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High-precision three-dimensional atom localization in a three-level pump-probe atomic system

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Abstract: We propose a new scheme for three-dimensional (3D) atom localization controlled by incoherent pump in a three-level Λ-type atomic system. The spatial position information of an atom in 3D space can be achieved via measuring probe gain and absorption when the atom passes through three mutually perpendicular standing-wave fields. It is found that high-detecting-probability and high-precision 3D atom localization can be obtained via properly adjusting the relevant parameters in the presence of the combination of a traveling-wave field and three orthogonal standing-wave fields. Furthermore, it is also shown that the incoherent pumping field can switch the localization patterns from probe-gain sphere to probe-absorption spheres and enhance 3D atom-localization precision.

Keywords: Three-dimensional atom localization; Pump-probe atomic system; Standing-wave field; Incoherent pump; Probe gain.

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(Some figures may appear in color online and be printed in black and white)

1. Introduction

In the past few years, much interest has been attracted by the study of the spatial position measurement of single atom when passing through the standing-wave fields. This research has many potential applications, which include trapping of neutral atoms, atom nanolithography and so on [1-4]. A large number of theoretical studies have been proposed by researchers for one-dimensional (1D) atom localization via the effect of atomic coherence and quantum interference [5-19]. In these schemes, the position information of the atom has been correlated with the spatial distribution of the quantities, i.e., resonance fluorescence, level population, spontaneous emission, probe absorption and gain, due to the intensity modulation of a standing-wave field. More recently, Proite et al. have

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experimentally observed 1D atom localization via utilizing electromagnetically induced transparency (EIT), which demonstrated that the population of an atomic level can be localized much more tightly than the spatial period [20].

On the other hand, the behaviors of two-dimensional (2D) localization of an atom passing through two orthogonal standing-wave fields have been widely investigated. For instance, Ivanov and Rozhdestvensky proposed a 2D-atom-localization scheme via measuring the up-level population or ground-level population in a four-level tripod system [21]. They found that the position-dependent atom-field coupling can determine the localization factor and lead to different localization patterns, such as spikes, craters and waves. And later 2D atom localization via controlled spontaneous emission in a five-level M-type atomic system was realized by Ding and his coworkers [22]. Wan et al. [23] presented two schemes for 2D atom localization via spontaneous emission from a driven tripod system and interacting double-dark resonances in a four-level $N$-type atomic system, respectively, and demonstrated that the probability of finding the atom can be increased to 50%. In order to improve the detecting probability of the atom and enhance the precision of atom localization, a series of scheme about 2D atom localization using these techniques, such as the control of the phase-sensitive optical properties of atomic system [24-29], the manipulation of the initial state of atom [30, 31], the superposition of standing-wave fields [32-34] and the combination of traveling-wave fields and standing-wave fields [35], have been proposed. In these studies, the single-localization peak in one period of standing waves can be achieved and the detecting probability of the atom can reach 100%.

In recent years, three-dimensional (3D) atom localization via applying three mutually perpendicular standing-wave fields has attracted considerable interest due to their clear physical significance and extensive applications. For example, Qi et al., for the first time, proposed a scheme for 3D atom localization via the measurement of probe absorption in a five-level $M$-type atomic system and observed various atom localization patterns from the view of the $x$-$y$ plane at different $z$ positions [36]. And later, instead of the measurement of probe absorption, the detection of the population in the excited state coupled to the standing-wave fields generated different localization patterns, such as spheres, hourglasses and bowls. This was shown by Ivanov and his colleagues [37]. Recently, several relevant schemes have also been put forward for 3D atom
localization in different multilevel atomic systems. The researches show that one can localize the atom at certain positions in 3D space via the measurement of resonance fluorescence [38], atomic population [39] and probe absorption [40-44].

In this paper, we investigate high-precision 3D atom localization controlled by an incoherent pumping field in a simple three-level Λ-type atomic system. It is worth pointing out that the incoherent pumping field plays an important role in manipulating the optical properties of the atomic configurations [45-48]. Motivated by these studies, we utilize probe gain or absorption, which strongly depends on incoherent pump, to achieve the precise position information of the atom in 3D space. In our scheme, the combination of a traveling-wave field and three mutually perpendicular standing-wave fields is used as the coupling field. Thus, the dependence of atom–field interaction on the spatial position in 3D space can lead to high-precision 3D atom localization. Our results show that the incoherent pumping field determines whether the atom localization is achieved by measuring probe gain or probe absorption. 3D atom localization can be realized via measuring the probe gain when pumping strength exceeds certain threshold and below threshold the probe absorption spectrum is used to describe 3D atom localization. By tuning the intensity combination, the atom can be localized at a particular position in 3D space with high precision and the detecting probability of the atom can reach 100%, which increases by a fact of 8 in comparison with the relevant schemes [37, 38].

2. Model and equations

As illustrated in Fig. 1(a), a three-level Λ-type atomic system with one excited state $|3\rangle$ and two ground states $|1\rangle$ and $|2\rangle$ is considered. Three orthogonal classical standing-wave fields aligned respectively along the $x$, $y$ and $z$ axis interact with the atom which moves along $-z$ direction in Fig. 1(b). The transition between level $|3\rangle$ and level $|1\rangle$ (resonant frequency $\omega_{31}$) is driven by a weak probe field with Rabi frequency $\Omega_p = \mu_{13} \cdot \vec{E}_p / 2\hbar$ (angular frequency $\omega_p$) and an incoherent pumping field with a rate $\Lambda$, while a coupling field with position-dependent Rabi frequency $\Omega(x,y,z)$ (angular frequency $\omega$) is applied to the transition between level $|3\rangle$ and level $|2\rangle$ (resonant frequency $\omega_{32}$). $\gamma_1$ and $\gamma_2$ are the spontaneous emission rates from state $|3\rangle$ to states $|1\rangle$ and $|2\rangle$, respectively. The position-dependent coupling field $\Omega(x,y,z)$ in our scheme is the combination of a
travelling-wave field $\Omega_T$ and three orthogonal classical standing-wave fields, i.e., $\Omega(x)$, $\Omega(y)$ and $\Omega(z)$:

$$\Omega(x,y,z) = \Omega(x) + \Omega(y) + \Omega(z) + \Omega_T,$$  \hspace{1cm} (1)

with

$$\Omega(x) = \Omega_1 \sin(kx), \quad \Omega(y) = \Omega_2 \sin(ky), \quad \Omega(z) = \Omega_3 \sin(kz),$$  \hspace{1cm} (2)

in which $k$ is the same wave-number of the three standing-wave fields and all the components of the position-dependent Rabi frequency $\Omega(x,y,z)$ have the same angular frequency $\omega$. The corresponding Rabi frequencies are defined as $\Omega_m = \tilde{\mu}_{n3} \cdot \bar{E}_m / 2\hbar \ (m=1,2,3,T)$. For simplicity, $\Omega_1 = \Omega_2 = \Omega_3 = \Omega_5$ is selected. Here, $\tilde{\mu}_{n3} (n=1,2)$ stands for the dipole matrix moment for the relevant transition from level $|n\rangle$ to level $|3\rangle$.

The center-of-mass position of the atom along the directions of the standing-wave fields is assumed to be nearly constant when an atom moves along $-z$ direction. We neglect the kinetic part of the atom in the Hamiltonian by applying the Raman–Nath approximation [5]. Therefore, the resulting interaction picture Hamiltonian, in the rotating-wave and electric-dipole approximations, for the system is ($\hbar = 1$)

$$H_{\text{int}} = \Delta_p [\langle 3 | 3 + (\Delta_p - \Delta) | 2 \rangle < 2 | - [\Omega(x,y,z)|3\rangle < 2 | + \Omega_p |3\rangle < 1 | + H.c.] ,$$  \hspace{1cm} (3)

where $H.c.$ means Hermitian conjugate. The detunings of the corresponding fields are represented by $\Delta_p = \omega_{31} - \omega_p$ and $\Delta = \omega_{31} - \omega$.

From the Liouville equation $\dot{\rho} = -i[H_{\text{int}}, \rho] - \{\Gamma, \rho\} / 2$, the equations of motion for density matrix elements can be derived as follow:

$$\dot{\rho}_{11} = \gamma_1 \rho_{33} - \Lambda \rho_{11} - i\Omega_p \rho_{13} + i\Omega_p \rho_{31} ,$$  \hspace{1cm} (4)

$$\dot{\rho}_{22} = \gamma_2 \rho_{33} - i\Omega(x,y,z) \rho_{23} + i\Omega(x,y,z) \rho_{32} ,$$  \hspace{1cm} (5)

$$\dot{\rho}_{21} = - \left[ \frac{\Lambda}{2} + i(\Delta_p - \Delta) \right] \rho_{21} - i\Omega(x,y,z) \rho_{31} + i\Omega_p \rho_{23} ,$$  \hspace{1cm} (6)

$$\dot{\rho}_{31} = - \left( \frac{\gamma_1 + \gamma_2 + \Lambda}{2} + i\Delta_p \right) \rho_{31} - i\Omega(x,y,z) \rho_{21} + i\Omega_p (\rho_{33} - \rho_{11}) ,$$  \hspace{1cm} (7)
\[
\dot{\rho}_{32} = -\left(\frac{\gamma_1 + \gamma_2}{2} + i\Delta\right)\rho_{32} + i\Omega_p\rho_{12} - i\Omega(x, y, z)(\rho_{33} - \rho_{22}), \tag{8}
\]

\[
\rho_{33} = 1 - \rho_{11} - \rho_{22}, \quad \rho_{0} = \rho_{0}^*.
\tag{9}
\]

Considering the probe field is weak, we can obtain the steady-state expression of \(\rho_{33}^{(0)}\) to the first order of the probe field as following:

\[
\rho_{31}^{(1)} = -i\Omega_p B_1 B_3 \left(\rho_{33}^{(0)} - \rho_{11}^{(0)}\right) + i\Omega_p \Omega(x, y, z)^2 \left(\rho_{33}^{(0)} - \rho_{22}^{(0)}\right) \over B_1 B_2 B_3 + B_3 \Omega(x, y, z)^2, \tag{10}
\]

where \(B_1 = i(\Delta_p - \Delta) + \Lambda / 2\), \(B_2 = i\Delta_p + (\gamma_1 + \gamma_2 + \Lambda) / 2\) and \(B_3 = -i\Delta + (\gamma_1 + \gamma_2) / 2\).

As we know that \(\rho_{11}^{(0)}\), \(\rho_{22}^{(0)}\) and \(\rho_{33}^{(0)}\) are the zeroth-order density matrix elements of the probe field. Here, the steady-state values of \(\rho_{11}^{(0)}\), \(\rho_{22}^{(0)}\) and \(\rho_{33}^{(0)}\) can be derived by neglecting the elements multiplied by \(\Omega_p\). We then obtain

\[
\rho_{11}^{(0)} = \frac{4\gamma_1(\gamma_1 + \gamma_2)\Omega(x, y, z)^2}{\Lambda\gamma_2\left((\gamma_1 + \gamma_2)^2 + 4\Delta^2\right) + 4(\gamma_1 + \gamma_2)(2\Lambda + \gamma_2)\Omega(x, y, z)^2}, \tag{11}
\]

\[
\rho_{22}^{(0)} = \frac{4\Lambda(\gamma_1 + \gamma_2)\Omega(x, y, z)^2}{\Lambda\gamma_2\left((\gamma_1 + \gamma_2)^2 + 4\Delta^2\right) + 4(\gamma_1 + \gamma_2)(2\Lambda + \gamma_2)\Omega(x, y, z)^2}, \tag{12}
\]

\[
\rho_{33}^{(0)} = \frac{4\Lambda(\gamma_1 + \gamma_2)\Omega(x, y, z)^2}{\Lambda\gamma_2\left((\gamma_1 + \gamma_2)^2 + 4\Delta^2\right) + 4(\gamma_1 + \gamma_2)(2\Lambda + \gamma_2)\Omega(x, y, z)^2}. \tag{13}
\]

We can see from Ref. [47] that the density matrix element \(\rho_{31}^{(1)}\) determines the linear susceptibility of atomic medium to the probe transition. The real part \(\chi'\) and imaginary part \(\chi''\) of the susceptibility stand for refractive index and probe absorption (or gain), respectively. Thus, we can obtain position information of the atom in 3D space from the probe absorption or gain, i.e., the imaginary part of the susceptibility, which can be given as

\[
\chi'' = M \frac{\text{Im}(\rho_{31}^{(1)})}{\Omega_p} = M \text{Im}\left\{\frac{-iB_1 B_3 \left(\rho_{33}^{(0)} - \rho_{11}^{(0)}\right) + i\Omega(x, y, z)^2 \left(\rho_{33}^{(0)} - \rho_{22}^{(0)}\right)}{B_1 B_2 B_3 + B_3 \Omega(x, y, z)^2}\right\}, \tag{14}
\]

where \(M = N|\mu_{13}|^2 / \varepsilon_0 \hbar\), \(N\) is the atom number density and \(\varepsilon_0\) is the permittivity in free space.
Eqs. (10)-(14) illustrate that the probe gain depends on the detunings and intensities of probe and coupling fields, as well as incoherent pumping field when incoherent pumping strength exceeds threshold. Due to the existence of the position-dependent Rabi frequency $\Omega(x, y, z)$, the probe gain can be encoded by the 3D spatial position information of the atom as it passes through three orthogonal standing-wave fields. Therefore, we can control 3D atom localization in a cubic volume with dimension $2\pi (kx, ky, kz \in [-\pi, \pi])$ from the probe gain via adjusting the relevant parameters of the system.

3. Numerical results and discussions

In this section, we investigate the behaviors of 3D conditional position probability distribution when an atom passes through three orthogonal standing-wave fields via a few numerical calculations based on Eq. (14). Then how to realize high-detecting probability and high-precision atom localization in 3D space are discussed via properly adjusting the relevant parameters of the system. Before presenting the numerical results, we first consider the following case. In the absence of incoherent pumping field, that is, $\Lambda = 0$, the steady-state solutions in Eqs. (11)-(13) are $\rho_{11}^{(0)} = 1$ and $\rho_{22}^{(0)} = \rho_{33}^{(0)} = 0$. Our scheme reduces to a simple $\Lambda$-type EIT system, which has been used to realize 2D and 3D atom localization via the measurement of probe absorption [34, 40]. When the incoherent pumping field is switched on, as shown in Eqs (11)-(13), the values of $\rho_{11}^{(0)}$, $\rho_{22}^{(0)}$ and $\rho_{33}^{(0)}$ are sensitive to the incoherent pumping rate. If $\Lambda > \gamma_1$ is satisfied, $\rho_{33}^{(0)} > \rho_{11}^{(0)}$ and the population inversion will lead to probe field being amplified. Therefore, we can utilize probe gain via only injecting the incoherent pumping field to achieve efficient atom localization in 3D space. It is worth noting that $\chi'' < 0$ stands for probe gain and $\chi'' > 0$ represents probe absorption. In the following numerical computation, $\gamma_1 = \gamma$, $\gamma_2 = 0.2\gamma$ and $M = \gamma$ are selected and all parameters are scaled with $\gamma$ [47,48].

First of all, we plot the probe gain $\chi''$ as functions of $(kx, ky, kz)$, $(kx, ky, kz \in [-\pi, \pi])$ for different probe detunings when the coupling field are resonance with transition between level $|3\rangle$ and level $|2\rangle$ in Fig. 2. Fig. 2 illustrates a strong correlation between the detuning of probe field and the precision of 3D atom localization. When probe detuning is $\Delta_p = 13.5\gamma$, as shown in Figs. 2(a) and 2(b), we can observe the localization patterns of two identical spheres in subspaces $(x, y, z)$ and
and the maxima of probe gain are localized at the spherical shells of two spheres. When the probe detuning increases from $13.5\gamma$ to $15\gamma$, the localization patterns are also situated in subspaces $(x, y, z)$ and $(-x, -y, -z)$, but the size of two spheres becomes small compared with Fig. 2(a) [see Fig. 2(c)]. In such case, the maxima of probe gain are situated at the two positions $(kx, ky, kz) = (-0.5\pi, -0.5\pi, -0.5\pi)$ and $(0.5\pi, 0.5\pi, 0.5\pi)$ in a volume of $V=(2\pi)^3$ [see Fig. 2(d)]. In other words, the atom can be localized at the two particular positions. In the case of $\Delta_p = 15.5\gamma$, Figs. 2(e) and 2(f) shown that one can localize the atom at the two positions $(kx, ky, kz) = (-0.5\pi, -0.5\pi, -0.5\pi)$ and $(0.5\pi, 0.5\pi, 0.5\pi)$ with a higher precision of the atom localization. According to the above discussions, one can conclude that the precision of atom localization depends on the detuning of probe field, and we can improve the precision of 3D atom localization via properly increasing probe detuning.

As we know, the intensity pattern can be encoded by the position information of the atom in 3D space due to the existence of three orthogonal standing waves. In order to better appreciate the physics behind 3D atom localization shown in Fig. 2, let us treat the position-dependent coupling field $\Omega(x, y, z)$ as a travelling-wave coupling field $\Omega$. When we set $\Omega_s = 5\gamma$ and $\Omega_t = 0$, the corresponding $\Omega(x, y, z) \in [-3\Omega_s, 3\Omega_s]$, we thus have $\Omega \in [-3\Omega_s, 3\Omega_s]$. In Fig. 3, we plot the probe gain as functions of $(\Delta_p, \Omega)$ for the coupling field on resonance with the transition $|3\rangle \leftrightarrow |2\rangle$. From Eqs. (1) and (2), points A1, B1 and C1 at $\Omega = 3\Omega_s$ corresponds to the probe gain at the position $(0.5\pi, 0.5\pi, 0.5\pi)$ and A2, B2, and C2 at $\Omega = -3\Omega_s$ represent probe gain at the position $(-0.5\pi, -0.5\pi, -0.5\pi)$ as shown in Fig. 2. It is found that the maximum of probe gain occurs at $\Delta_p = \pm\Omega$, which is similar to EIT configuration. If $\Delta_p < 3\Omega_s$, probe gain has a maximum value at $\Omega = \pm\Delta_p$, not at $\Omega = \pm3\Omega_s$ [see points A1 and A2], the probe gain patterns in the cubic wavelength display two hollow spheres at the two particular positions [see Fig. 2(b)]. When $\Delta_p = 3\Omega_s$ [see points B1 and B2] and $\Delta_p > 3\Omega_s$ [see points C1 and C2], the maximum of the probe gain is situated at $\Omega = \pm3\Omega_s$ and the probe gain show the patterns of two solid spheres [see Figs. 2(d) and 2(f)], which can give physical reason for the atom being localized at the two positions $(\pm0.5\pi, \pm0.5\pi, \pm0.5\pi)$.

In the study of atom localization, improving the probability of finding the atom in one period of the standing-wave fields is an important index. In order to obtain single-sphere atom localization in a cubic optical wavelength, we adopt the technique of the combination of a travelling-wave field and
three orthogonal classical standing-wave fields, which have been used to realize high-detecting-
probability and high-precision 2D and 3D atom localization [35,40,41]. Therefore, we investigate the
influence of different combinations of \((\Omega_s, \Omega_t)\) on 3D atom localization in Fig. 4. In the case of
\((\Omega_s, \Omega_t) = (5\gamma, 0)\), as shown in Fig. 2(c), the symmetry of \(\Omega(x, y, z)\) leads to two equal
localization spheres in subspaces \((x, y, z)\) and \((-x, -y, -z)\). When \(\Omega_s\) is fixed and \(\Omega_t\) increases to
0.5\(\gamma\), the size of the localization sphere in subspace \((x, y, z)\) becomes large with low precision while
the size of the localization sphere in subspace \((-x, -y, -z)\) becomes small with high precision in Fig.
4(a). Furthermore, when \(\Omega_t\) increases from 0.5\(\gamma\) to \(\gamma\), one can find that only a single-localization
sphere occurs in subspace \((x, y, z)\) and the size of localization pattern is larger [see Fig. 4(b)]. Direct
comparison between Fig. 2(c) and Fig. 3(b) illustrates that increasing the intensity of the travelling-
wave field can improve the probability of finding the atom by a fact of 2 compared with the case in
Fig. 2(b), but the localization precision becomes worse. We then consider controlling the behaviors
of 3D atom localization via decreasing the intensity of the standing-wave fields in the present of the
travelling-wave field. When keeping \(\Omega_t\) being fixed and decreasing \(\Omega_s\) to 4.7\(\gamma\) [see Fig. 4(c)] and
then to 4.4\(\gamma\) [see Fig. 4(d)], the size of probe-gain sphere in subspace \((x, y, z)\) becomes smaller and
smaller, which means that 3D-localization precision becomes higher and higher. Therefore, properly
tuning the intensities of the combination of the travelling-wave field and the standing-wave fields
can improve the detecting probability of the atom and the precision of atom localization.

Finally, it is necessary to study the effect of incoherent pumping field on the behaviors of 3D
atom localization. Eqs. (11)-(14) illustrates that the incoherent pumping field plays an important role
in realizing the transformation between probe absorption and probe gain. We plot the imaginary part
\(\chi''\) of susceptibility as functions of \((\Lambda, kz)\) at the expected position \((kx, ky) = (0.5\pi, 0.5\pi)\) in the
condition of \((\Omega_s, \Omega_t) = (4.7\gamma, \gamma)\) in Fig. 5. It is clear from Fig. 5 that, at the particular position
\((0.5\pi, 0.5\pi, 0.5\pi)\), the population inversion, i.e., \(\rho_{33}^{(0)} > \rho_{11}^{(0)}\), which leads to probe gain builds up
when \(\Lambda > \gamma_1\). The condition \(\Lambda = \gamma_1\) describes the critical value between the probe absorption and the
probe gain. Below the critical value, i.e., \(\Lambda < \gamma_1\), the probe field is absorbed. Thus, we can switch 3D
localization pattern from probe-gain sphere to probe-absorption sphere via adjusting the rate of
incoherent pumping field. The probe absorption has been plotted as functions \((kx, ky, kz)\) for
\(\Lambda = 0.75\gamma\) and \(\Lambda = 0.9\gamma\) in Figs. 6(a) and 6(b), respectively. It can be seen that the precision of 3D
atom localization can be enhanced via measuring probe absorption when increasing $\Lambda$ from $0.75\gamma$ to $0.9\gamma$. Figs. 6(c) and 6(d) give the plot of the probe gain as functions $(kx, ky, kz)$ when $\Lambda = 1.1\gamma$ and $\Lambda = 1.25\gamma$. It is shown that increasing incoherent pumping rate from $1.1\gamma$ to $1.25\gamma$ can lower 3D-localization precision via the measurement of probe gain as shown in Figs. 6(c) and 6(d).

Before concluding, let us give the possible experimental realization of our proposed scheme for 3D atom localization. The three-level $\Lambda$-typed atomic configuration can be realized in D1 line of cold $^{133}\text{Cs}$ atoms [47, 48]. The designated states are chosen as follows: $|1\rangle = |6^2S_{1/2}, F = 3\rangle$, $|2\rangle = |6^2S_{1/2}, F = 4\rangle$, and $|3\rangle = |6^2P_{1/2}, F = 4\rangle$. Here, the weak probe field $\Omega_p$ and incoherent pumping field with a rate $R$ are applied to the transition $|6^2S_{1/2}, F = 3\rangle \leftrightarrow |6^2P_{1/2}, F = 4\rangle$ and the position-dependent coupling field $\Omega(x, y, z)$ interacts with the transition $|6^2S_{1/2}, F = 4\rangle \leftrightarrow |6^2P_{1/2}, F = 4\rangle$. Motivated by Ref. [20], the experiment can be performed using cold $^{133}\text{Cs}$ atoms, which are trapped in a magneto-optical trap (MOT).

4. Conclusion

In summary, we have investigated 3D atom localization controlled by the incoherent pumping field in a three-level $\Lambda$-type atomic system. The position-dependent atom-field interaction leads to the probability distribution of the atom depending on the spatial position in 3D space. The results clearly show that, in the present of the combination of a travelling-wave field and three orthogonal standing-wave fields, the atom can be localized at a particular position with high precision and the detecting probability of the atom can reach 100% via properly adjusting the relevant parameters of the system. More importantly, the incoherent pumping field can switch the 3D atom localization pattern from probe gain sphere to probe absorption sphere and improve the precision of 3D atom localization. The proposed scheme may be used to improve capability of atom imaging and optical microscopy.

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References


**Figure captions**

**Fig. 1.** (a) Schematic diagram of a three-level Λ-type atomic system. (b) The atom passes through a 3D space which is formed by three orthogonal standing-wave fields \( \Omega(x) \), \( \Omega(y) \) and \( \Omega(z) \) aligning along \( x \), \( y \) and \( z \) directions, respectively. While the probe field \( \Omega_p \), incoherent pumping field \( \Lambda \) and travelling-wave coupling field \( \Omega_T \) propagate along \( x \), \( y \) and \( z \) directions, respectively.

**Fig. 2.** Isosurface plots for the probe gain \( \chi'' = -0.01 \) versus positions \((k_x,k_y,k_z)\) for three different values of probe detuning. (a) \( \Delta_p = 13.5 \gamma \); (c) \( \Delta_p = 15 \gamma \); (e) \( \Delta_p = 15.5 \gamma \). (b), (d) and (f) are the corresponding density plots of probe gain \( \chi'' \) in 3D space. The other parameters are \( \Lambda = 1.1 \gamma \), \( \Omega_S = 5 \gamma \), \( \Omega_T = 0 \) and \( \Delta = 0 \).

**Fig. 3.** The probe gain \( \chi'' \) as functions of \((\Delta_p,\Omega)\) for the coupling field on resonance with the transition \( |3\rangle \leftrightarrow |2\rangle \), i.e., \( \Delta = 0 \). The other parameters are \( \Lambda = 1.1 \gamma \).

**Fig. 4.** Isosurface plots for the probe gain \( \chi'' = -0.01 \) versus positions \((k_x,k_y,k_z)\) for three different combinations of \((\Omega_S,\Omega_T)\). (a) \((5 \gamma, 0.5 \gamma)\); (b) \((5 \gamma, \gamma)\); (c) \((4.7 \gamma, \gamma)\); (d) \((4.4 \gamma, \gamma)\). The other parameters are \( \Lambda = 1.1 \gamma \), \( \Delta_p = 15 \gamma \) and \( \Delta = 0 \).

**Fig. 5.** the probe gain and absorption \( \chi'' \) as functions of \((\Lambda,k_z)\) for the particular situation \((k_x,k_y) = (0.5 \pi, 0.5 \pi)\). The other parameters are \( \Lambda = 1.1 \gamma \), \( \Delta_p = 15 \gamma \) and \( \Delta = 0 \).

**Fig. 6.** Isosurface plots for the probe absorption \( \chi'' = 0.01 \) versus positions \((k_x,k_y,k_z)\) for (a) \( \Lambda = 0.75 \gamma \) and (b) \( \Lambda = 0.9 \gamma \); Isosurface plots for the probe gain \( \chi'' = -0.01 \) versus positions \((k_x,k_y,k_z)\) for (c) \( \Lambda = 1.1 \gamma \) and (d) \( \Lambda = 1.25 \gamma \). The other parameters are \( \Omega_S = 4.7 \gamma \), \( \Omega_T = \gamma \), \( \Delta_p = 15 \gamma \) and \( \Delta = 0 \).

**Fig. 7.** Possible experimental scheme for a Λ-type \(^{133}\)Cs atomic system.
Fig. 2
Fig. 3
Fig. 4
Fig. 6
Fig. 7