Localization of an atomic system in 2D subwavelength domain

Neeraj Singh[1*], Ajay Wasan[1]

[1] Quantum Optics Lab, Physics Department, Indian Institute of Technology Roorkee, 247667, India
*E-mail: nrjsingh413@gmail.com

1. Introduction

According to Werner Heisenberg, atom cannot be localized in a domain less than half of field's wavelength. Several approaches have been made to overcome this limitation via incorporating the atomic coherences and quantum interferences. In order to this, researchers utilize the atomic energy levels and couple them with coherent standing-wave couple fields [1]. In case of standing-wave couple fields, spatial probe absorption provides the precise information of atom localization in subwavelength domain [2, 3]. Atom localizes at positions where it has larger probe absorption. The motivation for present study is to find the atom localization for a realistic atomic system where nearby levels, thermal atomic velocity cannot be ignored.

2. Theoretical model and results

We consider Ξ-type atomic system with nearby upper levels as shown in Fig. 1. This system is driven by a running probe (G_p) and standing-wave couple (G_c(x,y)) fields.

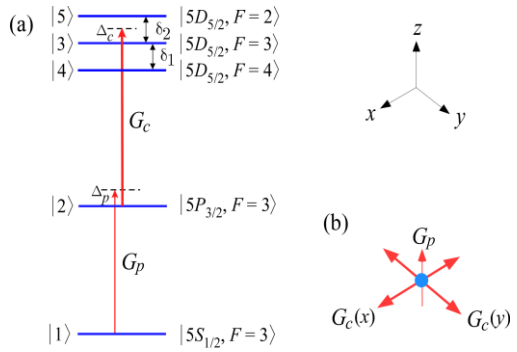

Fig.1. (a) A detailed energy level diagram of Ξ-type atomic system by considering ^{87}Rb. (b) Field configuration

The Hamiltonian of atom-light system after carrying out rotating wave approximation (RWA) is given by

$$H = -(\Delta_p + \Delta_c - \delta_2)|5\rangle\langle 5| - (\Delta_p + \Delta_c + \delta_1)|4\rangle\langle 4| - (\Delta_p + \Delta_c)|3\rangle\langle 3| - \Delta_p|2\rangle\langle 2|$$
$$-\frac{i}{2}\left[G_p|1\rangle\langle 2| + a_{32}G_c|2\rangle\langle 3| + a_{42}G_c|2\rangle\langle 4| + a_{52}G_c|2\rangle\langle 5| + H.c.\right],$$

where a's and Δ's are relative transition strengths and fields detuning between levels. The dynamics of atom-light system can be described using Louville equation given as

$$\dot{\rho} = -\frac{i}{\hbar}[H\rho] + L\rho,$$

Imaginary part of ρ_{21} provides the spatial probe absorption which is a key factor for determining the atom localization position. It directly reflects the conditional probability.

Case 1. Stationary atom: We first consider the case where G_c create the standing wave along the x- and y-axis, i.e., G_c=Ω(Sin kx+ Sin ky) with $k = 2\pi/\lambda$, shown in Fig. 1(b). As can be seen in Fig. 2(a), contour plot shows that atom localizes only in two quadrants with high precision in position. Therefore, the probability of finding atom at a position is only 1/2. On addition of extra running-wave field (g_c) in previous field configuration (i.e., G_c=Ω (Sin kx + Sin ky) + g_c), it causes the atom to localize in only one quadrant [Fig. 2(b)], i.e., probability of finding atom become unity under specific parametric condition. This kind of atom localization can be understood on the basis of dresses state picture.

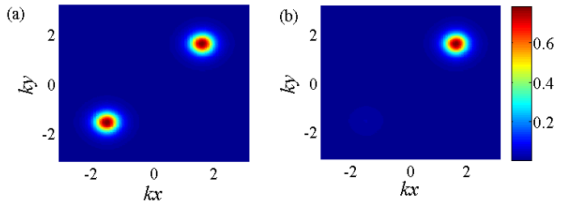

Fig. 2. Variation of Im (ρ_{21}) vs position (kx, ky). (a) Δc = g_c=0 (b) Δ_c = 2g_c = 2Γ_{21}. The other parameters are Ω = 5Γ_{21}, Δ_p = 9 Γ_{21}, G_p=0.001 Γ_{21}, $\delta_1/2\pi$=9 MHz and $\delta_2/2\pi$=7.6 MHz.

Case 2. Moving atom: The velocity of moving atom (v) can be integrated in numerical analysis by replacing Δ_p with (Δ_p+k_pv) due to Doppler effect. Therefore, thermal averaging of ρ_{21} has been carried out with Maxwell-Boltzmann velocity distribution. Fig. 3 shows the atom localization in sub-wavelength domain for moving atom in absence (Fig. 3a) and presence (Fig. 3b) of nearby upper levels. One can conclude here that it is hard to find exact localization position of a moving atom as absorption maxima distributed all over the subwavelength domain.

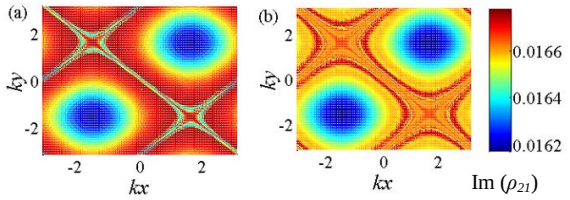

Fig. 3. Variation of Im (ρ_{21}) vs position (kx, ky). (a) Without nearby levels, (b) With nearby levels. The other parametric conditions are same as in Fig. 2(a).

3. Conclusions

Atom localization has been discussed for Ξ-type atomic system under the influence of nearby levels as well as of thermal motions. Thermal motion of atomic system results in lowering in precision of atom position.

References:

[1] V. Ivanov and Y. Rozhdestvensky, Phys. Rev. A 81, 033809 (2010).
[2] Z. Zhu, W.-X. Yang, A.-X. Chen, S. Liu, and R.-K. Lee, J. Opt. Soc. Am. B 32, 1070–1077 (2015).
[3]N. Singh and A. Wasan, JOSA B 35, 1318–1327 (2018).