Localizing of a Four-Level Atom via Absorption Spectrum

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Abstract

We propose a scheme for localizing an atom in a four-level configuration inside a classical standing wave field, conditioned upon the measurement of frequency of a weak probe field. In the classical standing wave field, the interaction between the atom and the field is position dependent due to the Rabi-frequency of the driving field. Hence, as the absorption frequency of the probe field is measured the position of the atom inside the classical standing wave field will be determined. Localizing of the atom via the absorption spectrum occurs during its motion in the standing wave field. The investigation of the probe field absorption shows that the degree of localization depends on the interaction parameters such as detuning, and Rabi-frequency of the driving field.

Keywords: Atom localization; Absorption; Susceptibility

I) Introduction

The precision position measurement of an atom with the optical technique is of considerable interest, both from the theoretical and experimental point of views. The most important interest in determination of the atomic position is due to the application in laser cooling and trapping [1], Bose-Einstein condensation [2], atom lithography [3], and measurement of the center of mass wave function of moving atoms [4]. Several schemes have been established to determine the position of an atom via optical methods. In the optical virtual slits scheme, the atom interacts with a standing-wave field and imparts a phase shift to the field. The measurement of this phase shift then gives the position information of the atom [5]. It is shown that by using Ramsey-interferometry, the use of coherent-state cavity field is better than the classical field to get higher resolution in

position information of the atom [6]. Resonance imaging methods have also been used for precision position measurement of the moving atoms [7]. Atom localization based on the detection of the spontaneously emitted photon during the interaction of an atom with a classical standing-wave field has also been proposed [8-12]. Qamar *et al.* [10] used a simple two level atomic system for localizing the atom during its motion in the classical standing wave field. This scheme utilizes the idea that the frequency of spontaneously emitted photon carries the information about the position of an atom due to its position dependent Rabi-frequency of the driving field. The effect of detuning between the atomic transition frequency and the frequency of driving fields on the precision information of a single atom inside the classical standing wave field has also been proposed [11]. It has been shown that a coherent control of spontaneous emission of a multi-level system gives line

narrowing and even spontaneous emission quenching [13-15]. It is shown that strong line narrowing and selective cancellation of the fluorescence decay can play an important role in enhancing the efficiency of the atom localization schemes. Ghafoor *et al.* [15] investigated the phase and amplitude control of driving fields on spontaneous emission spectrum in a four-level atomic system. This scheme was also utilized for the localization of the atom [12]. It is shown that phase and amplitude control of driving fields yield a better spatial resolution in position measurement of the single atom through the standing-wave field with respect to the other related studies. Although the measurement of spontaneously emitted photon gives a better resolution of the atomic wave function than the other methods [10, 11], from the experimental point of view the detection of spontaneously emitted photon is difficult. In another study based on the measurement of population in the upper level, Paspalakis and Knight [16] have used a three-level Λ-type medium to sub-wavelength localization of the atom during its motion in the standing-wave field.

Recently, we proposed another method for localizing the atom inside the classical standing wave field based on the electromagnetically induced transparency (EIT) [17]. The basic idea of this scheme is that of the probe field absorption measurement at appropriate frequencies which localizes the atom inside the classical standing-wave field.

In this article, we consider another scheme based on the four-level EIT to determine the position of an atom inside the classical standing-wave field. We show that the position of the atom along the standing wave is determined when the probe frequency absorption is measured. The effects of Rabi-frequencies of the driving field as well as the detuning parameters on the atom localization are then discussed. We find that an appropriate choice of these parameters leads to a very narrow localization structure at a particular frequency. The absorption of the weak probe field has been also investigated by the imaginary part of the susceptibility. The motivation for considering this scheme goes back to our recent study of the absorption and the dispersion properties of the weak probe field in this system [18]. In another related study, we employed this system to investigate switching from subluminal to superluminal light propagation [19]. We have also investigated the phase dependence of the group velocity via EIT with three driving fields and a weak probe field in this system [20]. The structure of the article continues as follows. In section II we introduce a model, giving the basic equations and their solution to determine the susceptibility. In section III, we present the results and discuss the behavior of the imaginary part of the susceptibility along with the normalized position coordinate of the standing wave for variety of system parameters. Finally, we present our conclusion in section IV.

II) Basic Equations

We consider a four-level atom moving in z direction and passes through a classical standing-wave field. The standing-wave field is aligned along the x-axis (Fig. 1a). The energy level structure of the atom is shown in Figure 1b. The classical standing-wave field with the wave vector $k = \dfrac{2\pi}{\lambda}$ and wavelength λ couples level $|b\rangle$ to the levels $|a_1\rangle$ and $|a_2\rangle$. A weak tunable probe field with frequency v_p couples the ground state $|c\rangle$ to the excited states $|a_1\rangle$ and $|a_2\rangle$, whose absorption we are interested in. The spontaneous decay rates from upper levels $|a_1\rangle$ and $|a_2\rangle$ to lower level $|c\rangle$ are displayed by γ_1 and γ_2, respectively. Here we consider that the atom is moving with high enough velocity that its interaction with the driving fields does not effete its motion along the z direction and, therefore, we may treat its motion in the z direction classically. Moreover, we assume that interaction time of the atom with the standing-wave field and hence the Rabi-frequencies are sufficiently small so that the center-of-mass position of the atom along the standing wave does not change during the interaction time and thus we may neglect the kinetic-energy term of the atom in the interaction Hamiltonian under the Raman-Nath approximation [21]. In another words the center-of-mass displacement of the atom along the x direction is smaller than the wavelength of the standing field. Therefore the cavity dissipation can be neglected under this approximation. The resulting Hamiltonian from atom-field system can be written as

$$H = V_0 + V_1 + V_2 + V_3, \qquad (1)$$

where V_0 is the free energy part, and V_1 denotes the interaction between standing field with levels $|a_1\rangle$, $|a_2\rangle$ and $|b\rangle$. V_2 displays the interaction of the atom with the vacuum filed, corresponding to the decay processes from levels $|a_1\rangle$, $|a_2\rangle$ and $|b\rangle$ to level $|c\rangle$. V_3 denotes the weak field absorption from level $|c\rangle$ to the level $|a_1\rangle$ and $|a_2\rangle$. The detailed form of these terms can be written as
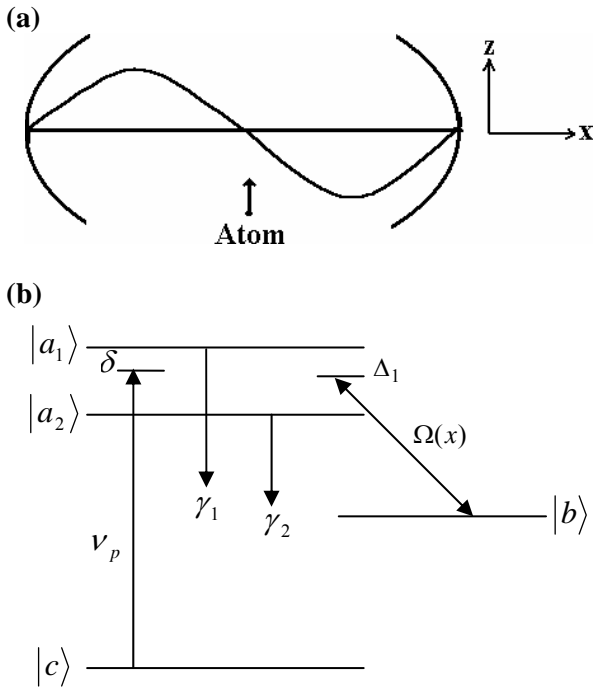
(a)

(b)

Figure 1. a) A four-level atom is moving in the z direction, and passing through the classical-standing wave field that is aligned in x direction. b) Proposed level scheme: A coherent strong standing wave couples level $|c\rangle$ to the excited levels $|a_1\rangle$ and $|a_2\rangle$, and a weak probe field applies from the $|b\rangle$ to the both excited levels $|a_1\rangle$ and $|a_2\rangle$.

$$V_0 = \hbar\omega_{a_1}|a_1\rangle\langle a_1| + \hbar\omega_{a_2}|a_2\rangle\langle a_2|$$
$$+\hbar\omega_b|b\rangle\langle b| + \hbar\omega_c|c\rangle\langle c| \tag{2}$$

$$V_1 = -\hbar\Omega_1(x)e^{-i\nu t}|a_1\rangle\langle b|$$
$$-\hbar\Omega_2(x)e^{-i\nu_p t}|a_2\rangle\langle b| + c.c. \tag{3}$$

$$V_2 = -\hbar\sum_k g_k^{(1)}e^{-i\nu_k t}|a_1\rangle\langle c|\hat{b}_k$$
$$-\hbar\sum_k g_k^{(2)}e^{-i\nu_k t}|a_2\rangle\langle c|\hat{b}_k + H.c. \tag{4}$$

$$V_3 = -\hbar\Omega_{p_1}e^{-i\nu_p t}|a_1\rangle\langle c|$$
$$-\hbar\Omega_{p_2}e^{-i\nu_p t}|a_2\rangle\langle c| + c.c. \tag{5}$$

Here $\hbar\omega_i$ are the energies of the levels $|i\rangle$. Here

$\Omega_i(x) = (|\Omega_i|\sin kx, \ i = 1,2)$ are the position-dependent Rabi-frequencies and $\Omega_i \ (= \dfrac{E\,\wp_{a_ib}}{\hbar}, \ i = 1,2)$ are the Rabi-frequencies of standing coupling field to transition $|a_i\rangle \leftrightarrow |b\rangle$. Note that the Rabi-frequencies $\Omega_1(x)$ and $\Omega_2(x)$ are the sinusoidal function of the position x due to the interaction of the atom and the standing field. $\Omega_{p_i} \ (= \dfrac{E_p\,\wp_{a_ic}}{\hbar}, \ i = 1,2)$ are the Rabi-frequencies of the probe field to transition $|c\rangle \to |a_i\rangle$ which are taken to be real. $\wp_{a_ib}$ and $\wp_{a_ic}$ are the induced atomic dipole moments, whereas E and E_p denote the amplitude of the standing and probe fields respectively. The terms $g_k^{(1,2)}$ are the coupling constant between the kth vacuum modes of frequency ν_k and the atomic transition between $|a_1\rangle \to |c\rangle$, $|a_2\rangle \to |c\rangle$ and $|b\rangle \to |c\rangle$, respectively. The terms ν and ν_p display the frequency of the coupling field and the weak probe field. The density matrix elements of the system in the rotating wave approximation and in the rotating frame are

$$\dot{\tilde{\rho}}_{a_1a_2} = -[\frac{1}{2}(\gamma_1+\gamma_2)+i\,\omega_{a_1a_2}]\tilde{\rho}_{a_1a_2} + i\,\Omega_1(x)\tilde{\rho}_{ba_2}$$
$$-i\,\Omega_2(x)\tilde{\rho}_{a_1b} + i\,\Omega_{p_1}\tilde{\rho}_{ca_2} + i\,\Omega_{p_2}\tilde{\rho}_{a_1c},$$

$$\dot{\tilde{\rho}}_{a_1b} = -[\frac{1}{2}\gamma_1+i\,\Delta_1]\tilde{\rho}_{a_1b} - i\,\Omega_1(x)(\tilde{\rho}_{a_1a_1}-\rho_{bb})$$
$$-i\,\Omega_2(x)\tilde{\rho}_{a_1a_2} + i\,\Omega_{p_1}\tilde{\rho}_{cb},$$

$$\dot{\tilde{\rho}}_{a_2b} = -[\frac{1}{2}\gamma_2+i\,\Delta_2]\tilde{\rho}_{a_2b} - i\,\Omega_2(x)(\tilde{\rho}_{a_2a_2}-\rho_{bb})$$
$$-i\,\Omega_1(x)\tilde{\rho}_{a_2a_1} + i\,\Omega_{p_2}\tilde{\rho}_{cb},$$

$$\dot{\tilde{\rho}}_{a_1c} = -(\frac{1}{2}\gamma_1+i\,\delta)\tilde{\rho}_{a_1c} + i\,\Omega_1(x)\rho_{bc}$$
$$-i\,\Omega_{p_1}(\tilde{\rho}_{a_1a_1}-\rho_{cc}) - i\,\Omega_{p_2}\tilde{\rho}_{a_1a_2},$$

$$\dot{\tilde{\rho}}_{a_2c} = -[\frac{1}{2}\gamma_2+i\,(\delta-\omega_{a_1a_2})]\tilde{\rho}_{a_2c} + i\,\Omega_2(x)\rho_{bc}$$
$$-i\,\Omega_{p_2}(\tilde{\rho}_{a_2a_2}-\rho_{cc}) - i\,\Omega_{p_1}\tilde{\rho}_{a_2a_1},$$

$$\dot{\tilde{\rho}}_{bc} = -i\,(\delta-\Delta_1)\tilde{\rho}_{bc} + i\,\Omega_1(x)\rho_{a_1c}$$
$$+i\,\Omega_2(x)\tilde{\rho}_{a_2c} - i\,\Omega_{p_1}\rho_{ba_1} + i\,\Omega_{p_2}\tilde{\rho}_{ba_2}, \tag{6}$$

Similarly, one can obtain the population elements of the density matrix equation. The detuning parameters are defined as $\Delta_1 = \omega_{a_1b} - v$, $\Delta_2 = \omega_{a_2b} - v$, and $\delta = \omega_{a_1c} - v_p$. We define the decay rate $\gamma_i = 2\pi D(v)\left[g_\omega^{(i)}\right]^2$ where $D(v_k) = \dfrac{V v_k^2}{\pi^2 c^3}$ represents the density of state and V is the volume. $\hat{b}_k$ $(\hat{b}_k^l)$ are the annihilation (creation) operators for the kth vacuum modes. Here the Weisskopf-Wigner approximation has also been used for the spontaneous emission [22]. Note that the probe field is weak compared to the coupling standing field and we keep the terms of all orders in the strong standing driving field, but keeping only the linear term in the probe field. Therefore we use

$$\tilde{\rho}_{cc}^{(0)} = 1, \tilde{\rho}_{bb}^{(0)} = 0, \tilde{\rho}_{a_1a_1}^{(0)} = 0, \tilde{\rho}_{a_2a_2}^{(0)}$$
$$= 0, \tilde{\rho}_{a_2a_1}^{(0)} = 0, \tilde{\rho}_{ba_1}^{(0)} = 0, \tilde{\rho}_{ba_2}^{(0)}. \tag{7}$$

The absorption of the weak probe field is proportional to $(\tilde{\rho}_{a_1c}^{(1)} + \tilde{\rho}_{a_2c}^{(1)})$. The necessary equations from the set of density matrix elements (Eqs. 6) under the linearization (7) are given by

$$\dot{\tilde{\rho}}_{a_1c} = -(\tfrac{1}{2}\gamma_1 + i\,\delta)\,\tilde{\rho}_{a_1c} + i\,\Omega_1(x)\,\rho_{bc} + i\,\Omega_{p_1},$$

$$\dot{\tilde{\rho}}_{a_2c} = -[\tfrac{1}{2}\gamma_2 + i(\delta - \omega_{a_1a_2})]\,\tilde{\rho}_{a_2c}$$
$$+ i\,\Omega_2(x)\,\rho_{bc} + i\,\Omega_{p_2},$$

$$\dot{\tilde{\rho}}_{bc} = -i(\delta - \Delta_1)\,\tilde{\rho}_{bc} + i\,\Omega_1(x)\,\rho_{a_1c}$$
$$+ i\,\Omega_2(x)\,\tilde{\rho}_{a_2c} \tag{8}$$

This set of equations can be solved by the matrix form, and the result for the steady state is

$$R = M^{-1}C, \tag{9}$$

where R and C are column matrixes and M is the 3×3 matrix which are given by

$$R = \begin{pmatrix} \tilde{\rho}_{a_1c} \\ \tilde{\rho}_{a_2c} \\ \tilde{\rho}_{bc} \end{pmatrix},$$

$$C = \begin{pmatrix} (\tfrac{1}{2}\gamma_1 + i\,\delta) & 0 & -i\,\Omega_1(x) \\ 0 & \tfrac{1}{2}\gamma_2 + i(\delta - \omega_{a_1a_2}) & -i\,\Omega_2(x) \\ -i\,\Omega_1(x) & -i\,\Omega_2(x) & i(\delta - \Delta_1) \end{pmatrix},$$

$$M = \begin{pmatrix} i\,\Omega_{p_1} \\ i\,\Omega_{p_2} \\ 0 \end{pmatrix}. \tag{10}$$

We investigate the response of the system to applied field by the susceptibility, which is defined as [23]

$$\chi = \frac{2N}{\varepsilon_0 E_p}(\wp_{ca_1}\rho_{a_1c} + \wp_{ca_2}\rho_{a_2c})e^{iv_p t}, \tag{11}$$

where N is the atomic density, $\rho_{a_1c} = \tilde{\rho}_{a_1c}e^{-iv_p t}$, and $\rho_{a_2c} = \tilde{\rho}_{a_2c}e^{-iv_p t}$. The imaginary part of susceptibility corresponding to the absorption of the weak probe field is given by

$$\chi'' = \frac{2N|\wp_{ca_1}|^2}{\hbar\varepsilon_0 Z}\{-\frac{\gamma_2}{2}(\Delta_1 - \delta)B + [\delta\Delta_1$$
$$+ \omega_{a_1a_2}(\delta - \Delta_1) - \delta^2 + \Omega_2^2(x)$$
$$- \Omega_1(x)\Omega_2(x)]A\} \tag{12}$$
$$+ \frac{2N|\wp_{ca_2}|^2}{\hbar\varepsilon_0 Z}\{-\frac{\gamma_1}{2}(\Delta_1 - \delta)B + [\delta\Delta_1$$
$$- \delta^2 + \Omega_1^2(x) - \Omega_1(x)\Omega_2(x)]A\}$$

where $Z = YY^*$, $Y = A + iB$,

$$A = (\frac{\gamma_1 + \gamma_2}{2})(\Delta_1 - \delta)\delta + \frac{\gamma_1}{2}\omega_{a_1a_2}(\delta - \Delta_1)$$
$$+ [\frac{\gamma_2}{2}\Omega_1^2(x) + \frac{\gamma_1}{2}\Omega_2^2(x)] \tag{13}$$

and

$$B = -\delta^3 + \delta^2(\Delta_1 + \omega_{a_1a_2}) + \Omega_1^2(x)(\delta - \omega_{a_1a_2})$$
$$+ \Omega_2^2(x)\delta + \frac{\gamma_1\gamma_2}{4}(\delta - \Delta_1) - \delta\Delta_1\omega_{a_1a_2}. \tag{14}$$

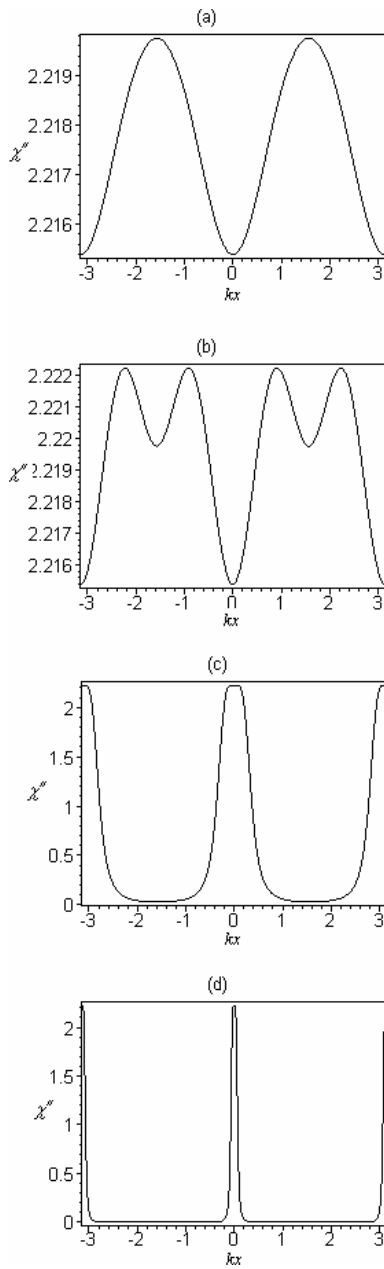Here Ω_{p_i} $(= \dfrac{E\wp_{a_ic}}{\hbar}, i = 1, 2)$ has also been used.

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Figure 2. Imaginary parts of susceptibility as a function of normalized position kx in the unit wavelength for the parameters $\gamma_1 = \gamma_2 = \gamma$, $\omega_{a_1a2} = \gamma$, $\delta = 0.25\gamma$, $\Delta_1 = 0.5\gamma$, and a) $\Omega_1 = \Omega_2 = 0.05\gamma$, b) $\Omega_1 = \Omega_2 = 0.1\gamma$, c) $\Omega_1 = \Omega_2 = 1\gamma$, and d) $\Omega_1 = \Omega_2 = 5\gamma$.

III) Results and Discussion

Expression (12) is our basic results for determining the position of a moving atom inside the classical standing-wave field. An atom is localized as soon as the particular frequency of the probe field is determined. This scheme exploits the fact that by measuring the particular frequency of the probe field we can localize the atom during its motion through the standing wave field. Expression (12) shows that the atom localization strongly depends on the Rabi-frequencies of standing wave field Ω_i ($i = 1,2$), and detuning parameters δ, Δ_1. It is our interest to have the maxima for the imaginary part of susceptibility at probe field absorption inside the standing-wave field. The position of the probe field absorption maxima are strongly depends on the probe field frequency through its detuning $\delta = \omega_{a_1c} - \nu_p$. To clarify this point we consider that the relation (12) is depends on the parameter δ. From this expression we observe that the imaginary part of susceptibility, i.e. χ'', has a direct relationship with the detuning parameters δ which is proportional to the measured frequency ν_p of the probe field. Here, it is noticed that the imaginary part of susceptibility depends not only on the frequency of probe field but also on the amplitudes of classical standing wave-field Ω_1 and Ω_2 as well as detuning of standing wave with atomic transitions. It should also be noted that the initial position distribution of the atom is a broad wave packet and the imaginary part of susceptibility, therefore, directly gives the position probability distribution. The results are displayed in Figures (2-4). In the figures we choose $\dfrac{2N \, | \wp_{ca_1} |^2}{\varepsilon_0 \, \hbar} = 1$, and $\wp_{ca_1} = \wp_{ca_2}$. We assume that $\gamma_1 = \gamma_2 = \gamma$, and all figures are plotted in the unit of γ. In our scheme the Rabi-frequencies are position dependent, and the atom undergoes different Rabi-frequencies at a different position in the standing wave and we get maxima in the position distribution corresponding to these Rabi-frequencies. In Figure 2 the imaginary part of susceptibility, χ'', are displayed as a function of normalized position, kx, for the parameters $\gamma_1 = \gamma_2 = \gamma, \omega_{a_1a2} = \gamma, \delta = 0.25\gamma, \Delta_1 = 0.5\gamma$, and for different values of Ω_1 and Ω_2 in the unit wavelength. An investigation of the figure shows that the position of maxima of the imaginary part of susceptibility strongly depends on the Rabi-frequencies of standing-wave field. For the small values of Rabi-frequencies, i.e. $\Omega_1 = \Omega_2 = 0.05\gamma$, we get peak maxima only at the antinodes of the standing-wave field. When the Rabi-frequencies of driving field increase, the initial two peaks start to split into four peaks and then move away from antinodes towards the nodes of the standing wave (see Figs. 2b and 2c). For the large values of Ω_1 and
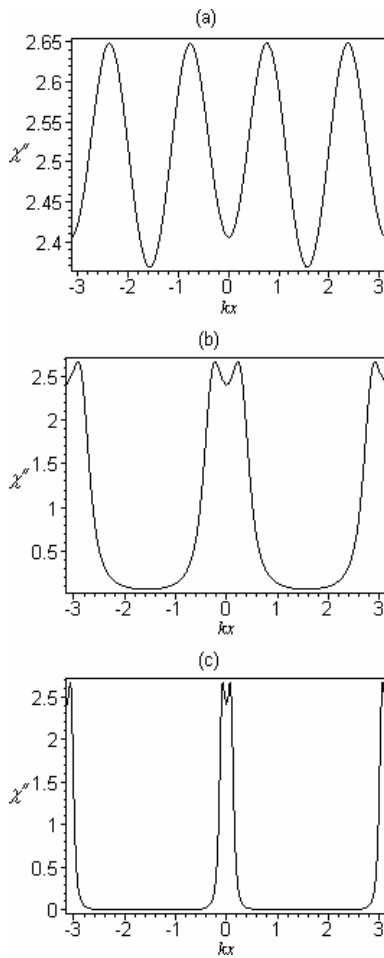
Figure 3. Imaginary parts of susceptibility as a function of normalized position kx in the unit wavelength for the parameters $\gamma_1 = \gamma_2 = \gamma$, $\omega_{a_1 a_2} = \gamma$, $\Omega_1 = \Omega_2 = 0.05\,\gamma$, and a) $\Delta_1 = 0.02\gamma$, $\delta = 0.01\gamma$, b) $\Delta_1 = 0.002\gamma$, $\delta = 0.001\gamma$, c) $\Delta_1 = 0.0002\gamma$, $\delta = 0.0001\gamma$.

Figure 4. Imaginary parts of susceptibility as a function of normalized position kx in the unit wavelength for the parameters $\gamma_1 = \gamma_2 = \gamma$, $\omega_{a_1 a_2} = \gamma$, $\Omega_1 = \Omega_2 = 1\gamma$, and a) $\Delta_1 = 0.02\gamma$, $\delta = 0.01\gamma$, b) $\Delta_1 = 0.002\gamma$, $\delta = 0.001\gamma$, c) $\Delta_1 = 0.0002\gamma$, $\delta = 0.0001\gamma$.

Ω_2 ($\Omega_1 = \Omega_2 = 5\gamma$), the localization peaks lies in the nodes of standing wave field, and the width of peaks decrease. The results indicate a strong correlation between the detuning of probe and coupling fields and the position of the atom. The measurement of a particular frequency is corresponding to the localization of the atom in a sub-wavelength domain of the standing wave. The width of localization peaks depends not only on the Rabi-frequencies but also on the detuning parameters. The effects of detuning parameters on the atom localization are shown in Figure 3 and Figure 4. In Figure 2a, we observe that for $\delta = 0.25\gamma$, $\Delta_1 = 0.5\gamma$, and $\Omega_1 = \Omega_2 = 0.05\gamma$ we get peak maxima only at the antinodes of standing wave. When the probe and
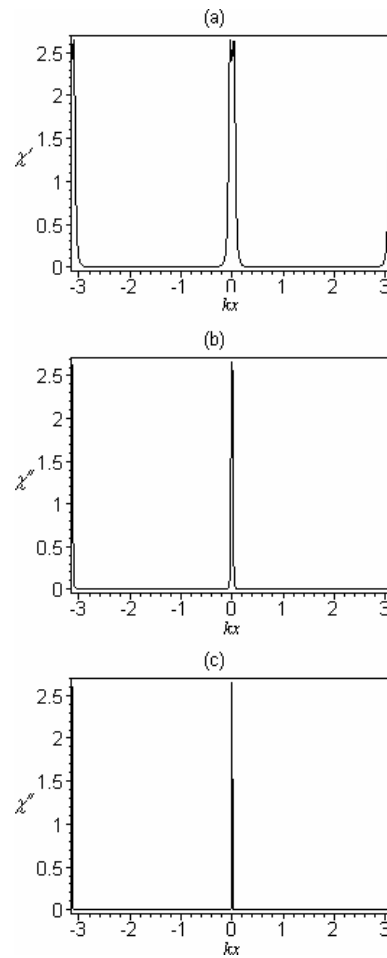
coupling laser field detuning decrease, the initial two peaks start to split into four peaks and move away from antinodes towards the nodes of the standing wave (see Figs. 3a-c). An increasing of the Rabi-frequencies and decreasing the detuning parameters give a very narrow structure in the atomic position at the unit wavelength (Fig. 4). Note that the heights of the peaks for all values of position are the same, but the width of peaks strongly depends on the Rabi-frequencies and the detuning parameters.

IV) Conclusion

The localization of the moving four-level atom inside the classical standing-wave field is investigated. In the

proposed scheme, interaction between atom and field is position dependent, so as soon as the particular frequency of the probe field is measured, the position of the atom inside the classical standing-wave field will be determined. The results show that atomic position strongly depends on the interaction parameters such as detuning, and Rabi-frequencies of driving field. Increasing the intensity of coupling field leads to a strong localization of the atom inside the classical standing wave-field.

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