44}-i\Omega_1\rho_{41}+i\Omega_1\rho_{14}-i\Omega_4\rho_{42}e^{i\Phi}+i\Omega_4\rho_{24}e^{-i\Phi}, \quad (5)$$

$$\frac{\partial\rho_{12}}{\partial t}=-i(\Delta_2-\Delta_3)\rho_{12}-i\Omega_3\rho_{13}+i\Omega_2\rho_{32}-i\Omega_4\rho_{14}e^{-i\Phi}+i\Omega_1\rho_{42}, \quad (6)$$

$$\frac{\partial\rho_{13}}{\partial t}=-\left(\frac{\gamma_2+\gamma_3}{2}+i\Delta_2\right)\rho_{13}-i\Omega_2(\rho_{11}-\rho_{33})-i\Omega_3\rho_{12}+i\Omega_1\rho_{43}, \quad (7)$$

$$\frac{\partial\rho_{14}}{\partial t}=-\left(\frac{\gamma_1+\gamma_4}{2}+i\Delta_1\right)\rho_{14}-i\Omega_1(\rho_{11}-\rho_{44})-i\Omega_4\rho_{12}e^{i\Phi}+i\Omega_2\rho_{34}, \quad (8)$$

$$\frac{\partial\rho_{23}}{\partial t}=-\left(\frac{\gamma_2+\gamma_3}{2}+i\Delta_3\right)\rho_{23}-i\Omega_3(\rho_{22}-\rho_{33})-i\Omega_2\rho_{21}+i\Omega_4\rho_{43}e^{i\Phi}, \quad (9)$$

$$\frac{\partial\rho_{24}}{\partial t}=-\left(\frac{\gamma_1+\gamma_4}{2}+i\Delta_4\right)\rho_{24}-i\Omega_4(\rho_{22}-\rho_{44})e^{i\Phi}-i\Omega_1\rho_{21}+i\Omega_3\rho_{34}, \quad (10)$$

$$\frac{\partial\rho_{34}}{\partial t}=-\left[\frac{\gamma_1+\gamma_2+\gamma_3+\gamma_4}{2}+i(\Delta_1-\Delta_2)\right]\rho_{34}-i\Omega_1\rho_{31} \\ +i\Omega_2\rho_{14}-i\Omega_4\rho_{32}e^{i\Phi}+i\Omega_3\rho_{24}, \quad (11)$$

where $\gamma_m(m=1\sim4)$ are decay rates $|4\rangle\leftrightarrow|1\rangle$, $|3\rangle\leftrightarrow|1\rangle$, $|3\rangle\leftrightarrow|2\rangle$ and $|4\rangle\leftrightarrow|2\rangle$, respectively.

Then the conditional position probability distribution is given by the probability of finding the atom in the two excited states $|3\rangle$ and $|4\rangle$,

$$W(x,y;t\to\infty)=|\mathbb{N}|^2|f(x,y)|^2[\rho_{33}(x,y;t\to\infty)+\rho_{44}(x,y;t\to\infty)], \quad (12)$$

where $\mathbb{N}$ is a normalization factor, and $f(x,y)$ is the center-of-mass wave function of the atom.

As $f(x,y)$ is assumed to be nearly constant over many wavelengths of the standing-wave field, the conditional position probability distribution is determined by the filter function

$$F(x,y;t\to\infty)=\rho_{33}(x,y;t\to\infty)+\rho_{44}(x,y;t\to\infty). \quad (13)$$

Therefore, the problem is now reduced to the determination of the populations in two excited states $|3\rangle$ and $|4\rangle$, which can be easily