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Inversionless gain enhancing due to Doppler broadening in a closed lambda-type system*

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An analysis is made of the effect of Doppler broadening on gain without inversion (GWI) from different aspects in a closed lambda-type three-level system with an incoherent pump. It is shown that, regardless of the driving field being on resonance or not, for the counter- or co-propagating of the probe and driving fields (PDF), GWI does not monotonically decrease or increase with increasing Doppler width. Except for the case of counter-propagating PDF with off-resonance driving field, at a suitable Doppler width one can obtain a gain maximum value much larger than that without Doppler broadening; especially in the situation of the resonant driving field, the co-propagating geometry leads to a larger GWI. In addition, for the counter-propagating geometry, when Doppler width is larger enough, GWI oscillation occurs, and the oscillation amplitude and region increase with increasing Doppler width. These conclusions are very different from that obtained in previous investigation (Lukin *et al*, *Laser Phys.* **6** 436 (1996)).

Keywords: closed system，Doppler broadening, gain without inversion
PACC: 4250

1. Introduction

Since the seminal works of Kocharovskaya and Khanin,[1] Scully *et al*[2] and Harris *et al*[3], lasing without inversion (LWI) has attracted tremendous attention (for example, see the recent review[4] and papers[5−13] and references in them). LWI is a result of atom coherent and quantum interference. It could achieve laser actions in the short wavelength (e.g. the x-ray even γ-ray) regions where lasing is impractical with conventional pumping schemes. Since the gain without inversion (GWI) one can realize is usually quite small, it is important not only to identify the optimal atom and field parameters, but also explore any other causes that may affect the maximal gain one can achieve. On the other hand, the experiment on LWI is usually performed using atomic vapour, which is typically accompanied by obvious Doppler broadening, so in attempting to isolate conditions that yield the best GWI, some attentions have been paid to the effect that Doppler broadening has on GWI.[14−24] Lukin *et al*[17] have shown that in a closed Λ-type system, when the driving and probe fields are propagating in the same direction, GWI decreases monotonically with increasing Doppler width, in this system an incoherent pumping is applied between the middle level $|2\rangle$ and the low level $|3\rangle$, while a coherent driving (probe) field couples the high level $|1\rangle$ and $|2\rangle$ ($|3\rangle$). In this paper, we use a scheme of closed Λ-type system different from that of Lukin *et al*, i.e. the incoherent pumping is applied between the high level $|1\rangle$ and the low level $|3\rangle$ to study the effect of Doppler broadening on GWI, and obtain a much different conclusion from that given by Lukin *et al*.

2. The model and equations of motion

Consider a closed lambda-type three-level atomic system with an upper state $|1\rangle$ and two lower states $|2\rangle$ and $|3\rangle$, as illustrated in Fig.1. The transition between levels $|1\rangle$ and $|2\rangle$ is driven by a strong coherent driving field with an amplitude $\boldsymbol{E}_{\rm d}$, frequency $\omega_{\rm d}$ and Rabi frequency Ω. An incoherent pump at a pump-

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ing rate 2Λ and a weak coherent probe field with an amplitude $\boldsymbol{E}_{\rm p}$, frequency $\omega_{\rm p}$ and Rabi frequency α are applied between levels $|1\rangle$ and $|3\rangle$. And let $2\gamma_1$ and $2\gamma_2$ denote the spontaneous emission rates from level $|1\rangle$ to $|3\rangle$ and $|2\rangle$, respectively.

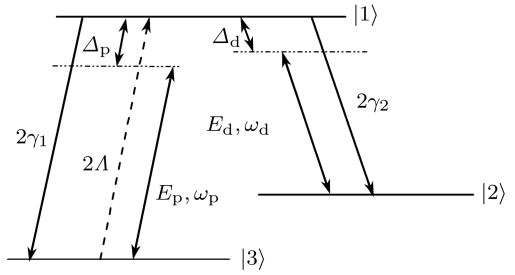


Fig.1. A closed three-level Λ-type atomic system.

In the interaction picture, by using the rotating-wave approximations, the semiclassical interaction Hamiltonian for the system can be written as follows:

$$H_{\rm I} = \Delta_{\rm p}|1\rangle\langle 1| + (\Delta_{\rm p}-\Delta_{\rm d})|2\rangle\langle 2| - [\Omega|1\rangle\langle 2| + \alpha|1\rangle\langle 3| + {\rm c.c.}], \tag{1}$$

where $\Delta_{\rm p}(=\omega_{13}-\omega_{\rm p})$ and $\Delta_{\rm d}$ $(=\omega_{12}-\omega_{\rm d})$ are the detunings of the probe and driving fields from their relevant atomic transitions, respectively.

Using the rotating-wave and the electric dipole approximations, the semiclassical density matrix equations of motion for a closed Λ-type atomic system can be written as follows:

$$\dot{\rho}_{11} = -2(\gamma_1+\gamma_2)\rho_{11} + {\rm i}\alpha\rho_{31} - {\rm i}\alpha\rho_{13} + 2\Lambda\rho_{33} + {\rm i}\Omega\rho_{21} - {\rm i}\Omega\rho_{12}, \tag{2a}$$

$$\dot{\rho}_{22} = 2\gamma_2\rho_{11} + {\rm i}\Omega\rho_{12} - {\rm i}\Omega\rho_{21}, \tag{2b}$$

$$\dot{\rho}_{12} = -(\gamma_1+\gamma_2+{\rm i}\Delta_{\rm d})\rho_{12} + {\rm i}\alpha\rho_{32} - {\rm i}\Omega(\rho_{11}-\rho_{22}), \tag{2c}$$

$$\dot{\rho}_{13} = -(\gamma_1+\gamma_2+\Lambda+{\rm i}\Delta_{\rm p})\rho_{13} + {\rm i}\Omega\rho_{23} - {\rm i}\alpha(\rho_{11}-\rho_{33}), \tag{2d}$$

$$\dot{\rho}_{23} = -(\Lambda+{\rm i}\Delta_{\rm p}-{\rm i}\Delta_{\rm d})\rho_{23} + {\rm i}\Omega\rho_{13} - {\rm i}\alpha\rho_{21}, \tag{2e}$$

along with the equations of their complex conjugates, $\rho_{ij}=\rho_{ji}^{*}(i\neq j,i,j=1,2,3)$ and the closure relation $\rho_{11}+\rho_{22}+\rho_{33}=1$.

The probe gain corresponds to the imaginary part of ρ_{31}. If ${\rm Im}\rho_{31}>0$, the system exhibits gain for the probe field; if ${\rm Im}\rho_{31}<0$, the probe field is attenuated. The inequalities $\rho_{11}-\rho_{33}>0$ and $\rho_{11}-\rho_{33}<0$ correspond to population inversion and inversionless transitions between levels $|1\rangle$ and $|3\rangle$, respectively. When $\rho_{11}-\rho_{33}<0$ and ${\rm Im}\rho_{31}>0$, the probe field has a gain without inversion. For the convenience of calculation, we choose α and Ω to be real, and this does not affect the generality of the following discussion. For the steady state case, ${\rm d}\rho_{mn}/{\rm d}t=0$, Eqs.(2) reduce to a set of coupled algebraic equations, then we can obtain the exact nonlinear analytical expressions for ${\rm Im}\rho_{31}$, $\rho_{11},\rho_{22},\rho_{33}$, which are complicated functions of Ω, α, $\Delta_{\rm p}$, $\Delta_{\rm d}$ and other parameters of the system. For simplicity, we do not give a detailed representation here.

3. Effect of the Doppler broadening on the GWI

As already stated, the calculations of the gain (absorption) ${\rm Im}\rho_{31}$ and the population $\rho_{11},\rho_{22},\rho_{33}$ outlined above are only valid for the static atoms. Now consider atomic motion and the resulting GWI when the Doppler effect is included. For a single atom, moving with a velocity v along the z-axis, the probe frequency $\omega_{\rm p}(v)$, seen by the atom, is given by

$$\omega_{\rm p}(v) = \omega_{\rm p}\left(1\pm\frac{v}{c}\right), \tag{3a}$$

where the negative (positive) sign corresponds to the co-propagating (counter-propagating) of atom and probe field. Similarly, the frequency of the driving filed $\omega_{\rm d}(v)$, seen by the atom, is

$$\omega_{\rm d}(v) = \omega_{\rm d}\left(1\pm\frac{v}{c}\right). \tag{3b}$$

We denote by $\delta_{\rm p}(v)$ $(\delta_{\rm p}(v)=\omega_{13}-\omega_{\rm p}(v))$ and $\delta_{\rm d}(v)(\delta_{\rm d}(v)=\omega_{12}-\omega_{\rm d}(v))$, the detunings of the probe and driving fields from their respective transitions, as seen by the moving atom. In terms of $\delta_{\rm p}(v)$ and stationary atom parameters, $\delta_{\rm d}(v)$ can be written as

$$\delta_{\rm p}(\nu) = \Delta_{\rm p} \mp \frac{\omega_{\rm p}v}{c}, \tag{4a}$$

$$\delta_{\rm d}(\nu) = \Delta_{\rm d} \mp \frac{\omega_{\rm d}}{\omega_{\rm p}}[\delta_{\rm p}(\nu)-\Delta_{\rm p}]. \tag{4b}$$

To further simplify the analysis, we let $\omega_{\rm p}=\omega_{\rm d}$ in Eq.(4). Assuming a Maxwell-Boltzmann distribution for the atomic velocities, we adopt a probability distribution function for $\delta_{\rm p}(v)$, which is given by

$$\rho(\delta_{\rm p}) = \exp[-(\delta_{\rm p}-\Delta_{\rm p})^2/2D^2]/\sqrt{2\pi D^2}. \tag{5}$$

The gain obtained by averaging over the Doppler distribution can be expressed as

$$G = \frac{2N\mu_{13}^2}{\hbar\alpha}{\rm Im}\int_{-\infty}^{\infty}\rho_{31}(\delta_{\rm p})\rho(\delta_{\rm p}){\rm d}\delta_{\rm p}, \tag{6}$$

where N is the medium density, μ_{13} is the electric dipole matrix element of the optical transition $|1\rangle \rightarrow |3\rangle$. Similarly, the populations ρ_{11}, ρ_{22} and ρ_{33} averaged over the Doppler distribution can be represented by

$$\bar{\rho}_{ii} = \int_{-\infty}^{\infty} \rho_{ii}\left(\delta_{\mathrm{p}}\right) \rho\left(\delta_{\mathrm{p}}\right) \mathrm{d}\delta_{\mathrm{p}}, \tag{7}$$

where $i = 1, 2, 3$. So, if $G > 0$ and $\bar{\rho}_{11} - \bar{\rho}_{33} < 0$, the probe field has a GWI. In the following we will discuss the effect of Doppler broadening on the GWI by numerical calculation. The numerical algorithm consists of calculating $\mathrm{Im}\rho_{31}$ and $\rho_{11} - \rho_{33}$ in the presence of Doppler broadening, i.e., we replace Δ_{p} and Δ_{d} in analytical $\mathrm{Im}\bar{\rho}_{31}$ and $\bar{\rho}_{11} - \bar{\rho}_{33}$ with $\delta_{\mathrm{p}}(v)$ and $\delta_{\mathrm{d}}(v)$. For a given D and Δ_{p}, we generate a probability distribution of $\delta_{\mathrm{p}}(v)$ using Eq.(5). The resulting values of δ_{p} are centred at the selected value of Δ_{p}. For each value of δ_{p}, we determine δ_{d} from Eq.(4b).

In the following we will discuss the effect of the Doppler broadening on the GWI according to the numerical calculation results from Eqs.(6) and (7). Equation (5) prevents us from studying $D = 0$, so we use $D = 0.0001$ as a representative of zero Doppler width. In the following discussions, $\bar{\rho}_{11} - \bar{\rho}_{33} < 0$ is always satisfied, and as an example, we only give the figure about $\bar{\rho}_{11} - \bar{\rho}_{33}$ as a function of Δ_{p} in Fig.2.

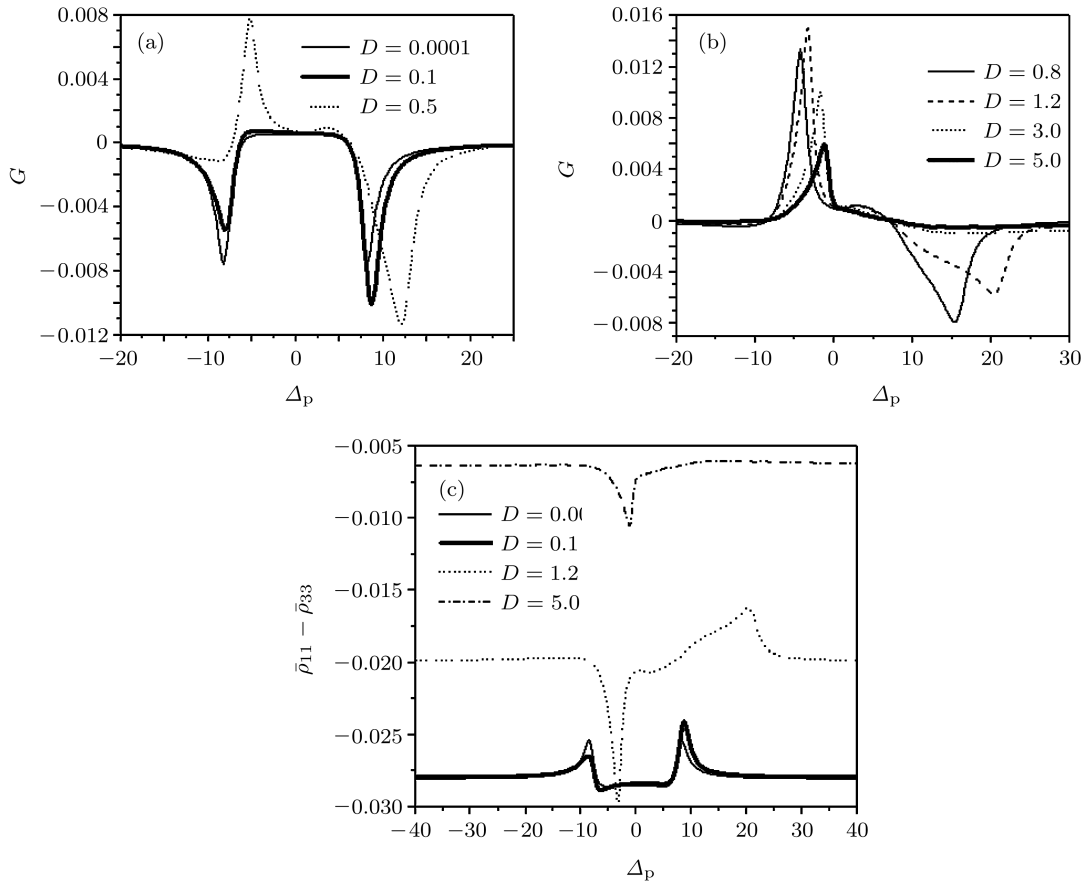


Fig.2. Gain, G, and population difference, $\bar{\rho}_{11} - \bar{\rho}_{33}$, versus probe detuning for different Doppler widths when the probe and driving fields are co-propagating, with $2\gamma_1 = 1.0, 2\gamma_2 = 1.0$, $2\Lambda = 0.92$, $\alpha = 0.3$, $\Omega = 8.0$, $\Delta_d = 0$.

In Fig.2, we plot the gain G and the population difference $\bar{\rho}_{11} - \bar{\rho}_{33}$ as functions of the probe detuning for different Doppler widths when the probe and drive fields (PDFs) are co-propagating. In Fig.2 and the following figures, the values of G are marked in unit of $N\mu_{13}^2/(\varepsilon_0\hbar)$. In Fig.2(c) we plot the population difference $\bar{\rho}_{11} - \bar{\rho}_{33}$ as a function of the probe detuning when $D = 0.0001, 0.1, 1.2, 5.0$. From Fig.2(c) we can see that $\bar{\rho}_{11} - \bar{\rho}_{33}$ has obvious variations with increasing Doppler width, however $\bar{\rho}_{11} - \bar{\rho}_{33} < 0$ is always satisfied. Similarly, when $D = 0.5, 0.8, 3.0$, $\bar{\rho}_{11} - \bar{\rho}_{33} < 0$ is also satisfied. So the gain is always inversionless. Figures 2(a) and 2(b) show that: (i) when $D = 0.0001$, i.e. Doppler broadening is absent, the gain curve has two similar peaks which have the same gain maximum value $G_{\max}$; when $D \neq 0.0001$, the gain curve has one

gain maximum value $G_{\max}$. (ii) $G_{\max}$ does not monotonically decrease or increase with increasing Doppler width; when $D > 1.2$, $G_{\max}$ decreases monotonically with increasing D; when $D < 1.2$, $G_{\max}$ increases monotonically with increasing D; when $D = 1.2$, we can obtain the largest gain $G_{\max}^{\text{co}-1}(= 0.015)$ which is much larger than the gain maximum value $G_{\max}^{0-1}(= 0.0008)$ obtained when Doppler broadening is absent.

Figure 3 illustrates the gain G as a function of the probe detuning for different Doppler widths when PDFs are counter-propagating.

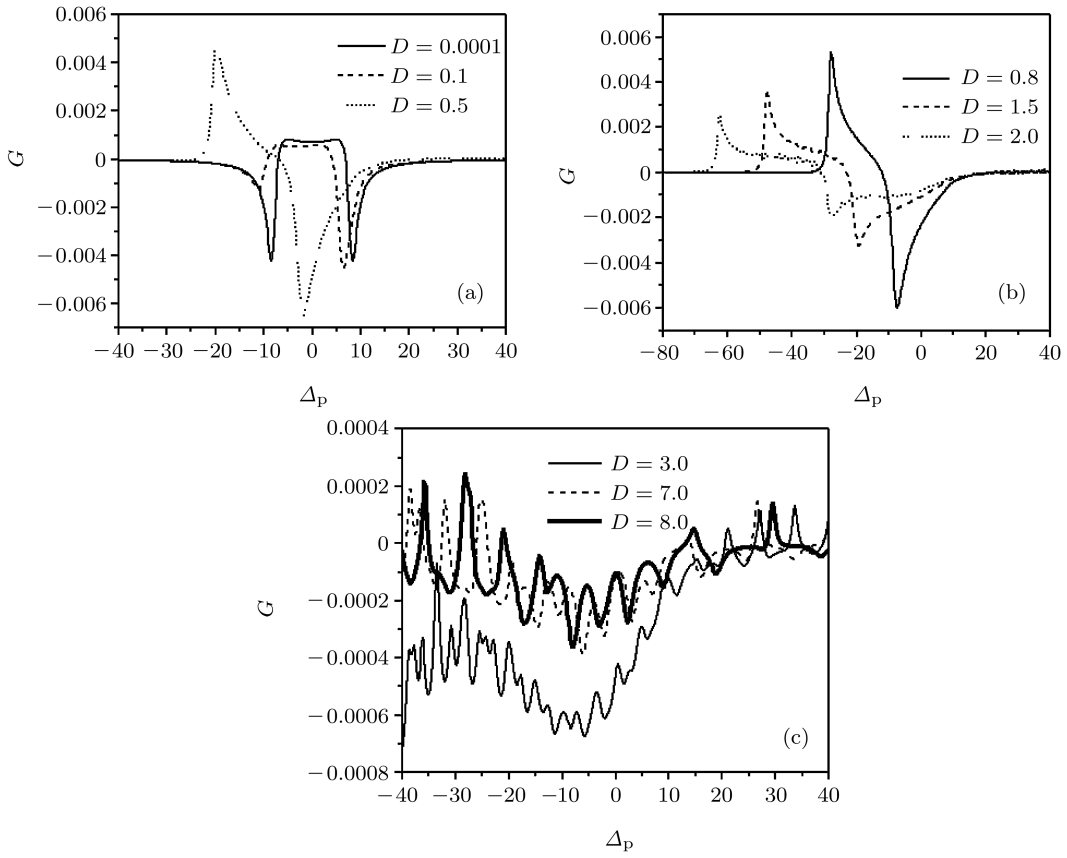


Fig.3. Gain versus probe detuning for different Doppler widths when the probe and driving fields are counter-propagating, with the same values of parameters as those in Fig.2.

Figures 3(a) and 3(b) show that $G_{\max}$ does not monotonically vary with increasing D. When $D < 0.1$ and $D > 0.8$, $G_{\max}$ decreases monotonically with increasing D; when $0.1 < D < 0.8$, $G_{\max}$ increases monotonically with increasing D; when $D = 0.8$, we can obtain the largest gain $G_{\max}^{\text{counter}-1}(= 0.0053)$ which is much larger than $G_{\max}^{0-1}(= 0.0008)$ for $D = 0.0001$, but obviously smaller than$G_{\max}^{\text{co}-1}(= 0.015)$ for the co-propagating PDFs.

When $D > 2.0$, gain oscillation occurs with increasing Δ_{p}, the oscillation amplitude and region increase with increasing D, but the largest gain is smaller than that for $D = 2$, as shown in Fig.3(c).

Taking the same values of system parameters as in Fig.2, Fig.4 presents $G_{\max}$ versus D for the co-propagating and counter-propagating PDFs, respectively.

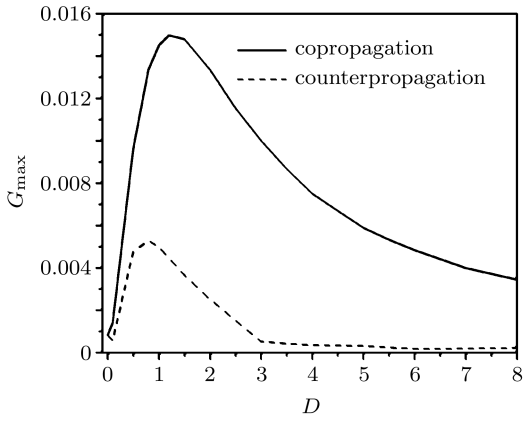


Fig.4. Gain maximum versus Doppler width with the same values of system parameters as in Figs.2 and 3.

Figure 4 shows that for the co-propagating and counter-propagating PDFs, $G_{\max}$ does not monotoni-

cally vary with increasing D; at a suitable D, we can obtain the largest $G_{\max}$ which is much larger than that obtained when Doppler broadening is absent; the co-propagating geometry yields higher gain than the counter-propagating geometry. So the co-propagating of PDFs is favourable to obtain a larger gain.

On the other hand, we also have investigated the cases of co-propagating and counter-propagating PDFs when the driving field is off-resonance. It is shown that: (i) when Doppler broadening is absent, different from that when the driving field is on-resonance, the gain curve is not symmetrical for $\Delta_{\rm p} > 0$ and $\Delta_{\rm p} < 0$. (ii) $G_{\max}$ does not monotonically vary with increasing D for the co-propagating and counter-propagating PDFs; for the case of co-propagating PDFs at a suitable Doppler width, we can obtain the largest gain which is much larger than that without Doppler broadening, but smaller than that when the driving field is on-resonance; for the case of counter-propagating PDFs, $G_{\max}$ is not larger than that without Doppler broadening, regardless of Doppler width being small or large. (iii) In the case of counter-propagating PDFs, when Doppler width is large enough, gain oscillation occurs with varying $\Delta_{\rm p}$, the oscillation amplitude and region increase with increasing D. (iv) When D is smaller, the gain curve and maximum value $G_{\max}$ in the case of the off-resonance driving field are obvious different from those in the case of the on-resonance driving field; when D is larger, the difference is small.

It is clear that the conclusion given above is much different from that given by Lukin *et al*,[17] i.e. GWI always decreases monotonically with increasing Doppler width or probe detuning. What is the cause producing this difference? Now we give a brief discussion as follows.

Quantum coherence and interference in an atomic system lead to the amplification without inversion and lasing without inversion. Generally speaking, Doppler broadening will produce detuning of the laser frequencies from the atomic transitions, which may affect the coherent recycling in atoms and damp the intensity of the laser radiation, and this leads to decreasing gain. The effects from the Doppler broadening, coherent PDFs will produce quantum destructive or constructive interference, and this is mainly determined by the Doppler width, propagating direction, strengths and detunings of the PDFs, and is also related to the incoherent pumping and the spontaneous emission rates. The scheme of introducing the incoherent pumping will affect the form of the density matrix equations of motion and its steady-state solutions, and then the gain without inversion. In some cases, quantum destructive interference arises and leads to decreasing gain; and in other cases, quantum constructive interference appears and leads to increasing gain. Firstly, as mentioned in Section 1, in the model of Lukin *et al*[17] an incoherent pumping is applied between the middle level $|2\rangle$ and the low level $|3\rangle$, while in the present paper the incoherent pumping is applied between the high level $|1\rangle$ and the low level $|3\rangle$. Secondly, comparing with Ref.[17], we have used different values of the system parameters (including strengths and detunings of the driving and probe fields, incoherent pumping, spontaneous emission rates). Hence we obtain a much different conclusion from that given by Lukin *et al*.[17]

In order to obtain a more clear picture about the difference produced due to the using of different incoherent pumping schemes, the scheme in this paper and that in Ref.[17], we study the gain (absorption) G and the population difference $\bar{\rho}_{11} - \bar{\rho}_{33}$ in the scheme of a closed Λ-type system from Ref.[17], i.e. an incoherent pumping is applied between the middle level $|2\rangle$ and the low level $|3\rangle$, by taking the same values of parameters as those in Fig.2. We plot G as a function of the probe detuning for different Doppler widths corresponding to the co-propagating PDFs in Fig.5.

From Fig.5 we can see that the system always exhibits absorption for different Doppler widths and when D is large enough, the absorption oscillation occurs, and the absorption (gain) curves are much different from those in Figs.2(a) and 2(b). While the population difference $\bar{\rho}_{11} - \bar{\rho}_{33}$ corresponding to Fig.5 is negative, i.e. the population is still inversionless, and the shape of the curve $\bar{\rho}_{11} - \bar{\rho}_{33}$ is considerably different from the corresponding one in Fig.2(c). In addition, for the counter-propagating PDFs, it is found that G and $\bar{\rho}_{11} - \bar{\rho}_{33}$ are always negative for different Doppler widths; when D is large enough, the absorption oscillation occurs, and the oscillation amplitude is smaller than that in Fig.3. Since Ref.[17] has not given all the parameter values of the system, we cannot obtain the result by using our scheme but the values of parameters from Ref.[17].

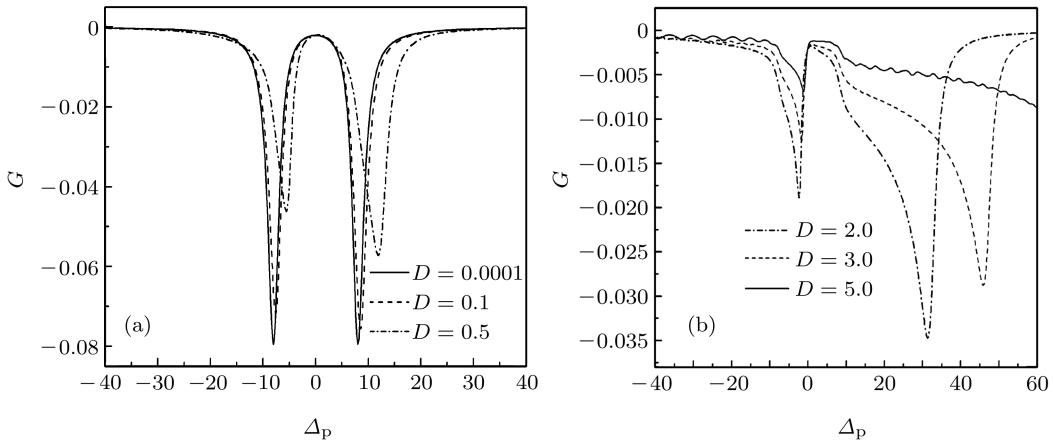


Fig.5. Gain versus probe detuning for different Doppler widths when the PDFs are co-propagating, with the same values of parameters as those in Fig.2.

Now we give a physical explanation for the striking behaviour, i.e. GWI does not monotonically decrease or increase with increasing Doppler width, and at a suitable Doppler width one can obtain a gain maximum value much larger than that without Doppler broadening, in terms of the dressed state. For the Λ-type atomic system without Doppler broadening, the probe amplification may proceed through the stimulated emission between the inverted dressed state transitions.[25] The gain appears due to the population inversion in the dressed state basis when the driving field detunes sufficiently from the resonance. Moreover, the gain has a maximum value when the driving detuning takes a suitable value. For the moving atoms, the Doppler effect will lead to detunings of the probe and driving frequencies from the resonance in the same direction, and then the relative populations of dressed states also change. The detuning from the inverted dressed state transition is dependent, via Doppler shifts, on the velocity for a given velocity group and on the relative magnitudes of the wave vectors between driving and generated waves. Thus some of the velocity groups contribute via this mechanism much more strongly to the observed gain than the other groups. At the same time, low-velocity groups contribute also to the gain due to the LWI mechanism in Ref.[25]. An amplification mechanism (and lasing) based on inverted dressed state transition has been studied in detail for homogeneously broadened systems.[26−28] The interesting feature of the inhomogeneously broadened Λ-type atomic system considered in this paper is that the required driving field detuning appears as Doppler shifts.

4. Conclusions

In the paper, using the numerical calculation results from the steady analytical solution of the density matrix equations of motion, we have analysed the effect of Doppler broadening on GWI in a closed Λ-type three-level system with an incoherent pump. We find that for the co- and counter-propagating PDFs, GWI does not monotonically vary with increasing Doppler width; except for the case of off-resonance driving field and the counter-propagating PDFs, at a suitable Doppler width, one can obtain a GWI maximum value much larger than that without Doppler broadening. Especially, in the situation of the resonant driving field, the co-propagating geometry is more favourable to yield a larger gain; for the case of the off-resonance driving and counter-propagating PDFs, when $D \neq 0$, i.e. Doppler broadening exists, we can have a largest gain value, but it is nearly equal to the maximum value of gain obtained when Doppler broadening is absent. In addition, for the on- or off-resonance driving field in the counter-propagating geometry, when the Doppler width is large enough, gain oscillation occurs, and the oscillation amplitude and its region increase with increasing Doppler width. These conclusions are quite different from that obtained in previous investigation by Lukin *et al*,[17] i.e. GWI decreases monotonically with increasing Doppler width in a closed Λ-type system. The cause leading to this difference is that the scheme of incoherent pumping and the values of parameters used in this paper are different from that in Ref.[17].

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