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Atom localization in a Doppler broadened medium via two standing-wave fields

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The atom localization has been achieved in a four-level V-type atomic system interacting with two classical unidirectional standing-wave fields and weak probe field in a Doppler broadened medium under several conditions at very low temperature. The precision of the atom localization is compared with the system in the presence and absence of the Doppler broadened medium. The influence of some parameters such as the amplitude, wave vectors and the phase shift of the standing-wave fields on the atom localization is studied and has been found to obtain various atom localization patterns with symmetric shape.

1. Introduction

The quantum coherence in an atomic medium has been applied in different areas of atomic optics [1–4] and led to modifying interesting phenomena in the fundamental studies and practical applications, such as electromagnetically induced transparency (EIT), coherent population trapping (CPT), refractive index, optical bistability and subluminal or superluminal light propagation [5–10]. Recent studies, for a simple scheme two-level atomic system interacting with a single mode standing-wave field in a cavity surrounded by Kerr-like medium and the atom moving in the Raman–Nath regime (i.e. where the kinetic energy term is neglected), show that some statistical properties of the field, such as Q distribution function, entropy and phase distribution can be affected by the spread of atomic wave function [11]. Other several schemes have been proposed for moving atoms through a standing-wave field of a cavity by studying the atom localization via quantum interference [12], spontaneous emission [13], the amplitude and phase of standing-wave field [14] and fluorescence [15].

Zubairy and co-workers [16–18] proposed a scheme based on Autler–Townes spontaneous emission spectrum in a three and four-level atomic system, they have shown that the precision of the position measurement of the atom depended on the relative phase of the driving fields, whereas the phase of the standing-wave driving field had an important role in reducing the number of localization peaks from the usual four to two, leading to a new localization scheme which is called sub-half-wavelength localization. The progress of the sub-wavelength atom localization techniques in the last couple of decades was reviewed by Kapale [19]. Atomic coherence effect, such as coherent population trapping, has been shown to be useful for sub-wavelength localization of the atom by Agarwal and Kapale [20]. The sub-wavelength localization of an ensemble of atoms was demonstrated in a four level atomic system via super fluorescence [21], probe absorption [22], and phase sensitive absorption [23] and has been also achieved by bichromatic phase control of the spontaneous emission spectrum [24]. In other interesting works [25,26], it was shown that the four-level scheme can be used to localize an atom flying through the standing-wave field to sub-wavelength domain via amplitude and phase control of the absorption spectrum.

Recently, one of the experiments has achieved the atom localization during the motion of atom through the standing-wave field, which is important to have as low of an atomic temperature as possible. This experiment was performed using ultracold ^{87}Rb atoms [27].

The present work is concerned with the study of a four-level V-type atomic system interacting with a weak probe field and passes through two unidirectional standing-wave fields. The purpose of the paper is to study the atom localization through the absorption spectrum of the imaginary part of the susceptibility for a weak probe field in the presence of a Doppler broadened medium at very low temperature of Rubidium atom ^{87}Rb, under the condition that the atom moves in the Raman–Nath regime (that is, where the kinetic energy term is neglected [11,19]). We analyze the effect of some parameters such as the detunings, wave-vector, amplitude and phase shift of the standing-wave fields on the precision of the atom localization. The precision of atom

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localization is obtained in the Doppler broadening medium and depends strongly on the parameters of standing-wave fields, especially on the detunings and the phase shift of the standing-wave fields. Various atom localization patterns could be achieved within the space period and may be useful for atom lithography. This is the motivation behind this work.

The paper is organized as follows: In Section 2, system description is given. In Section 3, numerical results and discussion is given. Finally, the conclusion is presented.

2. System description

Consider a four-level atomic system in V-type with states $|1\rangle$, $|2\rangle$, $|3\rangle$ and $|4\rangle$ in relevant parts of the level scheme for ^{87}Rb of the atomic state $|5P_{1/2}, F=3\rangle$, $|5S_{1/2}, F=2\rangle$, $|5P_{1/2}, F=1\rangle$ and $|5P_{3/2}, F=1\rangle$, respectively (as shown in Fig. 1), with the density of atom N. A weak probe field of frequency ω_p (amplitude E_p) is applied to the transition $|2\rangle \leftrightarrow |3\rangle$ (transition frequency ω_{32}) with a Rabi frequency $\Omega_p = E_p d_{23}/\hbar$ (where d_{ij} is the dipole moment between the states $|i\rangle$ and $|j\rangle$). Assuming the atom moving in the z-direction passes through two classical standing-wave fields aligned along the x-direction and the interactions between the atom and two standing-wave fields are position-dependent with different transitions. The transitions $|2\rangle$ to $|1\rangle$ (transition frequency ω_{12}) and $|3\rangle$ to $|4\rangle$ (transition frequency ω_{43}) interact with two unidirectional standing-wave fields (with frequency ω_1, ω_2) and having Rabi frequencies $\Omega_1(x)$ and $\Omega_2(x)$ as pump and control fields, respectively. The corresponding position-dependent Rabi frequencies are defined as

$$\Omega_1(x) = \Omega_1 \sin(k_1 x + \eta_1) \tag{1}$$

$$\Omega_2(x) = \Omega_2 \sin(k_2 x + \eta_2) \tag{2}$$

where Ω_i (i=1,2), $k_i = 2\pi/\lambda_i$ and η_i are the amplitude, the wave number and the phase shift, respectively, associated with the standing-wave field. We may assume that the center-of-mass position of the atom is nearly constant along the direction of the standing-waves. Hence, by applying the Raman–Nath approximation [11,19,28], we may neglect the kinetic energy term from the Hamiltonian and the corresponding term from the density matrix elements. The Hamiltonian of the system in the rotating-wave approximation [29] can be written as

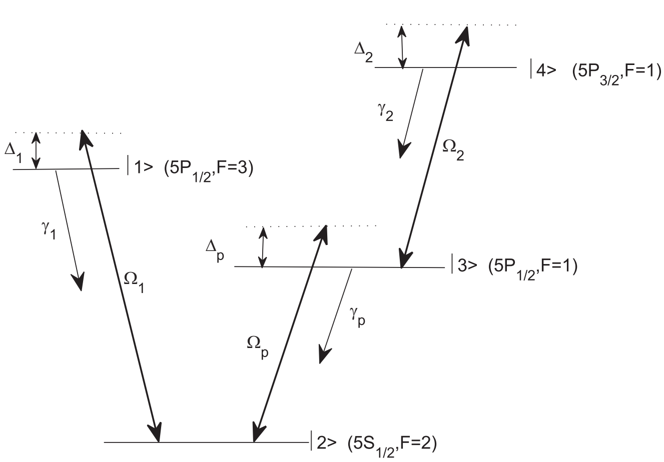

Fig. 1. The scheme of a four-level V-type atom in a Doppler-broadened medium.

$$H = H_0 + H_I, \tag{3}$$

where

$$H_0 = -\hbar\Delta_1|1\rangle\langle 1| - \hbar\Delta_p|3\rangle\langle 3| - \hbar(\Delta_p + \Delta_2)|4\rangle\langle 4|, \tag{4}$$

$$H_I = -\frac{1}{2}\hbar\left(\Omega_1(x)|1\rangle\langle 2| + \Omega_p|3\rangle\langle 2| + \Omega_2(x)|4\rangle\langle 3| + h.c.\right). \tag{5}$$

The detunings are denoted by $\Delta_1 = \omega_1 - \omega_{12}$, $\Delta_p = \omega_p - \omega_{32}$, $\Delta_2 = \omega_2 - \omega_{43}$. The master equation for the density matrix [28] to our model takes the following form:

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] + \gamma_1 J_{21}\rho + \gamma_p J_{23}\rho + \gamma_2 J_{34}\rho, \tag{6}$$

where

$$J_{ij}\rho = \frac{1}{2}(2|i\rangle\langle j|\rho|j\rangle\langle i| - |j\rangle\langle i||i\rangle\langle j|\rho - \rho|j\rangle\langle i||i\rangle\langle j|), \quad i, j = 1, 2, 3, 4. \tag{7}$$

The spontaneous decay rates from the atomic level $|1\rangle$ to $|2\rangle$, $|3\rangle$ to $|2\rangle$ and $|4\rangle$ to the level $|3\rangle$ are labeled as γ_1, γ_p and γ_2, respectively. According to Eq. (6), we can obtain the equations of motion for the density matrix elements as (for simplicity $\hbar = 1$)

$$\dot{\rho}_{11} = -\gamma_1\rho_{11} - \frac{i}{2}\Omega_1(x)(\rho_{12} - \rho_{21}), \tag{8}$$

$$\dot{\rho}_{33} = -\gamma_p\rho_{33} + \gamma_2\rho_{44} - \frac{i}{2}\Omega_2(x)(\rho_{34} - \rho_{43}) + \frac{i}{2}\Omega_p(\rho_{23} - \rho_{32}), \tag{9}$$

$$\dot{\rho}_{44} = -\gamma_2\rho_{44} + \frac{i}{2}\Omega_2(x)(\rho_{34} - \rho_{43}), \tag{10}$$

$$\dot{\rho}_{12} = \left[i\Delta_1 - \frac{1}{2}\gamma_1\right]\rho_{12} - \frac{i}{2}\Omega_p\rho_{13} + \frac{i}{2}\Omega_1(x)(\rho_{22} - \rho_{11}), \tag{11}$$

$$\dot{\rho}_{31} = \left[-i(\Delta_1 - \Delta_p) - \frac{1}{2}\left(\gamma_1 + \gamma_p\right)\right]\rho_{31} - \frac{i}{2}\Omega_1(x)\rho_{32} + \frac{i}{2}\Omega_2(x)\rho_{41} + \frac{i}{2}\Omega_p\rho_{21}, \tag{12}$$

$$\dot{\rho}_{32} = \left[i\Delta_p - \frac{1}{2}\gamma_p\right]\rho_{32} - \frac{i}{2}\Omega_1(x)\rho_{31} + \frac{i}{2}\Omega_2(x)\rho_{42} + \frac{i}{2}\Omega_p(\rho_{22} - \rho_{33}), \tag{13}$$

$$\dot{\rho}_{42} = \left[i(\Delta_2 + \Delta_p) - \frac{1}{2}\gamma_2\right]\rho_{42} - \frac{i}{2}\Omega_1(x)\rho_{41} + \frac{i}{2}\Omega_2(x)\rho_{32} - \frac{i}{2}\Omega_p\rho_{43}, \tag{14}$$

$$\dot{\rho}_{41} = \left[-i(\Delta_1 - \Delta_2 - \Delta_p) - \frac{1}{2}\left(\gamma_1 + \gamma_2\right)\right]\rho_{41} - \frac{i}{2}\Omega_1(x)\rho_{42} + \frac{i}{2}\Omega_2(x)\rho_{31}, \tag{15}$$

$$\dot{\rho}_{43} = \left[i\Delta_2 - \frac{1}{2}\left(\gamma_2 + \gamma_p\right)\right]\rho_{43} - \frac{i}{2}\Omega_p\rho_{42} + \frac{i}{2}\Omega_2(x)(\rho_{33} - \rho_{44}), \tag{16}$$

with the trace condition $\sum_{i=1}^{4} \rho_{ii} = 1$.