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Controlling the gain shape of Er^{3+}-doped fluorozirconate fibre amplifier by a coherent field*

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We proposed a four-level system to explore the quantum interference effects on optical amplification. We found that the gain of the probe, including positions and values of gain peaks, can be adjusted by changing the coherent field and the incoherent pumping. At the same time, we can also modify the absorption profile of electromagnetically induced transparency by the incoherent pump. The results provide a method to flatten the gain of Erbium-doped fibre amplifiers.

Keywords: electromagnetically induced transparency, erbium-doped fibre amplifiers
PACC: 4250, 4265, 3280

1. Introduction

Electromagnetically induced transparency (EIT) is a process where one laser (or electromagnetic field) is used to modify the absorption coefficient and refractive index seen by a probe laser, thereby allowing it to propagate in what would otherwise be an optically thick medium. There exists by now a large amount of papers on this subject.[1−5] Many theoretical and experimental studies of EIT in atomic gas media have been carried out.[6−10] Recently, EIT in solid media[11,12] has attracted much interest because it presents potential applications of EIT in nonlinear optical processes, such as inversionless lasers,[13−15] high-density, high-speed optical memory,[16] and high-gain phase conjugation.[17]

Light amplification in rare-earth doped fibres has been studied for a long time.[18] High-gain erbium-doped fibre amplifiers (EDFA)[19] and high-gain, high output power Praseddymiun-doped fluoride fibre amplifier (PDFFA)[20] all have been accomplished. With the widespread use of internet services, major attention has been focused, in recent years, on the wavelength division multiplexing (WDM), a technique whereby optical signals of a number of different wavelengths are multiplexed for transmission. The EDFA is a key device in WDM systems, for its comparatively wide wavelength range of amplification allows it to provide batch amplification of signals within the wavelength range. Unfortunately, the gain shapes are not perfectly flat, and change as a function of absolute gain level. In the WDM systems the deviation in power levels of the signals can cause a decrease in transmission distance and wavelength range, so EDFA needs to have a flat gain spectra within the signal range.

In this paper, we propose a four-level system which involves light amplification with population inversion and EIT. On the one hand, the gain profile of the Er^{3+}-doped ZrF_4-BaF_2-LaF_3-AlF_3-NaF (ZBLAN) optical fibre amplifier can be controlled by a coherent field. That is to say, under a large Rabi frequency and a large detuning of the coherent field, the position of the probe gain peak moves and the amplitude of probe gain decreases. On the other hand, the absorption profile of EIT can also be modified by incoherent pump: under a large incoherent pump, the probe goes through a process from absorption to amplification. We hope these results could provide a method to flatten the gain of EDFA.

2.The model and equations

We consider a closed four-level system shown in Fig.1. The energy-level scheme is relevant to the Er^{3+}

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ions in the ZBLAN glass, where levels $|1\rangle$, $|2\rangle$, $|3\rangle$ and $|4\rangle$ correspond to the energy levels $^4I_{15/2}$, $^4I_{13/2}$, $^4I_{11/2}$, $^4I_{9/2}$ of Er^{3+} ions, respectively. In this system, via a fast phonon decay from $|3\rangle$, level $|2\rangle$ is populated by an incoherent pump process Λ interacting with the transition $|1\rangle \leftrightarrow |3\rangle$. A coherent driving field E_c with Rabi frequency Ω_c drives the $|2\rangle \leftrightarrow |4\rangle$ atomic transition, and a probe field E_p with Rabi frequency Ω_p interacts with the transition labelled $|1\rangle \leftrightarrow |2\rangle$. $\Gamma_4 = \Gamma_{41} + \Gamma_{42} + \Gamma_{43}$ is the spontaneous decay rate of level $|4\rangle$, $\Gamma_3 = \Gamma_{31} + \Gamma_{32}$ is the spontaneous decay rate of level $|3\rangle$, $\Gamma_2 = \Gamma_{21}$ is the spontaneous decay rate of level $|2\rangle$. When the incoherent pump rate Λ=0, it is obvious that this system can be treated as a three-level ladder-type EIT system composed of levels $|1\rangle$, $|2\rangle$ and $|4\rangle$, however, when the Rabi frequency of the coherent field Ω_c=0, the system is a traditional optical amplification system with a population inversion.

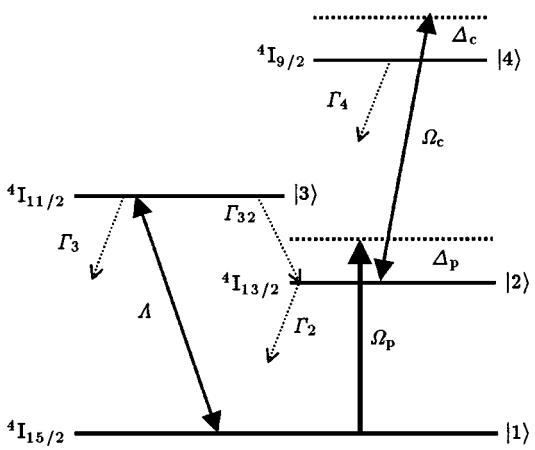


Fig.1. Schematic diagram of a four-level system, where levels $|1\rangle$, $|2\rangle$, $|3\rangle$ and $|4\rangle$ correspond to the energy levels of Er^{3+} ions, $^4I_{15/2}$, $^4I_{13/2}$, $^4I_{11/2}$ and $^4I_{9/2}$ in ZBLAN glass, respectively. Levels $|1\rangle$, $|2\rangle$ and $|4\rangle$ form an EIT subsystem, while levels $|1\rangle$, $|3\rangle$ and $|2\rangle$ form a light amplification subsystem.

Within the framework of the semiclassical theory, using the standard density matrix formalism with the dipole approximation and the rotating wave approximation, we can write the description equations for this system as

$$\begin{aligned}
\dot\rho_{11} =& \Lambda(\rho_{33}-\rho_{11}) + \Gamma_{21}\rho_{22} + \Gamma_{31}\rho_{33} \\
&+ \Gamma_{41}\rho_{44} + \mathrm{i}\Omega_p^*\rho_{21} - \mathrm{i}\Omega_p\rho_{12}, \\
\dot\rho_{22} =& -\Gamma_{21}\rho_{22} + \Gamma_{32}\rho_{33} + \Gamma_{42}\rho_{44} \\
&+ \mathrm{i}\Omega_p\rho_{12} - \mathrm{i}\Omega_p^*\rho_{21} + \mathrm{i}\Omega_c^*\rho_{42} - \mathrm{i}\Omega_c\rho_{24}, \\
\dot\rho_{33} =& -\Lambda(\rho_{33}-\rho_{11}) - \Gamma_{31}\rho_{33} - \Gamma_{32}\rho_{33} + \Gamma_{43}\rho_{44}, \\
\dot\rho_{41} =& -[\gamma_{41} - \mathrm{i}(\Delta_p+\Delta_c)]\rho_{41} + \mathrm{i}\Omega_c\rho_{21} - \mathrm{i}\Omega_p\rho_{42}, \\
\dot\rho_{42} =& -(\gamma_{42} - \mathrm{i}\Delta_c)\rho_{42} + \mathrm{i}\Omega_c(\rho_{22}-\rho_{44}) - \mathrm{i}\Omega_p^*\rho_{41}, \\
\dot\rho_{43} =& -[\gamma_{43} - \mathrm{i}(\Delta_p+\Delta_c)]\rho_{43} + \mathrm{i}\Omega_c\rho_{23}, \\
\dot\rho_{32} =& -(\gamma_{32} + \mathrm{i}\Delta_p)\rho_{32} - \mathrm{i}\Omega_p^*\rho_{31} - \mathrm{i}\Omega_c\rho_{34}, \\
\dot\rho_{31} =& -\gamma_{31}\rho_{31} - \mathrm{i}\Omega_p\rho_{32}, \\
\dot\rho_{21} =& -(\gamma_{21} - \mathrm{i}\Delta_p)\rho_{21} + \mathrm{i}\Omega_p(\rho_{11}-\rho_{22}) + \mathrm{i}\Omega_c^*\rho_{41}, \\
&\rho_{11}+\rho_{22}+\rho_{33}+\rho_{44} = 1, \\
&\rho_{ij} = \rho_{ji}^*. \qquad (1)
\end{aligned}$$

Here Γ_{ij} designates the population spontaneous damping from $|i\rangle$ to $|j\rangle$, γ_{ij} refers to the coherence decay rate between $|i\rangle$ and $|j\rangle$, Δ_p and Δ_c describe the detunings of the probe and the coherent field, respectively. In the radiative limit, the coherence decay rates are given by

$$\begin{aligned}
\gamma_{41} &= (\Gamma_{41}+\Gamma_{42}+\Gamma_{43}+\Lambda)/2, \\
\gamma_{42} &= (\Gamma_{41}+\Gamma_{42}+\Gamma_{43}+\Gamma_{21})/2, \\
\gamma_{43} &= (\Gamma_{41}+\Gamma_{42}+\Gamma_{43}+\Gamma_{32}+\Gamma_{31}+\Lambda)/2, \\
\gamma_{32} &= (\Gamma_{32}+\Gamma_{31}+\Gamma_{21}+\Lambda)/2, \\
\gamma_{31} &= (\Gamma_{32}+\Gamma_{31}+\Lambda+\Lambda)/2, \\
\gamma_{21} &= (\Gamma_{21}+\Lambda)/2. \qquad (2)
\end{aligned}$$

3. Analytical discussions

In the limit of weak probe, under a steady-state condition, the solutions of Eq.(1) for ρ_{21} to the first order of the probe field and to the zero the order for other ρ_{ij} are

$$\begin{aligned}
\rho_{22} &= \frac{\Lambda\Gamma_{32}/(\Lambda+\Gamma_{31}+\Gamma_{32})}{\left[\Gamma_{21} + \left(\Gamma_{41} + \dfrac{\Gamma_{43}(\Lambda+\Gamma_{31})}{\Lambda+\Gamma_{31}+\Gamma_{32}}\right)\dfrac{D_2}{D_1}\right]}\rho_{11}, \\
\rho_{33} &= \left[\Gamma_{21} + (\Gamma_{41}+\Gamma_{43})\frac{D_2}{D_1}\right]\frac{\rho_{22}}{\Gamma_{32}}, \\
\rho_{44} &= \frac{D_2}{D_1}\rho_{22}, \\
\rho_{42} &= \frac{\mathrm{i}\Omega_c(\rho_{22}-\rho_{44})}{\gamma_{42}-\mathrm{i}\Delta_c} \qquad (3)
\end{aligned}$$

and

$$\begin{aligned}
\rho_{12} =& \rho_{21}^* \\
=& \frac{\mathrm{i}\Omega_p(\rho_{22}-\rho_{11}) - \dfrac{\mathrm{i}|\Omega_c|^2\Omega_p(\rho_{22}-\rho_{44})}{[\gamma_{41}+\mathrm{i}(\Delta_p+\Delta_c)](\gamma_{42}+\mathrm{i}\Delta_c)}}{\gamma_{21}+\mathrm{i}\Delta_p + \dfrac{|\Omega_c|^2}{\gamma_{41}+\mathrm{i}(\Delta_p+\Delta_c)}}, \qquad (4)
\end{aligned}$$

where $D_1 = \Gamma_{41} + \Gamma_{42} + \Gamma_{43} + \dfrac{2|\Omega_c|^2\gamma_{42}}{\gamma_{42}^2 + \Delta_c^2}$, $D_2 = \dfrac{2|\Omega_c|^2\gamma_{42}}{\gamma_{42}^2 + \Delta_c^2}$.

The gain-absorption coefficient on transition $|2\rangle \leftrightarrow |1\rangle$ is proportional to the imaginary part of ρ_{12}, and we obtain the probe gain if $\mathrm{Im}\rho_{12} > 0$.

Without the incoherent pump ($\Lambda = 0$), it is easy to obtain $\rho_{22} = \rho_{33} = \rho_{44}$=0, and $\rho_{11} \cong 1$ from Eq.(3), thus Eq.(4) can be simplified to

$$\rho_{12} = -\frac{\mathrm{i}\Omega_p}{\gamma_{21} + \mathrm{i}\Delta_p + \dfrac{|\Omega_c|^2}{\gamma_{41} + \mathrm{i}(\Delta_p + \Delta_c)}}. \qquad (5)$$

From Eq.(5), we can see that the numerator of ρ_{12} could never be zero, and the term $|\Omega_c|^2/(\gamma_{41} + \mathrm{i}\Delta_p)$ in the denominator leads to a resonant absorption reduction, which is commonly known as EIT phenomenon.[21]

Without the coherent field (Ω_c=0), it is found from Eq.(4) that the negative contribution of the second term tends to zero and EIT phenomenon disappears, so this system degenerates into a pure three-level light amplification system. With the restriction of Ω_c=0, from Eqs.(3) and (4), we have

$$\rho_{22} = \frac{\Lambda\Gamma_{32}(\Lambda + \Gamma_{31} + \Gamma_{32})^{-1}}{\Gamma_{21}}\rho_{11},$$

$$\rho_{33} = \Gamma_{21}\frac{\rho_{22}}{\Gamma_{32}},$$

$$\rho_{44} = 0,$$

$$\rho_{12} = \frac{\mathrm{i}\Omega_p(\rho_{22} - \rho_{11})}{\gamma_{12} + \mathrm{i}\Delta_p}. \qquad (6)$$

From Eq.(6), it is obvious that the probe can be amplified when the population inversion between levels $|2\rangle$ and $|1\rangle$ is established at the incoherent pumping rate $\Lambda > \Gamma_{21}(\Gamma_{31} + \Gamma_{32})/(\Gamma_{32} - \Gamma_{21})$.

When both the incoherent pumping and the coherent field are in action, the probe gain is contributed by the incoherent pump ($\propto (\rho_{22} - \rho_{11})$) and the atomic coherence ($\propto -|\Omega_c|^2(\rho_{22} - \rho_{44})$) (see Eq.(4)). In the incoherent pump process, level $|2\rangle$ could trap a large fraction of population decayed non-radiatively from level $|3\rangle$, thus we can obtain rather high population inversion on transition $|2\rangle \leftrightarrow |1\rangle$. When the coherent field is included, it not only populate level $|4\rangle$ from level $|2\rangle$, but also split level $|2\rangle$ into two dressed sublevels. If the positive contribution from the incoherent pump is larger than the negative contribution from the coherent field, the probe still can be amplified under the steady-state condition. However, if the negative contribution from the atomic coherence is dominant, the probe gain becomes smaller, and even changes into absorption.

4. Numerical results

In the following, we discuss the effects of light amplification and EIT by numerical solutions to obtain a few important conclusions on the change of the gain profile.

Based on Refs.[22] and [23], it is reasonable that we always choose the parameters to be Γ_{41}=1.0, Γ_{42}=0.3, Γ_{43}=0.0, Γ_{31}=1.0, Γ_{32}=20.0 in the following. In this paper, all the parameters have been scaled by Γ_{21}.

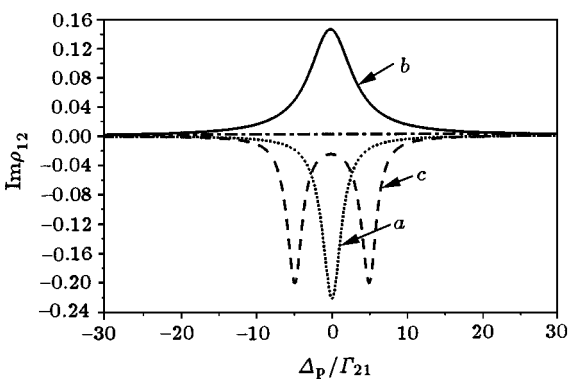


Fig.2. Plots of the dimensionless probe gain coefficient $\mathrm{Im}(\rho_{12})$ versus probe detuning Δ_p/Γ_{21} at different incoherent pumping rates and Ribi frequencies of the resonant coherent field. The curves *a*, *b*, *c* correspond to (1) Λ=0.0, Ω_c=0.0; (2) Λ=5.0, Ω_c=0.0; (3) Λ=0.0, Ω_c=5.0. Other parameters used are Γ_{21}=1.0, Γ_{31}=1.0, Γ_{41}=1.0, Γ_{42}=0.3, Γ_{43}=0.0, Γ_{32}=20.0, Ω_p=1.0.

To illustrate the effects of the incoherent pumping rate Λ and the Rabi frequency of the coherent field Ω_c on the absorption (gain) of the probe field, we depict the variation of the absorption (gain) of the probe field versus the detuning of the probe in Figs.2–4 whether the incoherent pumping and the coherent field are in action or not. When the incoherent pumping and the Rabi frequency of the coherent field both equal zero, this model is simplified to a two-level system, and the corresponding absorption of the probe field is shown by curve *a* in Fig.2. When the strong incoherent pump Λ=5.0 interacts with transition $|1\rangle \leftrightarrow |3\rangle$ only, this model becomes a three-level system in which the probe beam is amplified because of the inversion of the population difference $(\rho_{22} - \rho_{11})$, as shown by curve *b* in Fig.2. When the strong coherent field Ω_c=5.0 exists between levels $|2\rangle$ and $|4\rangle$ only, this model becomes a

three-level ladder-type EIT model where the absorption of the probe beam at $\Delta_p=0$ is greatly reduced because of the ac-Stark splitting and quantum interference in the decay of the dressed sublevels created by the coherent field,[24,25] as shown by curve c in Fig.2.

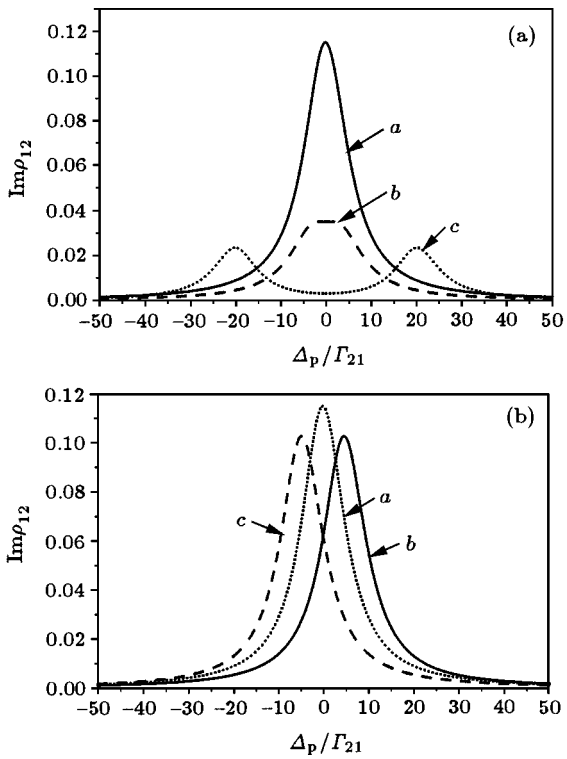


Fig.3. Plots of the dimensionless probe gain coefficient $\mathrm{Im}(\rho_{12})$ versus probe detuning Δ_p/Γ_{21} at different Ribi frequencies of the coherent field. Curves a, b, c in fig.3(a) correspond to Λ=10.0 and Ω_c=0.0, Δ_c=0.0; Ω_c=3.0, Δ_c=0.0; Ω_c=20.0; Δ_c=0.0; respectively. Curves a, b, c in Fig.3 (b) correspond to Λ=10.0 and Ω_c=0.0, Δ_c=0.0; Ω_c=20.0, Δ_c=80.0; Ω_c=20.0, Δ_c=–80.0; respectively. Other parameters used are the same as those in Fig.2.

Figure 3 is drawn to explore the effect of the atomic coherence on light amplification, when Λ=10.0 and Ω_c=0.0. It is obvious that there is only one gain peak at the position of Δ_p=0, as shown by curve a in Figs.3 (a) and (b). With the variation of the Rabi frequency Ω_c and the detuning Δ_c of the coherent field, the gain profile of the probe field is changed. When Ω_c=3.0 and Δ_c=0.0, as shown by curve b in Fig.3 (a), we still observe only one probe gain peak at Δ_p=0, but the gain peak becomes low and flat. When the coherent field becomes stronger (Ω_c=20.0 and Δ_c=0.0), as shown by curve c in Fig.3 (a), we find that there are two lower symmetric gain peaks at the position of $\Delta_p=\pm$20.0. We fix the Rabi frequency Ω_c=20.0, but change the detuning of the coherent field Δ_c, for example Δ_c=80.0 (Δ_c=–80.0), as shown by curve b, c in Fig.3 (b), the two gain peaks are not symmetric. They move to the left (right) hand side simultaneously, and the amplitude of the peak on the right (left) hand side becomes much higher than that of the left (right) hand side peak. This is very important because it means that we can obtain the high gain in a certain range of detuning of the probe field. It should be noted that the smaller peaks in both curves b and c are not shown because of the limited x-coordinate.

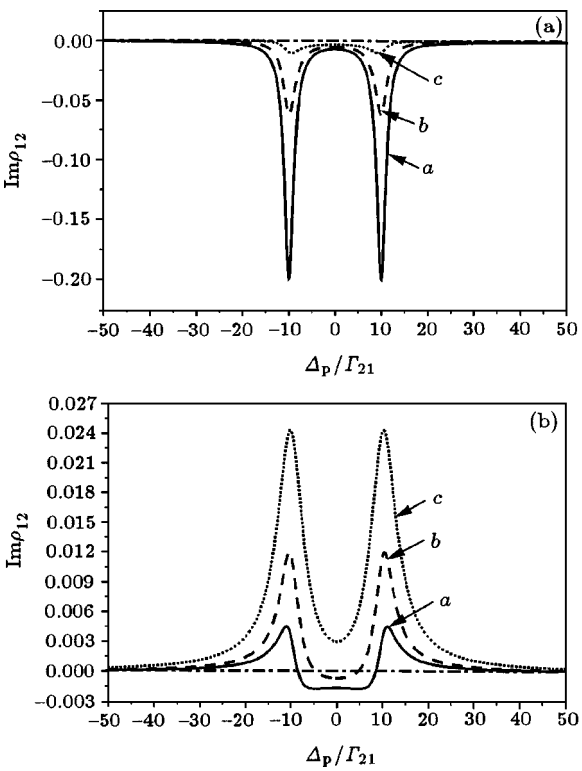


Fig.4. Plots of the dimensionless probe gain coefficient $\mathrm{Im}(\rho_{12})$ versus probe detuning Δ_p/Γ_{21} at different incoherent pumping rates. Curves a, b, c in Fig.4 (a) correspond to Λ=0.0, 1.0, 2.0. Curves a, b, c in Fig.4 (b) correspond to Λ=2.5, 3.0, 5.0, and the Ribi frequency and the detuning of the coherent field are Ω_c=10.0, Δ_c=0.0. Other parameters used are the same as those in Fig.2.

Figure 4 shows the effect of the incoherent pump on EIT. We choose the Rabi frequency and the detuning of the coherent field to the Ω_c=10.0 and Δ_c=0.0, and change the incoherent pumping rate Λ. When Λ=0.0, the phenomenon is the familiar EIT, as shown by curve a in Fig.4 (a). With increasing the incoherent pumping rate, the two absorption peaks at $\Delta_p=\pm$10.0 decrease, and the effect of EIT is weakened, as shown by curves b and c in Fig.4 (a). When $\Lambda \geq$2.5, the two peaks display the gain because the positive contribution from the incoherent pump becomes dominant, as

shown by curve a in Fig.4 (b). The larger the incoherent pumping rate is, the higher the gain values of the two peaks become, as shown by curve b and c in Fig.4 (b).

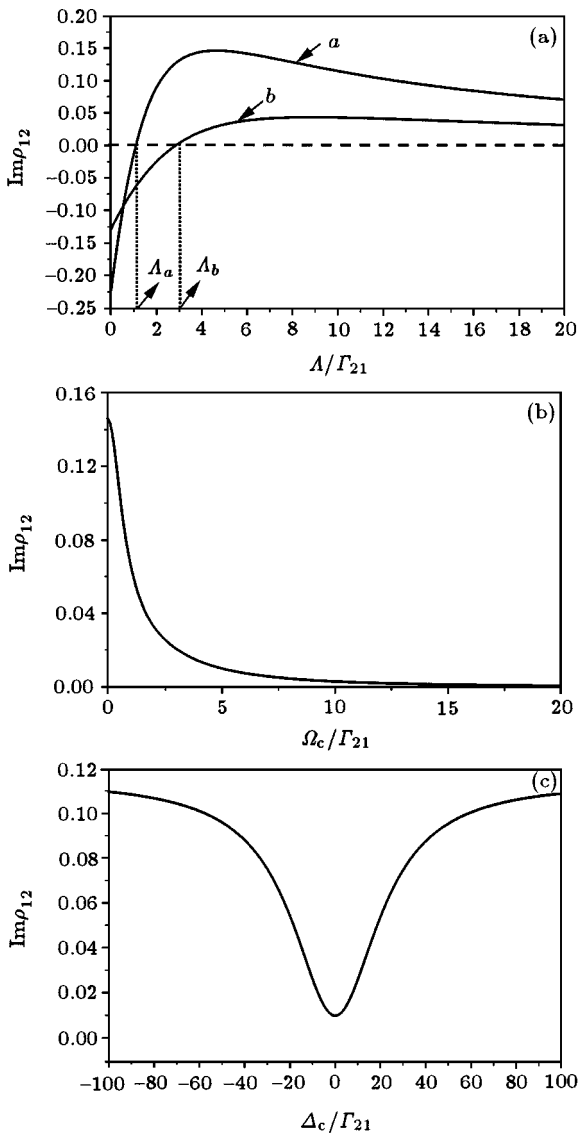


Fig.5. Plots of the dimensionless probe gain coefficients $\mathrm{Im}(\rho_{12})$ at Δ_p=0.0 versus: (a) the incoherent pumping Λ/Γ_{21}, where curves a and b correspond to the resonant coherent field Ω_c=0.0 and 2.0 respectively; (b) the Rabi frequency of the resonant coherent field Ω_c/Γ_{21} at Λ=5.0; (c) the detuning of the coherent field Δ_c/Γ_{21} at Λ=10.0, Ω_c=10.0. Other parameters used are the same as those in Fig.2.

There are three parameters which influence the gain of the probe, i.e. the incoherent pumping rate Λ, the Rabi frequency of the coherent field Ω_c and its detuning Δ_c. To show the effect of the incoherent pumping rate Λ on the probe, we depict the gain (absorption) amplitude of the probe, $\mathrm{Im}(\rho_{12})$, at Δ_p=0.0 when the Rabi frequency of the resonant coherent field Ω_c=0.0 and 1.0. In the case of Ω_c=0.0, the probe gain does not occur before the population inversion is established between level $|2\rangle$ and level $|1\rangle$ at Λ_a/Γ_{21}=1.1. After this point, the probe gain appears, and then it becomes larger and larger with increasing Λ before it reaches saturation, as shown by curve a in Fig.5 (a). In the presence of the resonant coherent field on transition $|2\rangle \leftrightarrow |4\rangle$, the probe gain decreases, and the position of the zero gain moves to Λ_b/Γ_{21}=2.8, as shown by curve b in Fig.5 (a). In Fig.5 (b), we depict the gain amplitude of the probe $\mathrm{Im}(\rho_{12})$ at Δ_p=0.0, versus the Rabi frequency of the resonant coherent field Ω_c when the incoherent pump rate Λ=5.0. The probe amplification can be observed when the Rabi frequency of the coherent field Ω_c is small, but it decreases very quickly at the beginning with increasing the Rabi frequency of the coherent field Ω_c, and approaches zero finally. In Fig.5 (c), we depict the gain amplitude of the probe $\mathrm{Im}(\rho_{12})$ at Δ_p=0.0, versus the detuning of the coherent field Δ_c when the incoherent pump rate Λ=10.0, and the Rabi frequency of the coherent field Ω_c=10.0. We find that the gain of the probe is symmetrical about the zero detuning of the coherent field. The gain of the probe reaches its minimum at the zero detuning, then increases when the detuning becomes large. This is easily understood because a large detuning means a weak action of the coherent field.

5. Conclusions

In this paper, we construct a four-level model in which the gain of the traditional light amplification system can be modified by the quantum interference caused by the coherent field. We have analysed the origin of the variation of the probe gain, which is distributed by the incoherent pump and the coherent field. We present the effects of quantum interference on the probe gain, namely, the variation of the position and the height of the gain peaks when the Rabi frequency and the detuning of the coherent field are changed. We have also discussed the effect of incoherent pump on the absorption profile of EIT. The system developed here may find its applications in optical communications.

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