Vol 12 No 4, April 2003
1009-1963/2003/12(04)/0403-05

Chinese Physics

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Light-induced nonlinear effects on dispersion relation of ultracold Bose gas*

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(Received 13 August 2002; revised manuscript received 25 December 2002)

We have investigated the optical properties of Λ-configuration ultracold dense Bose gas interacting with two laser pulses, which usually result in electromagnetically induced transparency. With the nonrelativistic quantum electrodynamics and taking into account the atomic dipole–dipole interaction and local field effect, we have derived the Maxwell–Bloch equations of the system. The dispersion relation of an ultracold Bose gas has been obtained and the light-induced nonlinear effects have been analysed. The light-induced nonlinear effects are different from the effects induced by two-body collision of Bose–Einstein condensation atoms which have a frequency shift of transparent window.

Keywords: photon-atom interaction, quantum condensation phenomena, optical susceptibility, Bose systems

PACC: 3280, 0375, 4250, 0530J

It is well known that light field as a means can be used to change the optical properties of originally optically opaque media to transparent ones in a hot atomic gas.[1−7] Recently, the propagation of laser pulse through optically dense media has been a very interesting topic, especially in the ultracold alkali-metal atomic gas[8,9] because of easy manipulation by laser cooling and trapping techniques. For an ultracold atomic gas, higher density can be obtained easily. Due to the high density of the atomic gas, light speed will be slowed down extremely. Lately, light pulse has been stopped and then regenerated for 1ms delay[10] experimentally. On the one hand, slow light phenomenon has potential applications in ultralow intensity nonlinear optics due to its huge nonlinear coefficient and very low absorption. On the other hand, in this kind of systems light information can be stored in an atomic medium. An atomic medium has the properties of longer-time storage and relatively less decoherence. These advantages give quantum information processing good prospects. Several authors have investigated theoretically the slow light in hot and cold atomic gases.[11−18] In previous studies, the research interest mainly focused on the effects of density variation of a Bose gas at different temperatures. When the temperature of the gas is just below the critical point, the density of the gas will increase dramatically. This high density is considered to be the main factor for slow light. As for the interaction between the laser light and atom, there are twofold influences in the interaction between the laser and ultracold Bose atom. One is that the properties of laser radiation is modified by atomic dipole–dipole interactions.[19−21] This can be described by the variation of refractive index. The other is the influence on the behaviour of an ultracold atomic medium. In recent works[22−24] the local field effect in atom optics of one-component and two-component ultracold Bose gases has been investigated. At reasonable detuning of laser pulses, the light will induce a nonlinear modulation in atomic matter waves. So the refractive index depends on the atomic density. Here we consider the light-induced nonlinear effects on an electromagnetically induced transparent system in an ultracold Bose gas. Indeed at a high

*Project supported by the National Natural Science Foundation of China(Grant No. 19975027) and the State Key Development Program for Basic Research of China(Grant No. 001CB309308)

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density of the ultracold atomic gas, atomic dipole–dipole interactions will change the optical properties. We will check the dispersion relation when there is a light-induced nonlinearity. It is found that although at the transparent centre, there is no influence observed. At the position away from the transparent point, the light-induced nonlinearity will show effects. The effect is also dependent on the density of the gas. The numerical results show that light-induced nonlinear effects cause dispersion relations to be no longer symmetric.

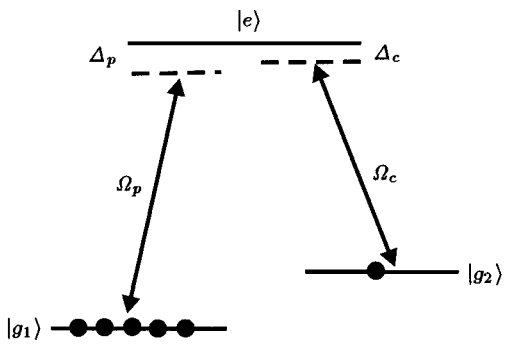


Fig.1. A three-level Λ-type ultracold Bose atom coupled to a classical coupling laser with Rabi-frequency $\Omega_c(t)$ and a classical probe laser with Rabi-frequency $\Omega_p(t)$.

We consider a Λ-configuration structure atom, labelled as $|g_1\rangle, |g_2\rangle$ and $|e\rangle$ as shown in Fig.1. $|g_1\rangle, |g_2\rangle$ are two ground states, such as Zeeman sublevels, and $|e\rangle$ is the excited state. A relatively strong coupling light field is applied to the transition $|g_2\rangle \leftrightarrow |e\rangle$. A weak probe light is applied to the transition $|g_1\rangle \leftrightarrow |e\rangle$. The transition between $|g_1\rangle \leftrightarrow |g_2\rangle$ is forbidden. For this system, Hamiltonian can be written as follows:

$$H = H_{\rm a} + H_{\rm f} + H_{\rm al} + H_{\rm af}, \tag{1}$$

where $H_{\rm a}$ is the atomic free moving part, $H_{\rm f}$ is the free photon Hamiltonian, $H_{\rm al}$ is the Hamiltonian of interaction between laser light and atom, and $H_{\rm af}$ is the Hamiltonian of interaction between atom and quantized light field in an ultracold Bose gas medium due to the high density of atoms.

$$H_{\rm a} = \sum_{j=g_1,g_2,e} \left[\int {\rm d}\boldsymbol{r} \psi_j^\dagger(\boldsymbol{r},t) \left(-\frac{\hbar^2\nabla^2}{2m} \right) \psi_j(\boldsymbol{r},t) + \int {\rm d}\boldsymbol{r} \psi_j^\dagger(\boldsymbol{r},t) \hbar\omega_j \psi_j(\boldsymbol{r},t) \right], \tag{2a}$$

$$H_{\rm f} = \sum_{k\lambda} \hbar\omega_k a_{k\lambda}^\dagger(t) a_{k\lambda}(t), \tag{2b}$$

$$H_{\rm al} = -\int {\rm d}\boldsymbol{r} \boldsymbol{P}(\boldsymbol{r},t) \cdot \boldsymbol{E}(\boldsymbol{r},t) = -\int {\rm d}\boldsymbol{r} \left[\boldsymbol{P}_c(\boldsymbol{r},t) \cdot \boldsymbol{E}_c(\boldsymbol{r},t) + \boldsymbol{P}_p(\boldsymbol{r},t) \cdot \boldsymbol{E}_p(\boldsymbol{r},t) \right], \tag{2c}$$

$$H_{\rm af} = -\int {\rm d}\boldsymbol{r} \left[\boldsymbol{P}_c(\boldsymbol{r},t) + \boldsymbol{P}_p(\boldsymbol{r},t) \right] \cdot \boldsymbol{D}_{md}(\boldsymbol{r},t), \tag{2d}$$

where $\psi_j(\boldsymbol{r},t)$ is the atomic field annihilation operator which satisfies the Bosonic commutation relation $[\psi_i(\boldsymbol{r},t), \psi_j^\dagger(\boldsymbol{r}',t')] = \delta_{ij}\delta(\boldsymbol{r}-\boldsymbol{r}')\delta(t-t')$. $\boldsymbol{E}_p(\boldsymbol{r},t)$ and $\boldsymbol{E}_c(\boldsymbol{r},t)$ are the coupling and probe lasers respectively. Here we consider these two laser pulses as the classical external light field. There are no operators related to them. $\boldsymbol{P}_c(\boldsymbol{r},t)$ and $\boldsymbol{P}_p(\boldsymbol{r},t)$ are the atomic polarizations induced by the coupling and probe fields respectively. The atomic interaction is the result of the resonant dipole–dipole interaction of the induced dipoles. This interaction is mediated by the exchange of photons. $a_{k\lambda}(t)$ is the destruction operator of photons. The operator of the microscopic displacement field is given by

$$\boldsymbol{D}_{md}(\boldsymbol{r},t) = \sum_{k\lambda} i\sqrt{\frac{2\pi\hbar\omega_{\boldsymbol{k}}}{V}} e_\lambda a_{k\lambda} \exp(i\boldsymbol{k}\cdot\boldsymbol{r}) + h.c. \tag{3}$$

The operators for the polarization field are

$$\boldsymbol{P}_p = \boldsymbol{d}_p(\psi_{g_1}^\dagger\psi_e + \psi_e^\dagger\psi_{g_1}), \tag{4a}$$

$$\boldsymbol{P}_c = \boldsymbol{d}_c(\psi_{g_2}^\dagger\psi_e + \psi_e^\dagger\psi_{g_2}), \tag{4d}$$

where $\boldsymbol{d}_c$ and $\boldsymbol{d}_p$ are the dipole moments related to the two transitions. The Heisenberg equations of motion for atom and photon operators can be easily obtained from the above system of Hamiltonian as follows.

$$\begin{aligned} & i\hbar\frac{\partial}{\partial t}\psi_{g_1}(\boldsymbol{r},t) \\ =& -\frac{\hbar^2\nabla^2}{2m}\psi_{g_1}(\boldsymbol{r},t) - \boldsymbol{d}_p\cdot\boldsymbol{E}_p(\boldsymbol{r},t)\psi_e(\boldsymbol{r},t) \\ & - \hbar\sum_{k\lambda}(g_{k\lambda}^p)^* a_{k\lambda}^\dagger \exp(-i\boldsymbol{k}\cdot\boldsymbol{r})\psi_e(\boldsymbol{r},t) \\ & - \hbar\sum_{k\lambda}(g_{k\lambda}^p) a_{k\lambda} \exp(i\boldsymbol{k}\cdot\boldsymbol{r})\psi_e(\boldsymbol{r},t), \end{aligned} \tag{5}$$

$$\begin{aligned} & i\hbar\frac{\partial}{\partial t}\psi_{g_2}(\boldsymbol{r},t) \\ =& -\frac{\hbar^2\nabla^2}{2m}\psi_{g_2}(\boldsymbol{r},t) + \hbar\omega_{g_2}\psi_{g_2} \\ & - \boldsymbol{d}_c\cdot\boldsymbol{E}_c(\boldsymbol{r},t)\psi_e(\boldsymbol{r},t) \\ & - \hbar\sum_{k\lambda}(g_{k\lambda}^c)^* a_{k\lambda}^\dagger \exp(-i\boldsymbol{k}\cdot\boldsymbol{r})\psi_e(\boldsymbol{r},t) \\ & - \hbar\sum_{k\lambda}(g_{k\lambda}^c) a_{k\lambda} \exp(i\boldsymbol{k}\cdot\boldsymbol{r})\psi_e(\boldsymbol{r},t), \end{aligned} \tag{6}$$

$$
\begin{aligned}
&i\hbar\frac{\partial}{\partial t}\psi_e(\boldsymbol{r},t)\\
=&-\frac{\hbar^2\nabla^2}{2m}\psi_e(\boldsymbol{r},t)+\hbar\omega_e\psi_e\\
&-\boldsymbol{d}_p\cdot\boldsymbol{E}_p(\boldsymbol{r},t)\psi_{g_1}(\boldsymbol{r},t)-\boldsymbol{d}_c\cdot\boldsymbol{E}_c(\boldsymbol{r},t)\psi_{g_2}(\boldsymbol{r},t)\\
&-\hbar\sum_{k\lambda}(g^p_{k\lambda})^*a^\dagger_{k\lambda}\exp(-i\boldsymbol{k}\cdot\boldsymbol{r})\psi_{g_1}(\boldsymbol{r},t)\\
&-\hbar\sum_{k\lambda}(g^p_{k\lambda})a_{k\lambda}\exp(i\boldsymbol{k}\cdot\boldsymbol{r})\psi_{g_1}(\boldsymbol{r},t)\\
&-\hbar\sum_{k\lambda}(g^c_{k\lambda})^*a^\dagger_{k\lambda}\exp(-i\boldsymbol{k}\cdot\boldsymbol{r})\psi_{g_2}(\boldsymbol{r},t)\\
&-\hbar\sum_{k\lambda}(g^c_{k\lambda})a_{k\lambda}\exp(i\boldsymbol{k}\cdot\boldsymbol{r})\psi_{g_2}(\boldsymbol{r},t),
\end{aligned}\tag{7}
$$

$$
\begin{aligned}
&i\hbar\frac{\partial}{\partial t}a_{k\lambda}(t)\\
=&\hbar\omega_{\boldsymbol{k}}a_{k\lambda}(t)-\hbar(g^p_{k\lambda})^*\int\mathrm{d}\boldsymbol{r}\exp(-i\boldsymbol{k}\cdot\boldsymbol{r})\\
&\times\left[\psi^\dagger_e(\boldsymbol{r},t)\psi_{g_1}(\boldsymbol{r},t)+\psi^\dagger_{g_1}(\boldsymbol{r},t)\psi_e(\boldsymbol{r},t)\right]\\
&-\hbar(g^c_{k\lambda})^*\int\mathrm{d}\boldsymbol{r}\exp(-i\boldsymbol{k}\cdot\boldsymbol{r})\\
&\times\left[\psi^\dagger_e(\boldsymbol{r},t)\psi_{g_2}(\boldsymbol{r},t)+\psi^\dagger_{g_2}(\boldsymbol{r},t)\psi_e(\boldsymbol{r},t)\right].
\end{aligned}\tag{8}
$$

A formal solution of Eq.(8) for the photon operator is given by

$$
\begin{aligned}
a_{k\lambda}(t)=&a_{k\lambda}(0)\exp(-i\omega_k t)\\
&+\int_0^t dt'\int\mathrm{d}\boldsymbol{r}'\exp\left[i\omega_k(t'-t)-i\boldsymbol{k}\cdot\boldsymbol{r}'\right]\\
&\times\{\hbar(g^p_{k\lambda})^*[\psi^\dagger_e(\boldsymbol{r}',t')\psi_{g_1}(\boldsymbol{r}',t')\\
&+\psi^\dagger_{g_1}(\boldsymbol{r}',t')\psi_e(\boldsymbol{r}',t')]\\
&+\hbar(g^c_{k\lambda})^*[\psi^\dagger_e(\boldsymbol{r}',t')\psi_{g_2}(\boldsymbol{r}',t')\\
&+\psi^\dagger_{g_2}(\boldsymbol{r}',t')\psi_e(\boldsymbol{r}',t')]\}.
\end{aligned}\tag{9}
$$

In Eq.(9), the first term is the free-space photon field and others are related interactions between the light field and atom. In order to obtain only atom operators motion equations, we substitute Eq.(9) into atomic operator equations. In the rotating wave approximation, by neglecting Lamb shift, we obtain following atomic operator motion equations.

$$
\begin{aligned}
i\hbar\frac{\partial}{\partial t}\psi_{g_1}(\boldsymbol{r},t)=&-\frac{\hbar^2\nabla^2}{2m}\psi_{g_1}(\boldsymbol{r},t)\\
&-\boldsymbol{d}_p\cdot\boldsymbol{E}^{p-}_{\mathrm{loc}}(\boldsymbol{r},t)\psi_e(\boldsymbol{r},t),
\end{aligned}\tag{10a}
$$

$$
\begin{aligned}
i\hbar\frac{\partial}{\partial t}\psi_{g_2}(\boldsymbol{r},t)=&-\frac{\hbar^2\nabla^2}{2m}\psi_{g_2}(\boldsymbol{r},t)+\hbar\omega_{g_2}\psi_{g_2}\\
&-\boldsymbol{d}_c\cdot\boldsymbol{E}^{c-}_{\mathrm{loc}}(\boldsymbol{r},t)\psi_e(\boldsymbol{r},t),
\end{aligned}\tag{10b}
$$

$$
\begin{aligned}
i\hbar\frac{\partial}{\partial t}\psi_e(\boldsymbol{r},t)=&-\frac{\hbar^2\nabla^2}{2m}\psi_e(\boldsymbol{r},t)+\hbar(\omega_e-i\gamma/2)\psi_e\\
&-\boldsymbol{d}_p\cdot\boldsymbol{E}^{p+}_{\mathrm{loc}}(\boldsymbol{r},t)\psi_{g_1}(\boldsymbol{r},t)\\
&-\boldsymbol{d}_c\cdot\boldsymbol{E}^{c+}_{\mathrm{loc}}(\boldsymbol{r},t)\psi_{g_2}(\boldsymbol{r},t).
\end{aligned}\tag{10c}
$$

In Eqs.(10a)–(10c) we have introduced the operators of local electric fields, which are the combination of incident fields, free-space photon field and polarization field, given as below.

$$
\begin{aligned}
\boldsymbol{E}^{p+}_{\mathrm{loc}}(\boldsymbol{r},t)=&\boldsymbol{E}^+_p(\boldsymbol{r},t)+\sum_{k\lambda}i\sqrt{\frac{2\pi\hbar\omega_{\boldsymbol{k}}}{V}}\\
&\times\boldsymbol{e}_\lambda a_{k\lambda}(0)\exp(i\boldsymbol{k}\cdot\boldsymbol{r}-i\omega_{\boldsymbol{k}}t)\\
&+\int\mathrm{d}\boldsymbol{r}'\nabla\times\nabla\times\frac{\boldsymbol{P}^+(\boldsymbol{r}',t-R/c)}{R},
\end{aligned}\tag{11}
$$

$$
\begin{aligned}
\boldsymbol{E}^{c+}_{\mathrm{loc}}(\boldsymbol{r},t)=&\boldsymbol{E}^+_c(\boldsymbol{r},t)+\sum_{k\lambda}i\sqrt{\frac{2\pi\hbar\omega_{\boldsymbol{k}}}{V}}\\
&\times\boldsymbol{e}_\lambda a_{k\lambda}(0)\exp(i\boldsymbol{k}\cdot\boldsymbol{r}-i\omega_k t)\\
&+\int\mathrm{d}\boldsymbol{r}'\nabla\times\nabla\times\frac{\boldsymbol{P}^+(\boldsymbol{r}',t-R/c)}{R},
\end{aligned}\tag{12}
$$

with $\nabla=\dfrac{\partial}{\partial\boldsymbol{r}}$. In order to avoid singularity, a small volume around the point $\boldsymbol{r}$ has been excluded from the integration. Equations (11) and (12) describe the detailed atomic operator evolution including the microscopic dipole–dipole interaction. For the ultracold dense atom gas we consider the macroscopic properties of the medium. For a charge-free and current-free medium we can use local-field correction. It is the combination of the macroscopic field and polarized field. The macroscopic field satisfies the Maxwell equations.

$$
\boldsymbol{E}^{p(c)\pm}_{\mathrm{loc}}(\boldsymbol{r},t)=\boldsymbol{E}^{p(c)\pm}_{\mathrm{mac}}(\boldsymbol{r},t)+\frac{4\pi}{3}\boldsymbol{P}^\pm_{p(c)}(\boldsymbol{r},t).\tag{13}
$$

Eq. (13) is the well-known Lorentz–Lorenz relation. The Maxwell equations of a macroscopic field is the following.

$$
\begin{aligned}
&\nabla\times\nabla\times\boldsymbol{E}^{p(c)\pm}_{\mathrm{mac}}(\boldsymbol{r},t)\\
=&-\frac{1}{c^2}\frac{\partial^2\boldsymbol{E}^{p(c)\pm}_{\mathrm{mac}}(\boldsymbol{r},t)}{\partial t^2}-\frac{4\pi}{c^2}\frac{\partial^2\boldsymbol{P}^\pm_{p(c)}(\boldsymbol{r},t)}{\partial t^2}.
\end{aligned}\tag{14}
$$

In this manner the interaction between the ultracold dense atomic gas and light field is similar to the interaction between light and a macroscopic dielectric medium. Therefore, with the local field expression and the rotating frame with a laser light frequency we can obtain the nonlinear matter equations.

$$
\begin{aligned}
i\hbar\frac{\partial}{\partial t}\psi_{g_1}=&-\frac{\hbar^2\nabla^2}{2m}\psi_{g_1}-\frac{\hbar}{2}\Omega^-_p(\boldsymbol{t})\psi_e\\
&-\frac{4\pi}{3}d_p^2\psi^\dagger_e\psi_{g_1}\psi_e-\frac{4\pi}{3}\boldsymbol{d}_p\cdot\boldsymbol{d}_c\psi^\dagger_e\psi_{g_2}\psi_e,
\end{aligned}\tag{15a}
$$

$$i\hbar\frac{\partial}{\partial t}\psi_{g_2} = -\frac{\hbar^2\nabla^2}{2m}\psi_{g_2} + \hbar(\Delta_c - \Delta_p)\psi_{g_2} - \frac{\hbar}{2}\Omega_c^-(t)\psi_e - \frac{4\pi}{3}d_c^2\psi_e^\dagger\psi_{g_2}\psi_e - \frac{4\pi}{3}\boldsymbol{d}_p\cdot\boldsymbol{d}_c\psi_e^\dagger\psi_{g_1}\psi_e, \quad (15b)$$

$$i\hbar\frac{\partial}{\partial t}\psi_e = -\frac{\hbar^2\nabla^2}{2m}\psi_e - \hbar(\Delta_p + i\gamma/2)\psi_e - \frac{\hbar}{2}\Omega_p^+(t)\psi_{g_1} - \frac{\hbar}{2}\Omega_c^+(t)\psi_{g_2} - \frac{4\pi}{3}d_p^2\psi_{g_1}\psi_{g_1}^\dagger\psi_e - \frac{4\pi}{3}d_c^2\psi_{g_2}\psi_{g_2}^\dagger\psi_e - \frac{4\pi}{3}\boldsymbol{d}_p\cdot\boldsymbol{d}_c\left(\psi_{g_1}\psi_{g_2}^\dagger + \psi_{g_2}\psi_{g_1}^\dagger\right)\psi_e. \quad (15c)$$

where $\Delta_p = \omega_p - \omega_{eg_1}, \Delta_c = \omega_c - \omega_{eg_2}$ are probe and coupling light detunings respectively. In the electromagnetically induced transparent system, usually most atoms stay at the $|g_1\rangle$ ground state. In the process of interaction between light and atoms, there is a little of atoms driven to another ground state. Also the probability for the atom in the excited state is small. For the ultracold atoms, the motion of the centre of mass can be neglected. Therefore, we can use the adiabatic approximation to gain ψ_e,

$$\psi_e = \frac{(\Delta_c - \Delta_p)\Omega_p^+\psi_{g_1}}{|\Omega_c|^2/2 - \frac{8\pi}{3\hbar}d_p^2|\psi_{g_1}|^2(\Delta_c - \Delta_p) - 2(\Delta_p + i\gamma/2)(\Delta_c - \Delta_p)}. \quad (16)$$

This solution is very different from those of the usual atomic system and the previous two-level ultracold atom system.[22–24] In the usual three-level atom system, there is no light-induced nonlinear term in the solution. This is also different from the case in which Bose–Einstein condensation atomic collisions are considered. It can be seen that as long as the existence of laser light detuning, the nonlinearity will have influence on the dispersion relation. According to the above expression, the electric susceptibility can be given as[25,26]

$$\chi = -\frac{4\pi|d_p|^2}{\hbar\Omega_p}\psi_{g_1}\psi_e^\dagger = \frac{C + iD}{A^2 + B^2}, \quad (17)$$

where A, B, C and D are defined as follows,

$$A = |\Omega_c|^2/2 - \frac{8\pi}{3\hbar}d_p^2|\psi_{g_1}|^2(\Delta_c - \Delta_p) - 2\Delta_p(\Delta_c - \Delta_p), \quad (18a)$$

$$B = i\gamma(\Delta_c - \Delta_p), \quad (18b)$$

$$C = 4\pi(\Delta_c - \Delta_p)|d_p|^2|\psi_{g_1}|^2A/\hbar, \quad (18c)$$

$$D = 4\pi(\Delta_c - \Delta_p)|d_p|^2|\psi_{g_1}|^2/\hbar. \quad (18d)$$

The complex susceptibility χ as a function of detuning Δ_p and atom density is calculated and plotted in Fig.2. Here we have chosen the reasonable parameters used in recent experiments.[10]

In Fig.3 the thick solid and dashed lines are the real and imaginary parts of the susceptibility with optical-induced nonlinearity respectively. The thin dot-dashed and dotted lines correspond to those without optical-induced nonlinearity. By comparing Fig.2

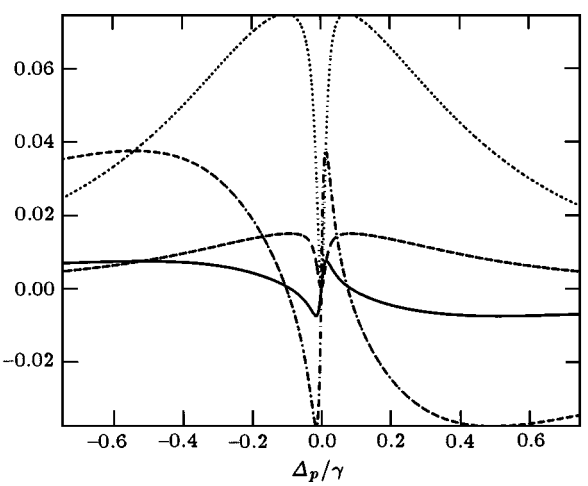


Fig.2. The solid and dot-dashed lines are the real part and the dashed and dotted lines are the imaginary part of the complex susceptibility χ plotted as a function of detuning Δ_p. The solid and dashed lines correspond to $\frac{8\pi}{3\hbar}d_p^2|\psi_{g_1}|^2 = 0.01\gamma$. The dashed and dotted lines correspond to $\frac{8\pi}{3\hbar}d_p^2|\psi_{g_1}|^2 = 0.05\gamma$. Other parameters are $\Omega_c = \gamma/8$, $\Delta_c = 0$.

with Fig.3, it is clear that the shape of the curve is determined mainly by the atomic density. When the atomic density is large, the transparent window will be narrow. At the same time, we see clearly that the gradient of the real part of susceptibility also becomes large with increasing the parameter. The light-induced nonlinearity has influence on the dispersion relation outside the transparent window. The absorptions of the two sides around the centre are no longer symmetric. The absorptions on the two sides of the central point are different. As we know for the Raman process with large one-photon detuning, the light-induced nonlinearity will have a significant effect which can influence the propagation of light pulse

in the media. This will be discussed elsewhere. We should mention that the effects are different from those induced by the two-body collision in Bose–Einstein condensation which have a frequency shift of the transparent window. This kind of difference may be used to distinguish the interactions between the atom dipole–dipole interaction mediated by exchange photons and the atom two-body collisions.

In summary, starting from the first principle of nonrelativistic quantum electrodynamics, we have derived the dielectric susceptibility of the ultracold dense atomic gas in an electromagnetically induced transparent-type laser light. It describes the modification of the dispersion relation by the light-induced atomic dipole–dipole interaction. This effect is different from the effect induced by the atom interaction in Bose–Einstein condensation. Therefore, it is possible to distinguish these two effects by using electromagnetically induced transparency.

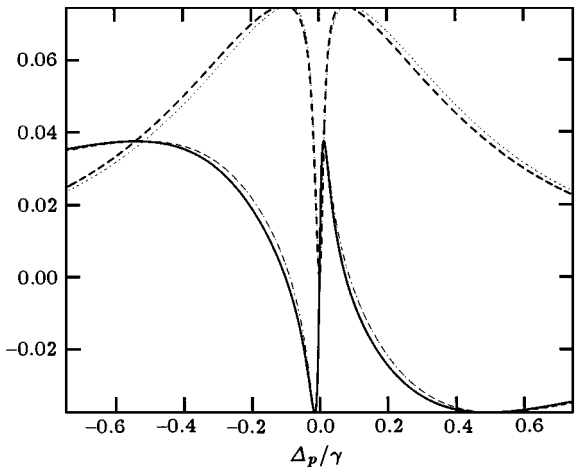


Fig.3. The solid and dot-dashed lines are the real part and the dashed and dotted lines are the imaginary part of the complex susceptibility χ plotted as a function of detuning Δ_p.

References

[1] Scully M O and Zubairy M S 1997 *Quantum Optics* (Cambridge: Cambridge University Press)

[2] Harris S E 1997 *Phys. Today* **50** 36

[3] Xiao M, Li Y Q, Jin S Z and Gea-Banachoche J 1995 *Phys. Rev. Lett.* **74** 666

[4] Zhao J M 2002 *Chin. Phys.* **11** 241

[5] Yang S H, Zhang H Z, Guo X Z and Gao J Y 1998 *Acta Phys. Sin.* **47** 931 (in Chinese)

[6] Yang S H, Wang D and Gao J Y 1999 *Chin. Phys.* **8** 443

[7] Popov, Gao J Y and Zhang H Z 2000 *Chin. Phys.* **9** 124

[8] Hau L V, Harris S E, Dutton Z and Behroozi C H 1999 *Nature* **397** 594

[9] Inouye S, Low R F, Gupta S, Pfau T, Gorlitz A, Gustavson T L, Pritchard D E and Ketterle W 2000 *Phys. Rev. Lett.* **85** 4225

[10] Liu C, Dutton Z, Behroozi C H and Hau L V 2001 *Nature* **409** 490

[11] Fleischhauer M and Lukin M D 2000 *Phys. Rev. Lett.* **84** 5094

[12] Mustecaplioglu O E and You L 2001 *Phys. Rev.* A **64** 013604

[13] Mustecaplioglu O E and You L 2001 *Opt. Commun.* **193** 301

[14] Morigi G and Agarwal G S 2000 *Phys. Rev.* A **62** 013801

[15] Juzeliunas G and Carmichael H J 2002 *Phys. Rev.* A **65** 021601

[16] Fleischhauer M and Lukin M D 2002 *Phys. Rev.* A **65** 022314

[17] Payne M G and Deng L 2001 *Phys. Rev.* A **64**, 031802

[18] Roberts D C, Gasenzer T and Burnett K 2002 Preprint quant-ph/0201062

[19] Morice O, Castin Y and Dalibard J 1995 *Phys. Rev.* A **51** 3896

[20] Ruostekoski J and Javanainen J 1997 *Phys. Rev.* A **55** 513

[21] Ruostekoski J and Javanainen J 1999 *Phys. Rev. Lett.* **82** 4741

[22] Krutitsky K V, Burgbacher F and Audretsch J 1999 *Phys. Rev.* A **59** 1517

[23] Krutitsky K V, Burgbacher F and Audretsch J 2000 *Laser Phys.* **10** 15

[24] Krutitsky K V, Marzlin K P and Audretsch J 2001 *Laser Phys.* **11** 449

[25] Angelakis D G, Paspalakis E and Knight P L 2001 *Phys. Rev.* A **64** 013801

[26] Agarwal G S, Dey T N and Menon S 2001 Preprint quant-ph/0106107