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# The probe gain with and without inversion in a four-level atomic model: light amplification at a short wavelength*

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We propose a new four-level atomic model for achieving light amplification at a short wavelength, where direct incoherent pumping into the top level is avoided by the advantage of coherent pumping. In this model, the lower level of the probe transition is an excited state but not the usual ground state. By analytical as well as numerical calculations, we find that the probe gain, either with or without population inversion, which depends on the relation between spontaneous decay rates $\gamma_{42}$ and $\gamma_{21}$, can be achieved with proper parameters. We note that the Raman scattering gain always plays an important role in achieving the probe amplification.

**Keywords:** probe gain with or without inversion, atomic coherence, Raman scattering gain
**PACC:** 4250, 3150

## 1. Introduction

In the previous two decades, different kinds of coherence phenomena in atomic systems resulting from strong coherent fields have been extensively investigated.[1−16] The attempt for many years to avoid the problem of population inversion in high-excited atomic levels, which stood in the way of short-wavelength laser development for a long time, has led to the prediction of light amplification (lasing) without inversion (LWI)[7−16] based on atomic coherence and quantum interference effects. Several experiments in the visible spectral region[17−20] confirm the initial ideas of LWI. The origin of the inversionless gain can be attributed to either inversion between dressed states or coherence among these states resulting from a strong coherent field.[21,22] However, the ultimate goal of LWI to generate high-frequency (in ultraviolet, x-ray, and even $\gamma$-ray ranges) coherent light is still far from being reached. One prominent reason for this situation is due to the fact that spontaneous decay rates of high-energy levels are so large that even a little population distribution in them needs very large incoherent pumping, and as we know, direct incoherent pumping into high-energy levels is very difficult to realize. Furthermore, large incoherent pumping and large spontaneous decay rates make against establishing atomic coherence necessary for LWI. Recently, Dong *et al*[23] have shown that direct incoherent pumping into the upper level of the probe transition is not absolutely necessary for LWI, and can be avoided via a fast decay from an excited state to a meta-stable state in a four-level model.

In this paper, we propose another four-level atomic model for achieving the probe gain at a short wavelength, where atoms in the ground state are pumped into the middle level by an incoherent pumping and then into the top level by a coherent field. In such a case, population distribution in the upper level of the probe transition, i.e. the top level, becomes much easier to achieve. Note that, in this model, the lower level of the probe transition is not the usual ground state but an excited state. By analytical as well as numerical calculations, we find that the population difference between levels of the probe transition only depends on their decay rates but not on external fields. So, depending on spontaneous decay rates $\gamma_{42}$ and $\gamma_{21}$, we can achieve the probe gain either with or without inversion. However, both the probe gain with inversion and that without inversion are, in doubt, involving the Raman scattering gain in that the population distribution in the top level is achieved by a coherent pumping but not by an inco-

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herent pumping. When $\gamma_{42}$ is smaller than $\gamma_{21}$, the probe gain stems from both the conventional population inversion and the atomic coherence induced by the coherent pumping. While in the opposite case, the probe gain only originates from the dynamically induced atomic coherence, since no population inversion occurs on the probe transition. In both cases of $\gamma_{42} > \gamma_{21}$ and $\gamma_{21} > \gamma_{42}$, the Raman scattering gain, which is related to the dynamically induced coherence, always plays an important role in achieving the probe gain. Light amplification at a short-wavelength is possible as long as the lower level of the probe transition is much closer to the ground state than the other middle level.

## 2. The model and analytical discussions

The $\Lambda$-type four-level atomic system under consideration is shown in Fig.1. An incoherent pumping process represented by a rate $2\Lambda$ populates atoms from level $|1\rangle$ to level $|3\rangle$. A strong coherent field $\boldsymbol{E}_{\rm c}$ ($\omega_{\rm c}$) with Rabi frequency $\Omega_{\rm c} = \boldsymbol{\mu}_{34} \cdot \boldsymbol{E}_{\rm c}/2\hbar$ interacts with transition $|3\rangle \leftrightarrow |4\rangle$ and establishes coherence between levels $|3\rangle$ and $|4\rangle$. A weak coherent field $\boldsymbol{E}_{\rm p}$ ($\omega_{\rm p}$) with Rabi frequency $\Omega_{\rm p} = \boldsymbol{\mu}_{24} \cdot \boldsymbol{E}_{\rm p}/2\hbar$ is used to probe the gain or absorption on transition $|2\rangle \leftrightarrow |4\rangle$. Here, $\boldsymbol{\mu}_{ij}$ designates the dipole matrix element of transition $|i\rangle \leftrightarrow |j\rangle$. $\Delta_{\rm p} = \omega_{42} - \omega_{\rm p}$ and $\Delta_{\rm c} = \omega_{43} - \omega_{\rm c}$ represent frequency detunings of the probe and coupling fields, respectively. $2\gamma_{ij}$ indicates the spontaneous decay rate from level $|i\rangle$ to level $|j\rangle$. It should be noted that atoms in level $|2\rangle$ could decay back to the ground level $|1\rangle$ via spontaneous emission.

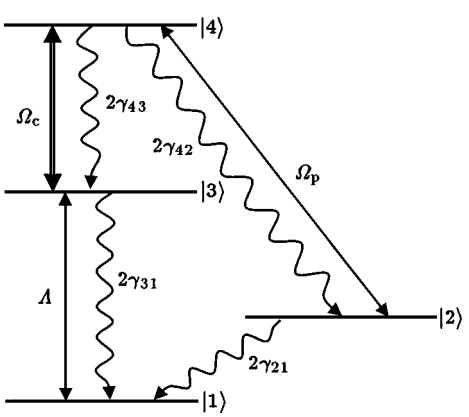



**Fig.1.** Schematic representation of a four-level atomic system driven by an incoherent field and a coherent field.

In the interaction picture, with the electric-dipole approximation and the rotating-wave approximation, the density-matrix equations of this atomic system can be derived as follows

$$\dot{\rho}_{11} = \Lambda(\rho_{33} - \rho_{11}) + 2\gamma_{21}\rho_{22} + 2\gamma_{31}\rho_{33}, \tag{1a}$$

$$\dot{\rho}_{22} = 2\gamma_{42}\rho_{44} - 2\gamma_{21}\rho_{22} + \mathrm{i}\Omega_{\rm p}\rho_{42} - \mathrm{i}\Omega_{\rm p}\rho_{24}, \tag{1b}$$

$$\dot{\rho}_{23} = \mathrm{i}(\Delta_{\rm p} - \Delta_{\rm c})\rho_{23} - \left(\gamma_{21} + \gamma_{31} + \frac{\Lambda}{2}\right)\rho_{23} + \mathrm{i}\Omega_{\rm p}\rho_{43} - \mathrm{i}\Omega_{\rm c}\rho_{24}, \tag{1c}$$

$$\dot{\rho}_{24} = (\mathrm{i}\Delta_{\rm p} - \gamma_{21} - \gamma_{42} - \gamma_{43})\rho_{24} + \mathrm{i}\Omega_{\rm p}(\rho_{44} - \rho_{22}) - \mathrm{i}\Omega_{\rm c}\rho_{23}, \tag{1d}$$

$$\dot{\rho}_{33} = \Lambda(\rho_{11} - \rho_{33}) + 2\gamma_{43}\rho_{44} - 2\gamma_{31}\rho_{33} + \mathrm{i}\Omega_{\rm c}\rho_{43} - \mathrm{i}\Omega_{\rm c}\rho_{34}, \tag{1e}$$

$$\dot{\rho}_{34} = \left(\mathrm{i}\Delta_{\rm c} - \gamma_{31} - \gamma_{42} - \gamma_{43} - \frac{\Lambda}{2}\right)\rho_{34} + \mathrm{i}\Omega_{\rm c}(\rho_{44} - \rho_{33}) - \mathrm{i}\Omega_{\rm p}\rho_{32}, \tag{1f}$$

$$\rho_{12} = \rho_{13} = \rho_{14} \equiv 0. \tag{1g}$$

The above equations are constrained by $\rho_{ij} = \rho_{ji}^*$ and $\rho_{11} + \rho_{22} + \rho_{33} + \rho_{44} = 0$. In Eq.(1g), $\rho_{12} = \rho_{13} = \rho_{14} \equiv 0$, for there is neither direct nor indirect coherent coupling between level $|1\rangle$ and levels $|2\rangle$, $|3\rangle$, and $|4\rangle$ at all. For simplicity in calculation, in the following, we always set $\Delta_{\rm c} = 0$, which allows the strongest coupling between level $|3\rangle$ and level $|4\rangle$.

In the limit of a weak probe, the steady-state solutions of Eqs.(1), for $\rho_{24}$ to the first (all) order of the probe (coherent) field $\Omega_{\rm p}$ ($\Omega_{\rm c}$), while for other density-matrix elements to the zeroth (all) order of the probe (coherent) field $\Omega_{\rm p}$ ($\Omega_{\rm c}$), are derived as follows

$$\rho_{22} = \frac{\gamma_{42}\Lambda\Omega_{\rm c}^2}{A\Omega_{\rm c}^2 + B}, \tag{2}$$

$$\rho_{33} = \frac{\gamma_{21}\Lambda[(\gamma_{43} + \gamma_{42})(\gamma_{43} + \gamma_{42} + \gamma_{31} + \Lambda/2) + \Omega_{\rm c}^2]}{A\Omega_{\rm c}^2 + B}, \tag{3}$$

$$\rho_{44} = \frac{\gamma_{21}\Lambda\Omega_{\rm c}^2}{A\Omega_{\rm c}^2 + B}, \tag{4}$$

$$\rho_{43} = \frac{\mathrm{i}\Omega_{\rm c}(\rho_{33} - \rho_{44})}{\gamma_{31} + \gamma_{42} + \gamma_{43} + \Lambda/2}, \tag{5}$$

$$\rho_{24} = \frac{\mathrm{i}\Omega_{\mathrm{p}}[(\gamma_{21}+\gamma_{31}+\Lambda/2-\mathrm{i}\Delta_{\mathrm{p}})(\rho_{44}-\rho_{22})-\mathrm{i}\Omega_{\mathrm{c}}\rho_{43}]}{(\gamma_{21}+\gamma_{42}+\gamma_{43}-\mathrm{i}\Delta_{\mathrm{p}})(\gamma_{21}+\gamma_{31}+\Lambda/2-\mathrm{i}\Delta_{\mathrm{p}})+\Omega_{\mathrm{c}}^2}, \tag{6}$$

$$A = \Lambda(\gamma_{21}+\gamma_{42})+2\gamma_{21}(\Lambda+\gamma_{31}+\gamma_{42}), \tag{7}$$

$$B = 2\gamma_{21}(\Lambda+\gamma_{31})(\gamma_{42}+\gamma_{43})(\gamma_{31}+\gamma_{42}+\gamma_{43}+\Lambda/2). \tag{8}$$

From Eqs.(2)–(8), it is easy to find that the necessary condition for achieving population inversion on transition $|2\rangle \leftrightarrow |4\rangle$ is simply $\gamma_{21} > \gamma_{42}$. Moreover, $\rho_{33}$ is always larger than $\rho_{44}$, i.e. population inversion always exists on the Raman transition $|3\rangle \rightarrow |4\rangle \rightarrow |2\rangle$. It is well known that in the limit of a weak probe the probe gain or absorption on transition $|4\rangle \leftrightarrow |2\rangle$ is proportional to the imaginary part of $\rho_{24}/\Omega_{\mathrm{p}}$, i.e. $\mathrm{Im}(\rho_{24}/\Omega_{\mathrm{p}})$. Just for simplicity in writing, in the following, we set $G_{42} = \mathrm{Im}(\rho_{24}/\Omega_{\mathrm{p}})$. Thus, the resonant probe gain or absorption ($\Delta_{\mathrm{p}} = 0$) can be expressed as

$$G_{42} = \frac{(\gamma_{31}+\gamma_{42}+\gamma_{43}+\Lambda/2)(\gamma_{21}+\gamma_{31}+\Lambda/2)(\rho_{44}-\rho_{22})+\Omega_{\mathrm{c}}^2(\rho_{33}-\rho_{44})}{[(\gamma_{21}+\gamma_{42}+\gamma_{43})(\gamma_{21}+\gamma_{31}+\Lambda/2)+\Omega_{\mathrm{c}}^2](\gamma_{31}+\gamma_{42}+\gamma_{43}+\Lambda/2)}. \tag{9}$$

In order to discern the different gain mechanisms, we rewrite $G_{42} = G_{\mathrm{p}} + G_{\mathrm{c}}$, where $G_{\mathrm{p}}$ (the inversion gain) designates the contribution of population difference $\rho_{44} - \rho_{22}$ to the probe gain, which can be positive or negative depending on the relation between $\gamma_{21}$ and $\gamma_{42}$, while $G_{\mathrm{c}}$ (the coherent gain) represents the contribution of atomic coherence $\rho_{43}$ induced by the coupling field, which is proportional to $\rho_{33} - \rho_{44}$ and is always positive. The relation between $G_{\mathrm{p}}$ and $G_{\mathrm{c}}$ can be obtained as

$$\frac{G_{\mathrm{p}}}{G_{\mathrm{c}}} = \frac{(\gamma_{21}-\gamma_{42})(\gamma_{21}+\gamma_{31}+\Lambda/2)}{\gamma_{21}(\gamma_{42}+\gamma_{43})}. \tag{10}$$

In the case of $\gamma_{21} > \gamma_{42}$, both $G_{\mathrm{p}}$ and $G_{\mathrm{c}}$ are positive, so the probe is always amplified, and we have the probe gain with inversion; while in the case of $\gamma_{21} < \gamma_{42}$, which is more common in real atomic systems if $|4\rangle$ is a highly excited level, only when the condition of $G_{\mathrm{c}} > -G_{\mathrm{p}}$, i.e. $\gamma_{31}\gamma_{42} < \gamma_{21}(\gamma_{21}+\gamma_{31}+\gamma_{43})$, is satisfied, can the probe be amplified, and we have the probe gain without population inversion. In the case of $\gamma_{21} < \gamma_{42}$ and $\gamma_{31}\gamma_{42} < \gamma_{21}(\gamma_{21}+\gamma_{31}+\gamma_{43})$, the range of $\Lambda$ where the probe can be amplified in the absence of population inversion is expected to be

$$0 < \Lambda < 2\left(\frac{\gamma_{21}(\gamma_{42}+\gamma_{43})}{\gamma_{42}-\gamma_{21}} - (\gamma_{21}+\gamma_{31})\right). \tag{11}$$

In other words, the probe could never be amplified in the case of $\gamma_{21} < \gamma_{42}$ and $\gamma_{31}\gamma_{42} > \gamma_{21}(\gamma_{21}+\gamma_{31}+\gamma_{43})$.

In order to gain a deeper insight into the mechanisms of the probe gain without inversion, we further rewrite the coherent gain $G_{\mathrm{c}}$ in two parts: $G_{\mathrm{c}} = G_{\mathrm{r}} + G_{\mathrm{i}}$, where $G_{\mathrm{r}}$ (the Raman gain) represents the contribution of population difference $\rho_{33} - \rho_{22}$ on the Raman transition, while $G_{\mathrm{i}}$ (the pure inversionless gain) indicates the contribution of population difference $\rho_{22} - \rho_{44}$ on the probe transition. The relation between $G_{\mathrm{r}}$ and $G_{\mathrm{i}}$ can be derived from Eqs.(2)–(9) as

$$\frac{G_{\mathrm{r}}}{G_{\mathrm{i}}} = \frac{\gamma_{21}(\gamma_{43}+\gamma_{42})(\gamma_{43}+\gamma_{42}+\gamma_{31}+\Lambda/2)}{(\gamma_{42}-\gamma_{21})\Omega_{\mathrm{c}}^2} - 1. \tag{12}$$

Note that $G_{\mathrm{i}}$ and $G_{\mathrm{p}}$ are always opposite in sign and cannot contribute to the probe gain, simultaneously. So the probe gain with inversion obtained in the case of $\gamma_{42} > \gamma_{21}$ is contributed by $G_{\mathrm{p}}$ and $G_{\mathrm{r}}$, while the probe gain without inversion obtained in the case of $\gamma_{21} < \gamma_{42}$ is contributed by $G_{\mathrm{i}}$ and $G_{\mathrm{r}}$. That is, the population inversion $\rho_{33} - \rho_{22}$ on the Raman transition always plays an important role in achieving the probe gain.

## 3. Numerical results about the probe gain

In this section, we show a few graphic results about the probe gain and its different mechanisms in different cases, i.e. with an inversion on transition $|2\rangle \leftrightarrow |4\rangle$ ($\gamma_{21} > \gamma_{42}$) or without an inversion ($\gamma_{21} < \gamma_{42}$).

First, we consider the case of $\gamma_{21} > \gamma_{42}$, where the probe can always be amplified due to the fact that $G_{\mathrm{p}} > 0$ and $G_{\mathrm{c}} > 0$. To show the effect of the incoherent pumping rate $\Lambda$ on the probe gain with population inversion, with $\gamma_{31} = \gamma_{42} = \gamma_{43} = 1$, $\Delta_{\mathrm{p}} = 0$, and $\Omega_{\mathrm{c}} = 3$, in Fig.2 we depict the probe gain $G_{42}$,

the contribution of atomic coherence $G_c$, and the contribution of population inversion $G_p$ versus $\Lambda$. It is obvious that, in the limit of $\gamma_{21} > \gamma_{42}$, we can always obtain the probe gain at $\Delta_p = 0$, and it is contributed by both the inversion gain $G_p$ and the coherent gain $G_c$. Comparing Figs.2(a)–(c), we can easily find that, with increasing $\gamma_{21}$, the inversion gain $G_p$ becomes more and more important, since much higher inversion can be established on transition $|2\rangle \leftrightarrow |4\rangle$. At the same time, the coherent gain $G_c$ becomes less, for it depends on $\rho_{33} - \rho_{44}$, and $\rho_{33} - \rho_{44}$ decreases with the increase of $\gamma_{21}$. Note that the maximal amplitude of the probe gain $G_{42}$ increases with increasing $\gamma_{21}$. We also find that, when the incoherent pumping $\Lambda$ is not very strong, i.e. in the range of $0 < \Lambda < 5$, we can obtain the maximal probe gain. When the incoherent pumping becomes strong enough, it destroys the atomic coherence (related to $G_c$) established by the coherent field $\Omega_c$, and the population inversion $\rho_{44} - \rho_{22}$ (related to $G_p$) reaches a saturated value, so the probe gain becomes lower and lower.

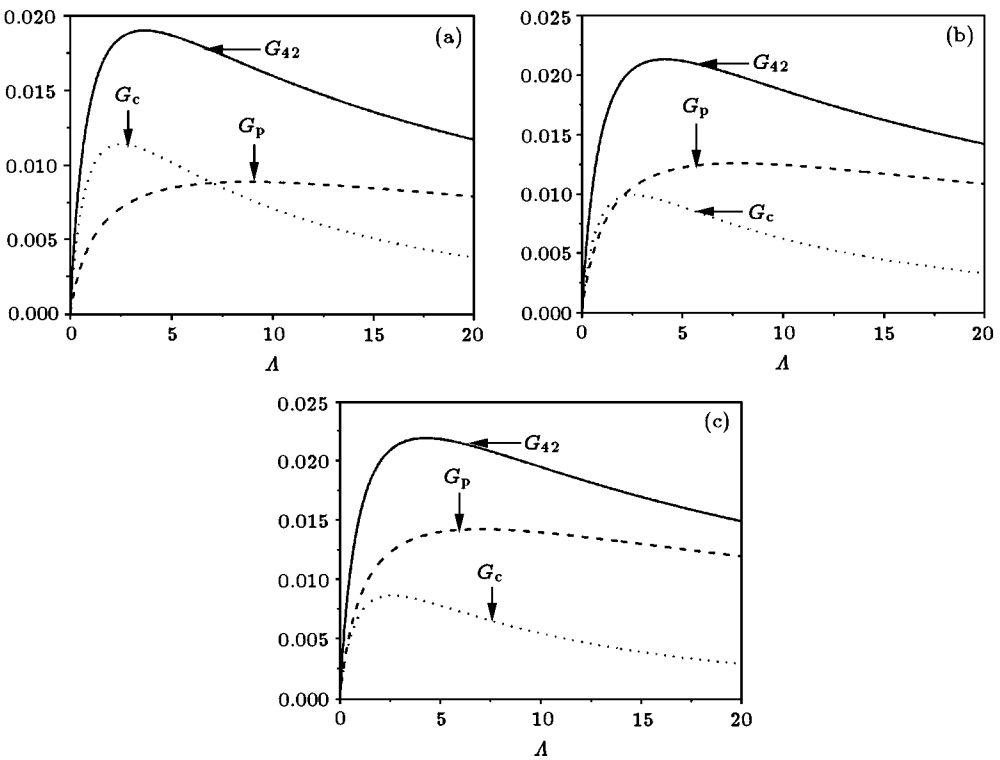



**Fig.2.** The probe gain $G_{42}$, the inversion gain $G_p$, and the coherent gain $G_c$ versus the incoherent pumping rate $\Lambda$ for (a) $\gamma_{21}$=1.5; (b) $\gamma_{21}$=2; (c) $\gamma_{21}$=2.5. Other parameters are set to be $\gamma_{31} = \gamma_{42} = \gamma_{43} = 1$, $\Delta_p = 0$, $\Delta_c = 0$, and $\Omega_c$=3.

Now, we consider the case of $\gamma_{21} < \gamma_{42}$, which is more common in real atomic systems. In this case, the probe gain without inversion is only contributed by the atomic coherence term $G_c$, which can further attribute to two terms $G_i$ and $G_r$. In a typical three-level $\Lambda$-type system composed of $|2\rangle$, $|3\rangle$, and $|4\rangle$, the necessary condition for achieving LWI is $\gamma_{43} > \gamma_{42}$.[8] However, in the four-level atomic system under consideration, the necessary condition for achieving LWI extends to $\gamma_{31}\gamma_{42} < \gamma_{21}(\gamma_{21} + \gamma_{31} + \gamma_{43})$. With three sets of parameters satisfied with $\gamma_{43} > \gamma_{42}$ or not, we plot in Fig.3 the probe gain $G_{42}$, the Raman gain $G_r$, and the inversionless gain $G_i$ at $\Delta_p$=0 as functions of incoherent pumping rate $\Lambda$. From Fig.3, we can see that, whether the condition of $\gamma_{43} > \gamma_{42}$ is fulfilled or not, there always exists a region of $0 < \Lambda < \Lambda_0$ where the probe can be amplified. But it is obvious that, in the case of $\gamma_{43} > \gamma_{42}$, the gain region of $0 < \Lambda < \Lambda_0$ is much larger, and we can obtain much higher inversionless gain. Note, just as in Fig.2, that the maximal gain in Fig.3 is also located in the region of $0 < \Lambda < 5$, but it is much nearer to the point of $\Lambda = 0$. As shown in Fig.3, the probe gain without inversion is contributed by two terms: the Raman gain $G_r$ and the inversionless gain $G_i$, but $G_r$ obviously plays a more important role.

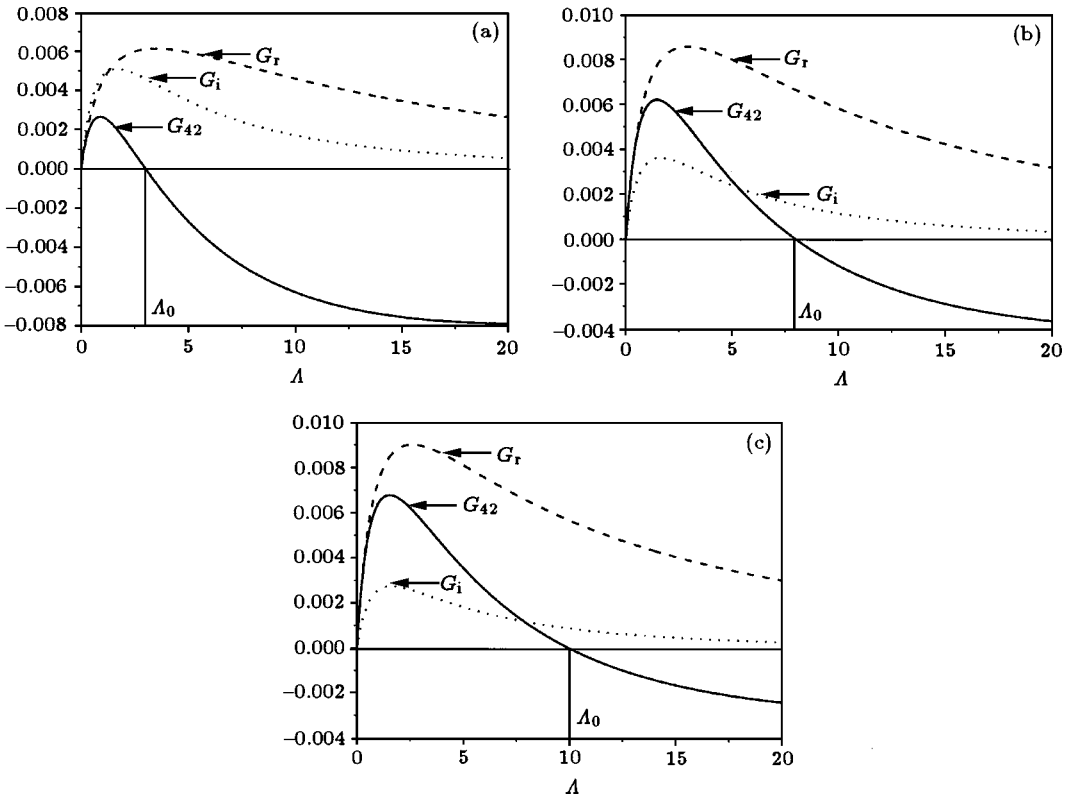



**Fig.3.** The probe gain $G_{42}$, the Raman gain $G_r$, and the inversionless gain $G_i$ versus the incoherent pumping rate $\Lambda$ for (a) $\gamma_{42}$=2, $\gamma_{43}$ = 1.5; (b) $\gamma_{42}$ = $\gamma_{43}$ = 1.5; (c) $\gamma_{42}$=1.5, $\gamma_{43}$=2. Other parameters are set as $\gamma_{21}$ = $\gamma_{31}$ = 1, $\Delta_p$ = 0, $\Delta_c$ = 0, and $\Omega_c$=3.

In the above, we always choose a relative small coherent field ($\Omega_c$=3) to couple levels $|3\rangle$ and $|4\rangle$. In Fig.4, we show that, in both cases of $\gamma_{21} > \gamma_{42}$ and $\gamma_{21} < \gamma_{42}$, the maximal amplitude of the probe gain $G_{42}$ decreases dramatically with increasing $\Omega_c$, since the probe gain is achieved in a much larger spectral range of $\Delta_p$. It is well known that level $|4\rangle$ can be split into two dressed sublevels $|+\rangle = (|3\rangle - |4\rangle)/\sqrt{2}$ and $|-\rangle = (|3\rangle + |4\rangle)/\sqrt{2}$ under the action of the resonant coherent field, with eigenvalues of $\omega_\pm = \omega_4 \pm \Omega_c$. Comparing Figs.4(a) with 4(b), it is easy to find that the profiles of the probe gain with inversion and that without inversion are quite different. In the case of $\gamma_{21} > \gamma_{42}$, we can achieve the probe gain with inversion in the whole range of $\Delta_p$, and the maximal probe gain is located at $\Delta_p = \pm\Omega_c$ when the coherent field becomes strong enough ($\Omega_c$=6,10) (see Fig.4(a)). In the case of $\gamma_{21} < \gamma_{42}$, we can obtain only the probe gain without inversion in a range smaller than $-\Omega_c < \Delta_p < \Omega_c$, and the maximal probe gain is always located at $\Delta_p$=0. However, it is obvious that, in both cases, it is much easier to obtain a high probe gain with a relative weak coherent field ($\Omega_c$=3).

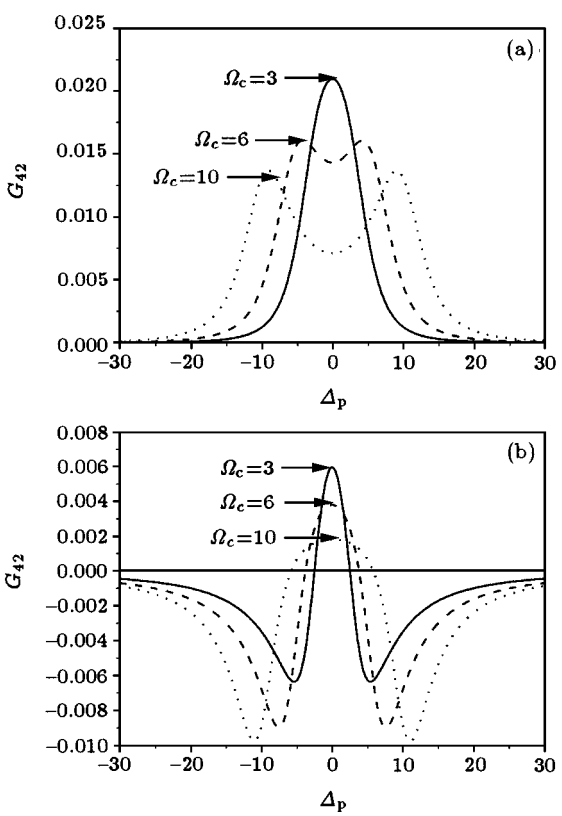



**Fig.4.** The probe gain $G_{42}$ with $\Delta_c$=0 and different values of $\Omega_c$ versus the probe detuning $\Delta_p$ for (a): $\Lambda$=3, $\gamma_{21}$ = 2, $\gamma_{31}$ = $\gamma_{42}$ = $\gamma_{43}$ = 1; (b): $\Lambda$ = 2, $\gamma_{21}$ = $\gamma_{31}$ = 1, $\gamma_{42}$ = $\gamma_{43}$=1.5.

## 4. Conclusions

In summary, we have investigated a Λ-type four-level atomic model driven by a coherent field and an incoherent pumping for achieving the probe gain at a short wavelength. One important feature that makes this model different from other models for LWI is that both the upper and lower levels of the probe transition are excited states and no incoherent pumping process interacts with them. Based on both analytical and numerical discussions, we find that, in the case of $\gamma_{21} > \gamma_{42}$, the probe gain $G_{42}$ with inversion is contributed by both the population inversion term $G_{\rm p}$ and the atomic coherence term $G_{\rm c}$. While in the case of $\gamma_{21} < \gamma_{42}$, the probe gain $G_{42}$ without inversion originates only from the atomic coherence term $G_{\rm c}$, which can be further attributed to two terms: the Raman scattering gain $G_{\rm r}$ and the pure inversionless gain $G_{\rm i}$. Population inversion $\rho_{33} - \rho_{44}$ always exists on the Raman transition $|3\rangle \rightarrow |4\rangle \rightarrow |2\rangle$, so the Raman scattering gain always plays an important role in achieving the probe amplification. We also find that, in order to obtain high probe gain with or without inversion, both the incoherent pumping process and the coherent pumping field should not be too strong, since a large incoherent pumping will destroy atomic coherence established by the coherent field, and a large coherent field will lead to a much broader gain spectral range.

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