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Response of the probe gain with or without inversion to the relative phase of two coherent fields in a three-level V model

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Abstract

We investigate a V-type three-level atomic system with two near-degenerate excited levels, which is driven by a strong coherent field and a weak probe field. We find that, due to the quantum interference between two spontaneous decay channels, even in the absence of an incoherent pumping, the probe gain can be achieved and modulated at different probe detunings just by tuning the relative phase between the probe and the coherent field to different regions. By demonstrating the gain-absorption coefficient as well as the population difference on the probe transition, we show that the probe gain can be either with or without population inversion, which depends on detunings, spontaneous decay rates, and the relative phase. In this atomic system, the phase-dependent probe gain originates from the internal quantum interference effect as well as the external dynamically induced coherence effect.

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1. Introduction

There have been considerable interests recently in the study of quantum interference effect due to spontaneous emission from two closely lying excited levels to a common ground level (the V model), or from a common excited level to two closely lying ground levels (the Λ model) [1–13]. It was reported that the quantum interference among spontaneous decay channels can lead to the modification of absorption and dispersion properties of atomic systems [5,6]. Moreover, it has been shown that atomic systems with spontaneously generated interference are sensitive to the relative phase of the applied fields [6–11]. Of course, the existence of the spontaneously generated quantum interference effect depends on the nonorthogonality of the two involved dipole matrix elements. In the language of quantum pathway interference, different pathways involving different spontaneously emitted photons may be indistinguishable

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only if the corresponding transitions give rise to photons of identical polarization. This means that, if the associated dipole matrix elements are orthogonal, no such effect exists.

Up to now, various schemes depending on either internal interference effect or coherence effect of external fields have been proposed and studied to realize lasing without population inversion (LWI) [14–21]. It has been demonstrated experimentally that, when it is difficult or even impossible to create population inversion by conventional incoherent pumping, LWI can provide us with an important alternative [22–24]. The origin of LWI achieved with external fields can be attributed to either inversion between dressed states or coherence among them [15,16]. As we know, in all early works related to LWI, the probe gain is independent of phases of the applied fields, though it is related to their frequencies (or detunings) and amplitudes (or Rabi frequencies). But recently, we found that, in a Λ-type three-level atomic system with two closely lying ground levels, the probe gain without population inversion can be modulated by changing the relative phase between the probe and the coherent field [25]. However, in such a system, population distributions are not sensitive to the relative phase, and we have to use an incoherent pumping to prepare atoms in the top level.

In the present contribution, we study a V-type three-level atomic system with two closely lying upper levels for achieving the phase-dependent probe gain in the absence of incoherent pumping. This atomic system is the same as those in [5,12], where gain features of the probe are demonstrated. However, in these works, the authors treated Rabi frequencies of the applied fields as real parameters, so they only obtained phase-independent probe gain. In this paper, we find that, if we take phases of the applied fields into account (i.e., treating Rabi frequencies as complex parameters), the probe gain becomes quite sensitive to the relative phase between the probe and the coherent field. When the relative phase is given different values, the gain behavior of the probe is quite different. We also show the dependence of population difference on the probe transition on the probe detuning and the relative phase, and find that the probe gain can be either with or without inversion, which depends on detunings of fields, spontaneous decay rates, as well as the relative phase. Note that, the phase-dependent probe gain with or without inversion is caused by both the dynamically induced coherence and the spontaneously generated interference.

2. The atomic model

We consider a closed, V-type, three-level atomic system with two near-degenerate excited levels $|2\rangle$ and $|3\rangle$, and a ground level $|1\rangle$, as illustrated in Fig. 1. A strong coherent field of frequency (amplitude) $\omega_c(\vec{E}_c)$ drives the transition $|1\rangle \leftrightarrow |2\rangle$ of frequency ω_{21} to prepare population distributions in the excited levels and produce the necessary dynamically induced coherence for the probe gain. A weak field of frequency (amplitude) $\omega_p(\vec{E}_p)$ is used to probe the gain or absorption on transition $|1\rangle \leftrightarrow |3\rangle$ of frequency ω_{31}. $2\gamma_{21}$ and $2\gamma_{31}$ are the spontaneous decay rates from levels $|2\rangle$ and $|3\rangle$ to level $|1\rangle$, respectively. $\Delta_p = \omega_{31} - \omega_p$ $(\Omega_p = \vec{E}_p \cdot \vec{d}_{13}/2\hbar)$ and $\Delta_c = \omega_{21} - \omega_c$ $(\Omega_c = \vec{E}_c \cdot \vec{d}_{12}/2\hbar)$ are detunings (Rabi frequencies) of the probe and the coherent field, respectively. In the interaction picture, the semiclassical density-matrix equations of motion under the electric-dipole and the rotating-wave approximations can be written as [5,12]

$$\dot{\rho}_{22} = -2\gamma_{21}\rho_{22} + i\Omega_c\rho_{12} - i\Omega_c^*\rho_{21} - \eta(\rho_{23} + \rho_{32}), \quad (1)$$

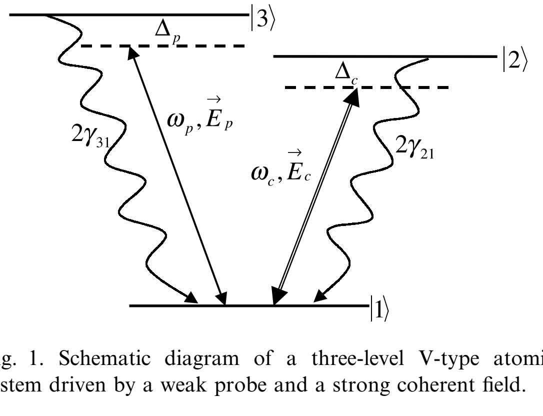

Fig. 1. Schematic diagram of a three-level V-type atomic system driven by a weak probe and a strong coherent field.

$$\dot{\rho}_{33} = -2\gamma_{31}\rho_{33} + i\Omega_p\rho_{13} - i\Omega_p^*\rho_{31} - \eta(\rho_{23} + \rho_{32}), \quad (2)$$

$$\dot{\rho}_{12} = (i\Delta_c - \gamma_{21})\rho_{12} + i\Omega_c^*(\rho_{22} - \rho_{11}) + i\Omega_p^*\rho_{32} - \eta\rho_{13}, \quad (3)$$

$$\dot{\rho}_{13} = (i\Delta_p - \gamma_{31})\rho_{13} + i\Omega_p^*(\rho_{33} - \rho_{11}) + i\Omega_c^*\rho_{23} - \eta\rho_{12}, \quad (4)$$

$$\dot{\rho}_{23} = (i\Delta_p - i\Delta_c - \gamma_{21} - \gamma_{31})\rho_{23} + i\Omega_c\rho_{13} - i\Omega_p^*\rho_{21} - \eta(\rho_{22} + \rho_{33}). \quad (5)$$

The closure of this atomic system requires that $\rho_{11} + \rho_{22} + \rho_{33} = 1$ and $\rho_{ij} = \rho_{ji}^*$. In Eqs. (1)–(5), those terms with $\eta = \sqrt{\gamma_{21}\gamma_{31}}\cos\theta$ are related to the quantum interference effect resulting from the cross-coupling between spontaneous emissions $|2\rangle \to |1\rangle$ and $|3\rangle \to |1\rangle$, where θ is the angle between the two induced dipole matrix elements $\vec{d}_{12}$ and $\vec{d}_{13}$. Obviously, when $\vec{d}_{12}$ and $\vec{d}_{13}$ are orthogonal, no such spontaneously generated interference effect exists ($\eta = 0$). While when $\vec{d}_{12}$ and $\vec{d}_{13}$ are parallel, we obtain the maximal spontaneously generated interference effect ($\eta = 1$). In this paper, we just consider linearly polarized electric fields with the restriction of $\vec{E}_p \cdot \vec{d}_{12} = 0$ and $\vec{E}_c \cdot \vec{d}_{13} = 0$, so Rabi frequencies Ω_p and Ω_c are connected to the angle θ by the relation of $\Omega_p = \Omega_p^0 \sin\theta$ and $\Omega_c = \Omega_c^0 \sin\theta$, with $\Omega_p^0 = |\vec{E}_p| \cdot |\vec{d}_{13}|$ and $\Omega_c^0 = |\vec{E}_c| \cdot |\vec{d}_{12}|$.

Taking phases of the probe and the coherent field ϕ_p and ϕ_c into account, we rewrite the Rabi frequencies as $\Omega_p = G_p\exp(i\phi_p)$ and $\Omega_c = G_c\exp(i\phi_c)$, where G_p and G_c are chosen to be real. By redefining the atomic variables as $\sigma_{ii} = \rho_{ii}$, $\sigma_{12} = \rho_{12}\exp(i\phi_c)$, $\sigma_{13} = \rho_{13}\exp(i\phi_p)$, and $\sigma_{23} = \rho_{23}\exp(i\Phi)$, where $\Phi = \phi_p - \phi_c$ is the relative phase between the two fields, we obtain the equations of motion for the redefined density matrix elements σ_{ij} as follows:

$$\dot{\sigma}_{22} = -2\gamma_{21}\sigma_{22} + iG_c(\sigma_{12} - \sigma_{21}) - \eta_\Phi(\sigma_{23} + \sigma_{32}), \quad (6)$$

$$\dot{\sigma}_{33} = -2\gamma_{31}\sigma_{33} + iG_p(\sigma_{13} - \sigma_{31}) - \eta_\Phi(\sigma_{23} + \sigma_{32}), \quad (7)$$

$$\dot{\sigma}_{12} = (i\Delta_c - \gamma_{21})\sigma_{12} + iG_c(\sigma_{22} - \sigma_{11}) + iG_p\sigma_{32} - \eta_\Phi\sigma_{13}, \quad (8)$$

$$\dot{\sigma}_{13} = (i\Delta_p - \gamma_{31})\sigma_{13} + iG_p(\sigma_{33} - \sigma_{11}) + iG_c\sigma_{23} - \eta_\Phi\sigma_{12}, \quad (9)$$

$$\dot{\sigma}_{23} = (i\Delta_p - i\Delta_c - \gamma_{21} - \gamma_{31})\sigma_{23} + iG_c\sigma_{13} - iG_p\sigma_{21} - \eta_\Phi(\sigma_{22} + \sigma_{33}). \quad (10)$$

From Eqs. (6)–(10), we can see that, due to the existence of the complex parameter $\eta_\Phi = \eta\exp(i\Phi)$, this atomic system becomes sensitive to the relative phase Φ between the probe and the coherent field, which means that we can change the gain or absorption property of this atomic system just by tuning the relative phase Φ to different regions. We should note that, only when ω_{32}, the energy difference between levels $|2\rangle$ and $|3\rangle$, is very close compared to γ_{21} and γ_{31}, is the spontaneously generated quantum interference effect important, otherwise it will be averaged out by fast oscillating (in fact, we have ignored the oscillating terms $\exp(\pm i\omega_{23}t)$ related to η in Eqs. (1)–(5)) [5–10].

The gain-absorption coefficient on transition $|1\rangle \leftrightarrow |3\rangle$ is proportional to the imaginary part of σ_{13}, and the probe gain will be obtained if $\mathrm{Im}(\sigma_{13}) > 0$. From Eq. (9) in steady state, we obtain

$$\sigma_{13} = \frac{iG_p(\sigma_{33} - \sigma_{11}) + iG_c\sigma_{23} - \eta_\Phi\sigma_{12}}{\gamma_{31} - i\Delta_p}. \quad (11)$$

Obviously, the probe gain or absorption consists of three terms: the population difference term (proportional to $\sigma_{33} - \sigma_{11}$), the dynamically induced coherence term (proportional to σ_{23}), and the spontaneously generated interference term (proportional to σ_{12}). The last term is an additional term compared to the first two terms that are common in usual atomic systems with well-separated levels. From Eqs. (8) and (10) in steady state, it is easy to find that the second term includes the contribution of spontaneously generated interference, and the last term includes the contribution of dynamically induced coherence. Since no incoherent process is included in this system, both population inversion and the probe gain observed in the next section are contributed by the spontaneously generated interference as well as the dynamically induced coherence. In what follows, we assume that G_p, G_c, Δ_p, Δ_c, and γ_{21} are in units of γ_{31}.

3. Results and discussion

In this section, in the limit of a weak probe and a strong coherent field (i.e., $G_c \gg \gamma_{31} \gg G_p$), we investigate the effect of the relative phase Φ on the probe gain $\mathrm{Im}(\sigma_{13})$ and population difference $\sigma_{33} - \sigma_{11}$ in the absence of an incoherent pumping. Obviously, under the action of the strong coherent field G_c, the ground level $|1\rangle$ will be split into two dressed sublevels

$$|+\rangle = \sin\psi|1\rangle + \cos\psi|2\rangle, \quad (12)$$

$$|-\rangle = \cos\psi|1\rangle - \sin\psi|2\rangle \quad (13)$$

with eigenvalues of $\omega_\pm = (\Delta_c \pm \sqrt{\Delta_c^2 + 4G_c^2})/2$, where $\tan\psi = -G_c/\omega_+$.

In Fig. 2, according to the numerical solutions of Eqs. (6)–(10), we plot population difference $\sigma_{33} - \sigma_{11}$ and the probe gain (or absorption) $\mathrm{Im}(\sigma_{13})$ versus the probe detuning Δ_p for different values of Φ. From the dashed curves in Fig. 2, we can see that, only when the probe is resonant or near resonant on transitions $|3\rangle \leftrightarrow |+\rangle$ or $|3\rangle \leftrightarrow |-\rangle$ (i.e., $\Delta_p \cong \omega_\pm$), is population difference $\sigma_{33} - \sigma_{11}$ sensitive to the relative phase Φ, and can population inversion be established on transition $|1\rangle \leftrightarrow |3\rangle$. However, the probe gain or absorption $\mathrm{Im}(\sigma_{13})$ is sensitive to the relative phase Φ in a much larger spectral range than $\omega_- < \Delta_p < \omega_+$. It is obvious that, in Fig. 2 we obtain both the probe gain with population inversion and the probe gain without population inversion, but the probe gain with population inversion only can be got in a small spectral range around $\Delta_p = \omega_\pm$. If we take Rabi frequencies Ω_p and Ω_c as real parameters (i.e., $\Phi = 0$), we can obtain the probe gain with or

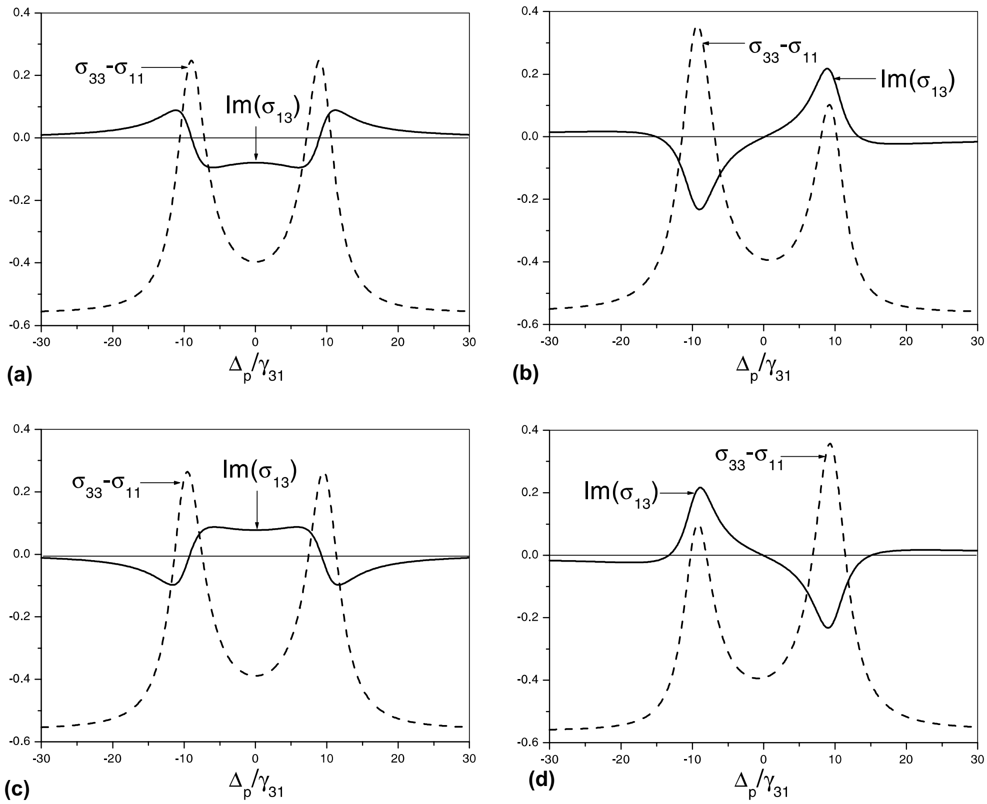

Fig. 2. Population difference $\sigma_{33} - \sigma_{11}$ and the probe gain or absorption $\mathrm{Im}(\sigma_{13})$ against the probe detuning Δ_p/γ_{31} for (a) $\Phi = 0$; (b) $\Phi = \pi/2$; (c) $\Phi = \pi$; (d) $\Phi = 3\pi/2$. Other parameters are chosen as $\gamma_{21} = 5\gamma_{31}$, $\Delta_c = 0$, $G_p = 1.0\gamma_{31}\sin\theta$, $G_c = 30\gamma_{31}\sin\theta$, and $\theta = \pi/10$.

without inversion in two small spectral ranges of $\Delta_p \succ \omega_+$ and $\Delta_p \prec \omega_-$ (see Fig. 2(a)). However, when the relative phase Φ is given different values, the gain profile changes remarkably. In the case of $\Phi = \pi/2$ (or $\Phi = 3\pi/2$), we only can achieve the probe gain with or without population inversion in a single small spectral range around $\Delta_p = \omega_+$ (or $\Delta_p = \omega_-$), but the maximal gain amplitude becomes larger (see Figs. 2(b) and (d)). Obviously, we can obtain Fig. 2(d) from Fig. 2(b) simply by replacing Δ_p with $-\Delta_p$. While in the case of $\Phi = \pi$, the probe gain with or without population inversion with a relative flat profile can be achieved in a much larger spectral range of $\omega_- < \Delta_p < \omega_+$, which corresponds to the frequency difference of dressed sublevels $|+\rangle$ and $|-\rangle$ (see Fig. 2(c)). The solid curve in Fig. 2(c) can be obtained from that in Fig. 2(a) just by replacing $\mathrm{Im}(\sigma_{13})$ with $-\mathrm{Im}(\sigma_{13})$.

To have a deeper insight into the modulation effect of the relative phase Φ on the probe gain with or without inversion, we plot population difference $\sigma_{33} - \sigma_{11}$ and the probe gain or absorption $\mathrm{Im}(\sigma_{13})$ at $\Delta_p = 0$ and $\Delta_p = \omega_\pm$ versus Φ in Fig. 3. It is clear that the probe gain or absorption at a fixed probe detuning is a periodical function of the relative phase Φ with the period of 2π. At $\Delta_p = 0$, population difference $\sigma_{33} - \sigma_{11}$ is not sensitive to the relative phase, and we can achieve the probe gain without inversion for some special values of Φ. While at $\Delta_p = \omega_\pm$, population difference $\sigma_{33} - \sigma_{11}$ is quite sensitive to the relative phase, and we can achieve the probe gain with inversion with proper values of Φ. Note that, the probe gain with inversion at $\Delta_p = \omega_\pm$ increases with the decreasing of population inversion $\sigma_{33} - \sigma_{11}$ when we change the relative phase Φ, and the maximal probe gain always corresponds to the

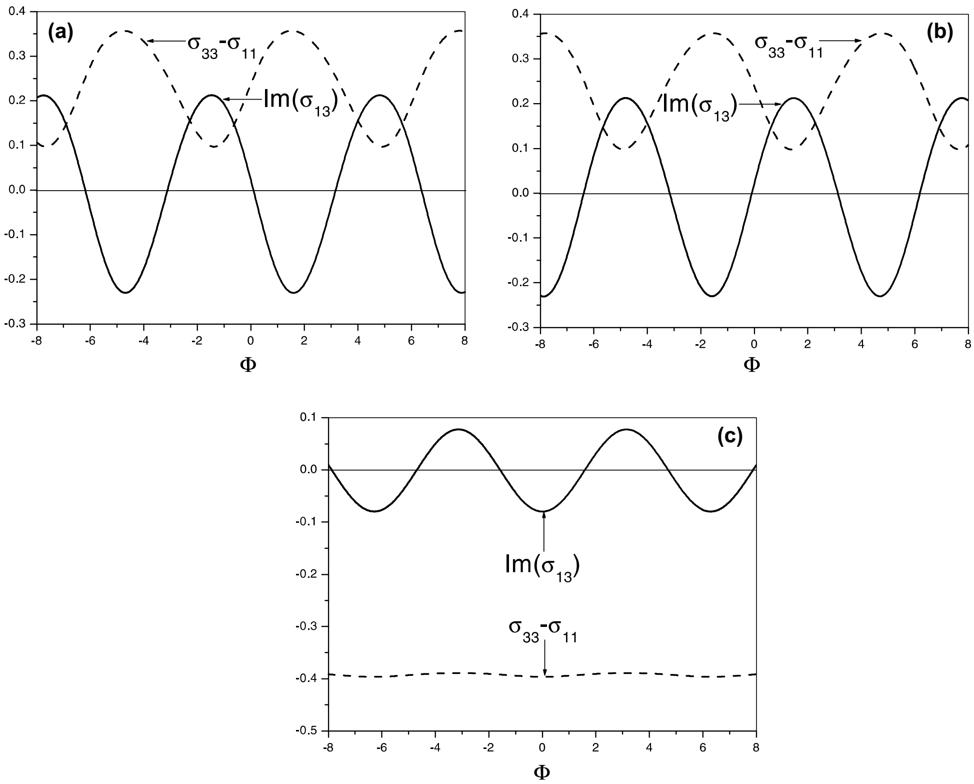

Fig. 3. Population difference $\sigma_{33} - \sigma_{11}$ and the probe gain or absorption $\mathrm{Im}(\sigma_{13})$ against the relative phase Φ for (a) $\Delta_p = -G_c$; (b) $\Delta_p = G_c$; (c) $\Delta_p = 0$. Other parameters are the same as those in Fig. 2.

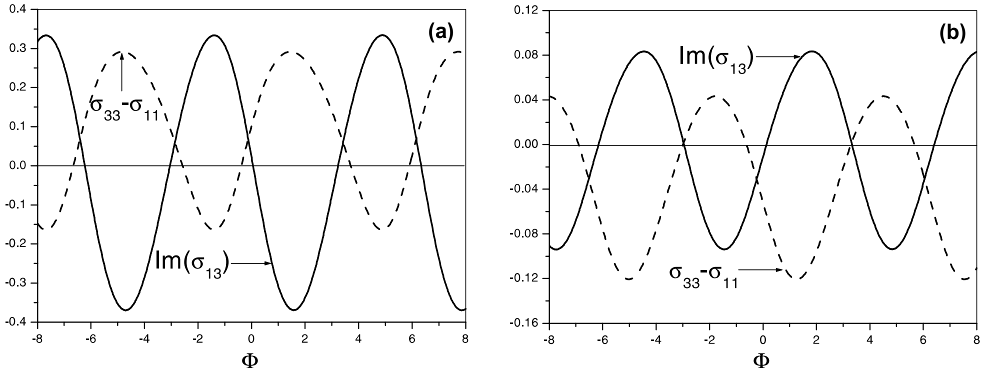

Fig. 4. Population difference $\sigma_{33} - \sigma_{11}$ and the probe gain or absorption $\mathrm{Im}(\sigma_{13})$ against the relative phase Φ for (a) $\Delta_p = \omega_-$; (b) $\Delta_p = \omega_+$. Other parameters are the same as those in Fig. 2 except $\Delta_c = 10\gamma_{31}$.

smallest inversion. That is to say, the dynamically induced coherent term (σ_{23}) and the spontaneously generated interference term (σ_{12}) contribute more to the probe gain with inversion than the population difference term ($\sigma_{33} - \sigma_{11}$). Comparing Fig. 3(a) with Fig. 3(b), it is easy to find that we can obtain Fig. 3(b) from Fig. 3(a) just by replacing Φ with $-\Phi$, and we cannot achieve the probe gain with inversion at $\Delta_p = \omega_\pm$, simultaneously.

We have chosen unequal spontaneous decay rates ($\gamma_{21} = 5\gamma_{31}$) and the resonant coherent field ($\Delta_c = 0$) for investigating the gain behavior of the probe. In the following, we will show that, when γ_{21} decreases to a proper value, or Δ_c becomes large enough, we also can obtain the probe gain without inversion at $\Delta_p = \omega_\pm$. In Fig. 4, with $\Delta_c = 10\gamma_{31}$, we repeat the same calculations as in Figs. 3(a) and (b). From Fig. 4(a) we can see that, for some values of the relative phase Φ, there exists population inversion on transition $|1\rangle \leftrightarrow |3\rangle$, while for other values of Φ, no population inversion occurs. It is obvious that both the probe gain with and without inversion can be obtained at $\Delta_p = \omega_-$ by tuning the relative phase Φ, but the probe gain without inversion is much larger. However, we only can achieve the probe gain without inversion at $\Delta_p = \omega_+$, though population inversion still can be established on transition $|1\rangle \leftrightarrow |3\rangle$ (see Fig. 4(b)). Moreover, with $\Delta_c = 10\gamma_{31}$, the maximal gain amplitude at $\Delta_p = \omega_-$ becomes much larger, but that at $\Delta_p = \omega_+$ becomes much smaller.

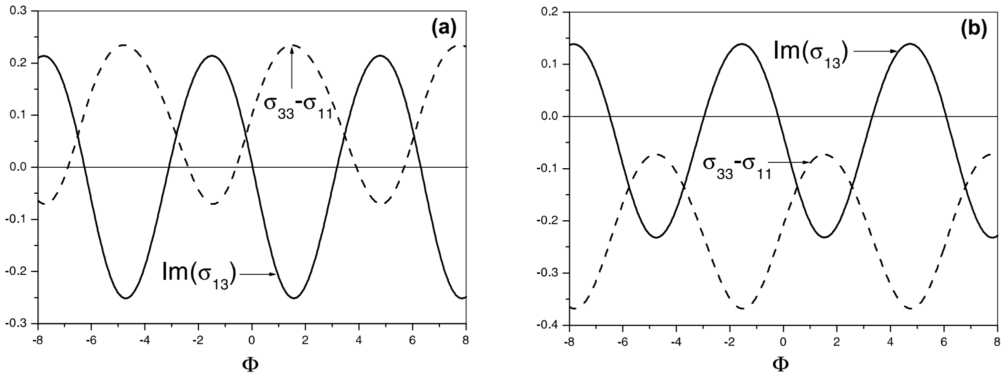

Fig. 5. Population difference $\sigma_{33} - \sigma_{11}$ and the probe gain or absorption $\mathrm{Im}(\sigma_{13})$ against the relative phase Φ for (a) $\gamma_{21} = 3\gamma_{31}$; (b) $\gamma_{21} = \gamma_{31}$. Other parameters are the same as those in Fig. 3(a).

In Fig. 5, for $\Delta_p = \omega_-$, we repeat the same calculations as in Fig. 3(a), but with different values for the spontaneous decay rate $2\gamma_{21}$. From Fig. 5(a), we find that, in the case of $\gamma_{21} = 3\gamma_{31}$, both the probe gain with and without inversion can be obtained at $\Delta_p = \omega_-$ by tuning the relative phase Φ, and the maximal probe gain corresponds to the minimal population inversion, which is similar to Fig. 4(a). From Fig. 5(b), we find that, in the case of $\gamma_{21} = \gamma_{31}$, population inversion cannot be established on transition $|1\rangle \leftrightarrow |3\rangle$ for all values of Φ, though it still can be modulated by Φ, so we always achieve the probe gain without inversion. By comparing Figs. 5(a) and (b) with Fig. 3(a), it is clear that, with the decreasing of γ_{21}, the maximal probe gain also becomes smaller. Similar results can be obtained for $\Delta_p = \omega_+$.

4. Conclusion

In summary, we have shown that, in a V-type atomic system with two closely lying excited levels, the phase-dependent probe gain with or without population inversion can be achieved due to the existence of the quantum interference effect among spontaneous decay channels. It is found that, in the case of $\gamma_{21} = 5\gamma_{31}$ and $\Delta_c = 0$, by tuning the relative phase Φ into proper regions, we can obtain the probe gain with inversion around $\Delta_p = \omega_\pm$, and obtain the probe gain without inversion in other regions of Δ_p. The probe gain with or without inversion is contributed by both the spontaneously generated interference effect and the dynamically induced coherence effect. Specially, (a) in the case of an off-resonant coherent field (i.e., $\Delta_c \neq 0$), we also can obtain the probe gain without inversion at $\Delta_p = \omega_\pm$; (b) when γ_{21} becomes small enough (i.e., not much larger than γ_{31}), no population inversion can be established on transition $|1\rangle \leftrightarrow |3\rangle$, so we always obtain the probe gain without inversion in the whole spectral range of Δ_p.

What we would like to emphasize here is that both the probe gain with and without inversion is achieved in the absence of an incoherent pumping, and in the absence of an incoherent pumping it is impossible to achieve the inversionless gain in a conventional V-type three-level atomic system with well-separated levels [26].

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