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# Sub-half-wavelength atom localization via probe absorption spectrum in a four-level atomic system

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ABSTRACT

We present a simple scheme of atom localization in a subwavelength domain via manipulation of probe absorption spectrum in a four-level atomic system. By applying two orthogonal standing-wave fields, the localization peak position and number as well as the conditional position probability can be controlled by the intensities and detunings of optical fields, and the sub-half-wavelength atom localization is also observed. More importantly, there is 100% detecting probability of the atom in the subwavelength domain when the corresponding conditions are satisfied.



## 1. Introduction

During the past few years, the precision position measurement of an atom has been the subject of many recent studies because of its potential wide applications in trapping of neutral atoms, laser cooling [1], atom nano-lithography [2], etc. Earlier studies for localization include the measurement of the phase shift of either the standing wave or the atomic dipole [3] due to the interaction of the atom with the standing-wave field, the entanglement between the atom's position and its internal states [4], and resonance imaging methods [5].

It is well known that lots of quantum optical phenomena based on quantum coherence and interference have also attracted attention of many researchers, such as coherent population trapping [6], electromagnetically induced transparency [7–10], lasing without inversion [11–13], multi-wave mixing [14–16], enhancing Kerr nonlinearity [17,18], optical soliton [19–21], enhancement of the refractive index with zero absorption [22], optical bistability/multistability [23–26], and so on. Furthermore, it has been shown that atomic coherence and quantum interference play crucial roles in atom localization. Based on atomic coherence and quantum interference, many schemes [27–37] have been proposed for atom localization. For example, Herkommer, Schleich, and Zubairy proposed a scheme in which the Autler–Townes spontaneous spectrum is used [27]. Qamar et al. suggested atom localization based on resonance fluorescence in a two-level system driven by a strong standing-wave field [28], and later Paspalakis and Knight proposed a quantum-interference-induced subwavelength atomic localization a three-level $\Lambda$-type atom interacting with a classical standing-wave field and a weak probe laser field, and they found that the atomic position with high precision can be achieved via the measurement of the upper-state population of the $\Lambda$-type atom as the atom moves in the standing-wave field [29]. Recently, in a four-level atomic system with a closed-loop configuration, Zubairy and coworkers again showed two atom localization schemes [30,31] that the phase of the standing-wave driving field played an important role in reducing the number of localization peaks from the usual four to two, leading to sub-half-wavelength localization. At the same time, Gong et al. presented atom localization schemes [32,33] based on double-dark resonance effects and demonstrated that the atom can be localized at the nodes of the standing-wave field, and the detecting probability can be increased to 1/2. Interestingly, instead of the measurement of the population in the excited state, the detection of the population in the ground state coupled to the standing-wave field leads to only two localization peaks in a unit wavelength region. This was shown by Agarwal and Kapale [34], who put emphasis on the momentum distribution and the role of the ratio of the intensities of the coupling and probe fields. Of course, some relative schemes for realizing atom localization are also studied [35–38].

In this Letter, we investigate the subwavelength localization of an atom in a four-level Y-type atomic system due to the interaction with a probe laser field and two orthogonal standing-wave

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fields. It is found that the localization peak position and number as well as the conditional position probability can be controlled by the intensities and detunings of optical fields. Our study and system are mainly based on Refs. [38–42], however, which are drastically different from those works. First and foremost is that we are mainly interested in showing the atom localization via probe absorption spectrum under corresponding conditions. Secondly, the sub-half-wavelength localization in this atomic system is also observed, and which has shown some intrinsical characteristics that other schemes of sub-half-wavelength atom localization do not have. Thirdly, an important advantage of our scheme is that the 100% detecting probability of this atom in the sub-wavelength domain can be achieved when the corresponding conditions are satisfied, which may provide some new possibilities for the technological applications in laser cooling or atom nano-lithography. Our Letter is organized as follows: in Section 2, we present the theoretical model and establish the corresponding equations. The possible experimental realization and numerical results are shown in Sections 3 and 4, respectively. In Section 5, some simple conclusions are given.

## 2. The model and dynamic equations

We consider the four-level Y-type atomic system as shown in Fig. 1(a). This system has one stable ground state $|0\rangle$, an intermediate level $|1\rangle$ and two nearly degenerate excited states $|2\rangle$ and $|3\rangle$. Two classical standing-wave fields $S_{x1}$ and $S_{x2}$ are applied to couple transitions $|2\rangle \leftrightarrow |1\rangle$ and $|3\rangle \leftrightarrow |1\rangle$, respectively. Their Rabi frequencies are dependent on the position and are defined by $2\Omega_{x1} = 2\Omega(x1)\sin(k_{x1}x)$ (frequency $\omega_{x1}$) and $2\Omega_{x2} = 2\Omega(x2)\sin(k_{x2}x)$ (frequency $\omega_{x2}$). We apply a weak probe field with the Rabi frequency $2\Omega_p$ (frequency $\omega_p$) to couple the transition $|3\rangle \leftrightarrow |1\rangle$. Here, we have assumed that a direct transition between the excited states $|2\rangle \leftrightarrow |3\rangle$ and that between the excited and ground states $|2\rangle$, $|3\rangle \leftrightarrow |0\rangle$ of the atom are forbidden in the dipole approximation. All the optical driving fields are applied in the $x$–$y$ plane, so that the atom meets them at the same time as it travels along the $z$ direction. The $\omega_{21}$, $\omega_{31}$, and $\omega_{10}$ are resonant frequencies which associate with the corresponding transitions $|2\rangle \leftrightarrow |1\rangle$, $|3\rangle \leftrightarrow |1\rangle$, and $|1\rangle \leftrightarrow |0\rangle$.

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 [20]. Note that during the interaction the atomic position does not change 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 ($\hbar = 1$) [14]

$$H_{int} = -\Delta_p|1\rangle\langle 1| - (\Delta_p + \Delta_{x1})|2\rangle\langle 2| - (\Delta_p + \Delta_{x2})|3\rangle\langle 3| - \big(\Omega_p|1\rangle\langle 0| + \Omega(x1)|2\rangle\langle 1| + \Omega(x2)|3\rangle\langle 1| + \text{H.c.}\big), \quad (1)$$

where H.c. means Hermitian conjugation. $\Delta_p = \omega_p - \omega_{10}$, $\Delta_{x1} = \omega_{x1} - \omega_{21}$, and $\Delta_{x2} = \omega_{x2} - \omega_{31}$ are the detunings of the probe field, the standing-wave field $S_{x1}$, and the standing-wave field $S_{x2}$, respectively. $2\Omega(x1) = E_{x1}\mu_{21}/\hbar$, $2\Omega(x2) = E_{x2}\mu_{31}/\hbar$, and $2\Omega_p = E_p\mu_{10}/\hbar$ are the Rabi frequencies of the optical fields. $\mu_{mn}$ $(m, n = 0, 1, 2, 3)$ are the dipole matrix elements and $E_j$ $(j = x1, x2, p)$ are the slowly varying amplitudes of the optical fields.

Under rotating-wave and slowly varying envelope approximations, the equation of motion that governs the probability amplitudes of the above four-level atomic system is given by

$$-i\frac{\partial A_1}{\partial t} = \Delta_p A_1 + i\gamma_1 A_1 + \Omega(x2)A_3 + \Omega(x1)A_2 + \Omega_p A_0,$$
$$-i\frac{\partial A_2}{\partial t} = (\Delta_p + \Delta_{x1})A_2 + i\gamma_2 A_2 + \Omega(x1)A_1,$$

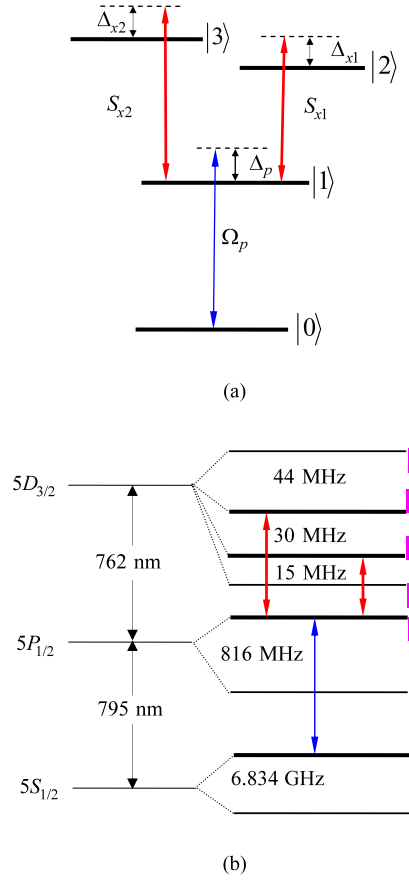


**Fig. 1.** (a) Schematic diagram of a four-level Y-type atomic system. (b) Specific case for $^{87}$Rb atom as an example in (a).

$$-i\frac{\partial A_3}{\partial t} = (\Delta_p + \Delta_{x2})A_3 + i\gamma_3 A_3 + \Omega(x2)A_1, \quad (2)$$

constrained by $|A_0|^2 + |A_1|^2 + |A_2|^2 + |A_3|^2 = 1$. $\gamma_i$ $(i = 1, 2, 3)$ are added phenomenologically to describe the corresponding decay rates of the state $|i\rangle$.

In the limit of the weak-probe field, almost all atoms will remain in the level $|0\rangle$ and we can assume that $|A_0|^2 \approx 1$ during the atom–field interaction. Under this assumption, we can then obtain straightforwardly the steady-state solutions of Eq. (2) and the susceptibility at the probe frequency can be written as

$$\chi = \frac{N|\mu_{10}|^2}{\varepsilon_0\hbar\Omega_p}A_1A_0^* = \frac{\mathbb{N}}{\Omega_p}A_1, \quad (3)$$

where

$$\mathbb{N} = \frac{N|\mu_{10}|^2}{\varepsilon_0\hbar}, \quad (4)$$

$$A_1 = \frac{\Omega_p}{\frac{\Omega^2(x1)}{\alpha_2} + \frac{\Omega^2(x2)}{\alpha_3} - \alpha_1}, \quad (5)$$

with $\alpha_1 = \Delta_p + i\gamma_1$, $\alpha_2 = \Delta_p + \Delta_{x1} + i\gamma_2$ and $\alpha_3 = \Delta_p + \Delta_{x2} + i\gamma_3$. $N$ is the atom number density in the medium.

It is well known that the imaginary part of the susceptibility accounts for absorption, based on Eqs. (3) and (5), which can be expressed as follows (keep $\mathbb{N} = 1$)

$$\text{Im}(\chi) \simeq \text{Im}\left(\frac{A_1}{\Omega_p}\right) = \text{Im}\frac{1}{\frac{\Omega^2(x1)}{\alpha_2} + \frac{\Omega^2(x2)}{\alpha_3} - \alpha_1}. \quad (6)$$