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Spontaneous emission-induced coherent effects in absorption and dispersion of a V-type three-level atom

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Abstract

We study the effects of quantum interference from spontaneous emission in the creation of atomic coherence in a closed V-type system. We find that the absorption and dispersion properties of this atom can be significantly modified if this interference is optimized. Lasing with or without inversion, electromagnetically-induced transparency and enhancement of the index of refraction are all dependent on this interference. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Quantum coherence and interference in atomic systems can lead to many interesting optical phenomena such as lasing without inversion (LWI) [1–4], enhancement of the index of refraction [5,6], electromagnetically-induced transparency (EIT) [7–9] and spontaneous emission modification [10,11]. There are many ways to prepare the atom in order for these phenomena to occur, and usually the phenomenon of spontaneous emission plays a destructive role in the creation of this coherence. However, there have been several proposals in which coherence induced from the spontaneous emission process itself is used for the preparation of the atom [2,9–11]. This kind of coherence is created by the interference of spontaneous emission of either two close lying atomic levels to a common atomic level (V-type atom), or by a single excited level to two close lying atomic levels (Λ-type atom).

In this paper, using a closed V-type atomic system which is excited by two different laser pulses (a strong drive field and a probe field), we investigate the effects of coherence created from spontaneous emission interference in the absorption and dispersion properties of this atom. Our atomic system (Fig. 1) is similar to that studied in Ref. [4]; however, the effects of quantum interference deriving from the spontaneous emission of the two closely spaced upper levels which are included in our model will substantially modify the behaviour of the system. We study the system in two separate cases: with and without the presence of a pump mechanism. For our pump mechanism, we choose to study only the case of an incoherent pumping (broad-bandwidth field). The effects of a coherent pump field, studied by Wilson et al. [4], are beyond the scope of this work. Using a steady state density matrix analysis we show that, in the presence of an incoherent pumping field, a transparency of the medium to the probe field can be induced from coherence which originates from spontaneous emission interference. In addition, the gain for LWI and the enhancement of the index of refraction increase as this interference increases. In the absence of incoherent pumping, the effects of EIT, lasing with inversion and enhancement of the index of refraction co-exist at the same time and these phenomena can be controlled using the coherence induced from spontaneous emission interference.

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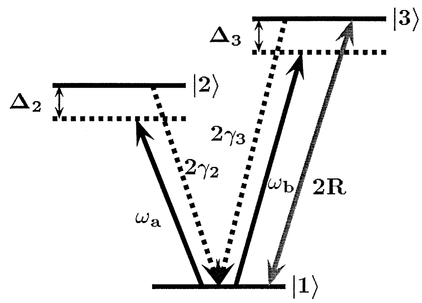

Fig. 1. The system under consideration. The ground state $|1\rangle$ is coupled to the excited state $|2\rangle$ with the drive laser ω_a and also to state $|3\rangle$ with the probe laser ω_b. The dashed lines indicate the spontaneous emission process from the closely spaced excited levels to the ground state and the grey double-headed line the incoherent pump field.

This article is organized as follows: in Section 2 we present the density matrix equations for the atomic model which are examined in the steady state case. In Subsection 3.1, the effects of spontaneous emission on LWI in the presence of an incoherent pumping field are given and in Subsection 3.2, the effects of spontaneous emission on probe absorption and dispersion in the absence of pumping field are presented. Finally, we conclude in Section 4.

2. The atomic model

The atomic system of interest here is shown in Fig. 1. We consider a V-type atomic model with two close lying upper states $|2\rangle$ and $|3\rangle$ and one ground state $|1\rangle$. The excited state $|2\rangle$ is coupled to the ground state through a strong drive field with frequency ω_a and Rabi frequency $\Omega = \boldsymbol{\mu}_{12} \cdot \mathscr{E}_a$. The excited state $|3\rangle$ is coupled to the ground state through a probe field with frequency ω_b and Rabi frequency $E = \boldsymbol{\mu}_{13} \cdot \mathscr{E}_b$. Both Rabi frequencies are considered real in our problem. Both excited levels ($|2\rangle$, $|3\rangle$) are considered to decay spontaneously to the ground level with decay rates $2\gamma_2$, $2\gamma_3$, respectively. We also consider an incoherent (broad-bandwidth) pump field which drives the transition $|1\rangle \leftrightarrow |3\rangle$ with rate $2R$. Such a pumping can be created, for example, using an electric discharge.

In this article we analyze the system using the density matrix approach. We begin by paying special attention to the effects of the vacuum on the system by solely considering spontaneous emission effects. The Hamiltonian that describes the atom–vacuum interaction, in the interaction representation, can be written as ($\hbar = 1$)

$$H_I = \sum_{\boldsymbol{k}} g_{2\boldsymbol{k}} |2\rangle\langle 1| \exp[-i(\omega_{\boldsymbol{k}} - \omega_{21})t] + \sum_{\boldsymbol{k}} g_{3\boldsymbol{k}} |3\rangle\langle 1| \exp[-i(\omega_{\boldsymbol{k}} - \omega_{31})t] + \text{h.c.} \quad (1)$$

We can proceed using the Liouville equation of motion for the density matrix and then use the Weisskopf-Wigner theory of spontaneous emission (or the Born-Markov approximation) [12] to obtain the following equations (for a detailed derivation see the articles by Fleischhauer et al. [1] and Zhou and Swain [11])

$$\dot{\rho}_{22} = -2\gamma_2 \rho_{22} - p\sqrt{\gamma_2\gamma_3}\,(\rho_{23}\,e^{i\omega_{32}t} + \rho_{32}\,e^{-i\omega_{32}t}), \quad (2)$$

$$\dot{\rho}_{33} = -2\gamma_3 \rho_{33} - p\sqrt{\gamma_2\gamma_3}\,(\rho_{23}\,e^{i\omega_{32}t} + \rho_{32}\,e^{-i\omega_{32}t}), \quad (3)$$

$$\dot{\rho}_{23} = -(\gamma_2 + \gamma_3)\rho_{23} - p\sqrt{\gamma_2\gamma_3}\,e^{-i\omega_{32}t}(\rho_{22} + \rho_{33}), \quad (4)$$

$$\dot{\rho}_{21} = -\gamma_2 \rho_{21} - p\sqrt{\gamma_2\gamma_3}\,e^{-i\omega_{32}t}\rho_{31}, \quad (5)$$

$$\dot{\rho}_{31} = -\gamma_3 \rho_{31} - p\sqrt{\gamma_2\gamma_3}\,e^{i\omega_{32}t}\rho_{21}, \quad (6)$$

constrained by $\rho_{11} + \rho_{22} + \rho_{33} = 1$ and $\rho_{nm}^* = \rho_{mn}$. An alternative way to determine these equations is to use the wavefunction approach, constructing the equations of motion for the probability amplitudes using the Schrödinger equation and the Weisskopf-Wigner approximation and then obtaining the equations for the density matrix from their relation to the probability amplitudes (for an example see the work of Zhu et al. [11]). An intuitive explanation of the origin of the term $p\sqrt{\gamma_2\gamma_3}$ is that it represents the effect of spontaneous emission of one photon from the transition $|2\rangle \to |1\rangle$ and absorption of the same photon in the transition $|1\rangle \to |3\rangle$ or vice versa. The physical explanation is that this term is the result of quantum interference of spontaneous emission from the two close lying upper levels. The parameter p denotes the alignment of the two matrix elements and is defined as $p \equiv \boldsymbol{\mu}_{21} \cdot \boldsymbol{\mu}_{13} / |\boldsymbol{\mu}_{21}||\boldsymbol{\mu}_{13}| = \cos\theta$. The parameter p plays a very important role in the creation of coherence as we will show later. From Eqs. (2)–(6) it can be seen that the effects of vacuum-induced coherence are possible only if the two levels are very close in energy compared to the decay rates γ_2, γ_3. In the case that the energy difference of the upper levels is large, then the oscillating terms $e^{\pm i\omega_{32}t}$ will average out and no effect from spontaneous emission interference can be obtained. So in order to study the effects arising by spontaneous emission interference in an optimal configuration, we will assume that the two excited states are nearly degenerate, i.e. $\omega_{32} \approx 0$. However, we should note, at this point, that the two upper levels need not be bare states of an atomic system. These levels may well be dressed states resulting from a weak coupling of two bare states. If the field that couples the bare states is weak and on-resonance then an off-diagonal radiative coupling of the two dressed states is also possible. This gives rise to interference terms in the system which have similar results from the p-dependent terms.

If we include the laser–atom interaction terms in our description, we obtain the following set of differential equations for the density matrix (in a rotating frame) [12]

$$\dot{\rho}_{22} = -2\gamma_2 \rho_{22} - p\sqrt{\gamma_2\gamma_3}\,(\rho_{23}+\rho_{32}) + i\Omega(\rho_{12}-\rho_{21}), \tag{7}$$

$$\dot{\rho}_{33} = 2R\rho_{11} - 2(\gamma_3+R)\rho_{33} - p\sqrt{\gamma_2\gamma_3}\,(\rho_{23}+\rho_{32}) + iE(\rho_{13}-\rho_{31}), \tag{8}$$

$$\dot{\rho}_{23} = -\left[\gamma_2+\gamma_3+R+i(\Delta_3-\Delta_2)\right]\rho_{23} - p\sqrt{\gamma_2\gamma_3}\,(\rho_{22}+\rho_{33}) + i\Omega\rho_{13} - iE\rho_{21}, \tag{9}$$

$$\dot{\rho}_{21} = -(\gamma_2+R-i\Delta_2)\rho_{21} - p\sqrt{\gamma_2\gamma_3}\,\rho_{31} + i\Omega(\rho_{11}-\rho_{22}) - iE\rho_{23}, \tag{10}$$

$$\dot{\rho}_{31} = -(\gamma_3+2R-i\Delta_3)\rho_{31} - p\sqrt{\gamma_2\gamma_3}\,\rho_{21} + iE(\rho_{11}-\rho_{33}) - i\Omega\rho_{32}. \tag{11}$$

Here, the detunings Δ_2, Δ_3 have been redefined to contain the radiative shifts. If we consider linearly polarized electric fields with the restriction that $\boldsymbol{\mu}_{12}\cdot\mathcal{E}_b = 0$ and $\boldsymbol{\mu}_{13}\cdot\mathcal{E}_a = 0$ we can show that the Rabi frequencies are connected to the p parameter by the relation $\Omega = \Omega_0\sqrt{1-p^2} = \Omega_0\sin\theta$ and $E = E_0\sqrt{1-p^2} = E_0\sin\theta$, with $\Omega_0 = |\boldsymbol{\mu}_{12}||\mathcal{E}_a|$ and $E_0 = |\mu_{13}||\mathcal{E}_b|$ [9]. In the case that the matrix elements $\boldsymbol{\mu}_{12}$, $\boldsymbol{\mu}_{31}$ are orthogonal, then $p=0$ and Eqs. (7)–(11) reduce to the equations used in Ref. [4]. For the steady state behaviour of the system we set $\dot{\rho}_{nm}=0$ and Eqs. (7)–(11) reduce to a set of coupled algebraic equations where, after splitting into real and imaginary parts, we obtain a system of 9×9 algebraic equations. These equations can be easily treated in all orders using the symbolic computation package *Mathematica*.

In this paper we are interested in the polarization induced in the $|1\rangle \leftrightarrow |3\rangle$ transition. The polarization ρ_{31} can be expanded in powers of the $|1\rangle \leftrightarrow |3\rangle$ probe field Rabi frequency E as follows [8]

$$\rho_{31} = A(\Omega,\gamma_2,\gamma_3,p,\Delta_2,\Delta_3) + B(\Omega,\gamma_2,\gamma_3,p,\Delta_2,\Delta_3)E, \tag{12}$$

where A is the lowest order non-linear susceptibility. The absorption and dispersion of the medium corresponds to the real and imaginary parts of $\rho_{31} - A \equiv \sigma_{31}$; their behaviour will be investigated for several cases in the following section.

3. Results

3.1. Results with incoherent pumping

Pump mechanisms have been shown to play a very important role in this system. Zhu and Xiao [4] showed that only in the case when incoherent pumping is present, this system can exhibit LWI. We should mention that, as proposed by Wilson et al. [4], the incoherent pump field can be replaced by a coherent pump field which produces favourable results in several cases. However, this approach will not be investigated here. From Eq. (11) in steady state we obtain in our full case

$$\rho_{31} = \frac{iE(\rho_{11}-\rho_{33}) - p\sqrt{\gamma_2\gamma_3}\,\rho_{21} - i\Omega\rho_{32}}{2R+\gamma_3-i\Delta_3}. \tag{13}$$

Here, the first term in the numerator depends on the population inversion and will always give absorption if the other two terms ($p\sqrt{\gamma_2\gamma_3}\,\rho_{21}, i\Omega\rho_{32}$) are absent and no

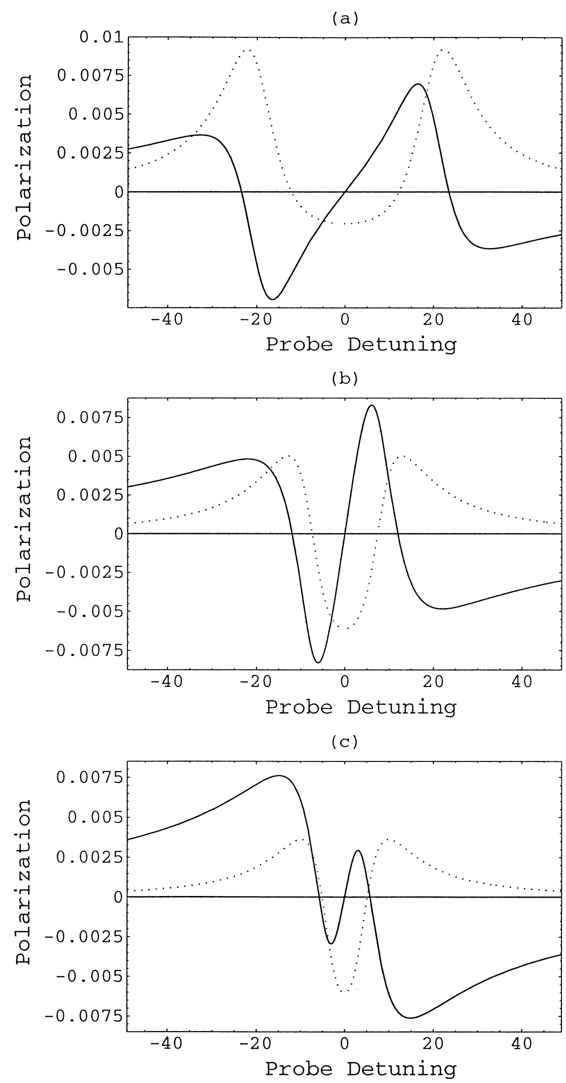

Fig. 2. The steady state results for absorption $\mathrm{Im}(\sigma_{31})/E$ (dotted line) and dispersion $\mathrm{Re}(\sigma_{31})/E$ (solid line) as a function of the probe detuning Δ_3 for parameters $\Delta_2 = 0$, $E_0 = \gamma_3$, $\Omega_0 = 20\gamma_3$, $\gamma_2 = 6\gamma_3$, $R = 2\gamma_3$. (a) $p = 0$, (b) $p = 0.95$ and (c) $p = 0.99$. Δ_3 is measured in units of γ_3.

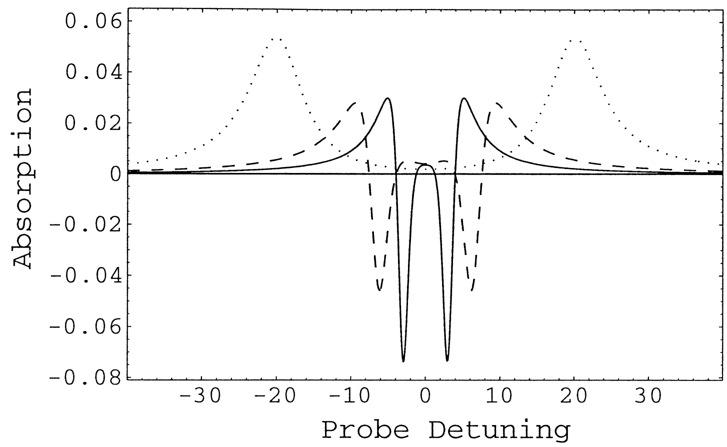

Fig. 3. The steady state results for absorption $\mathrm{Im}(\sigma_{31})/E$ as a function of the probe detuning Δ_3 for the same parameters as in Fig. 2 but with no incoherent pumping ($R=0$). The dotted curve shows results with $p=0$, dashed curve with $p=0.95$ and finally solid curve with $p=0.99$.

inversion exists. The second term ($p\sqrt{\gamma_2\gamma_3}\,\rho_{21}$) depends on the interference created from spontaneous emission and, as we will show later, plays a very important role in the creation of inversionless lasing. The third term ($i\Omega\rho_{32}$) depends on the induced coherence between the two excited states. Initially, we choose $p=0$ and present in Fig. 2(a) the absorption (shown as a dotted curve) and dispersion (shown as a solid curve) of the probe laser, i.e. $\mathrm{Im}(\sigma_{31})/E$ and $\mathrm{Re}(\sigma_{31})/E$ respectively as a function of the probe detuning Δ_3. In our notation, gain will be obtained if $\mathrm{Im}(\sigma_{31})/E<0$. From this figure we can see that gain in the absence of population inversion occurs for a wide region of probe detunings. The fact that no inversion occurs has been checked from a plot of the population inversion (not given here) which demonstrates that $\rho_{33}-\rho_{11}<0$ for the entire gain region. The absence of inversion will also hold for every figure in this subsection where gain is exhibited. Large enhancement of the index of refraction also occurs, as we obtain zero absorption accompanied by large (however, not maximum) dispersion.

We repeat the same calculations as presented above, but for the case that $p\neq 0$. For small values of p the change in the behaviour of the system is small and the results are quite similar to Fig. 2(a). However, for large values of p (which implies large interference of the spontaneous emission channels) the gain in the LWI and the enhancement of the index of refraction increase. In particular for $p=0.95$ [Fig. 2(b)] the gain is three times larger at resonance than previously. Also, the zero absorption for negative values of the probe detuning is accompanied with larger dispersion than previously. In the case of $p=0.99$ [Fig. 2(c)] the gain remains of the same order of magnitude as in Fig. 2(b) but another interesting phenomenon also occurs. Absorption and dispersion disappear almost simultaneously both for positive and negative values of probe detuning out of resonance. This leads to EIT for these values of the probe detuning. This means that both LWI and EIT can be realized at the same time by just tuning the probe laser to the corresponding regions. All of these phenomena are, of course, induced by the coherence created by spontaneous emission interference and for that reason are more pronounced as the interference increases.

3.2. Results without incoherent pumping

In the case that no pumping is present, Zhu and Xiao [4] showed that LWI cannot be realized in this system. For $p=0$ we repeat the same calculations as before, without incoherent pumping, and from the dotted curve of Fig. 3 we conclude that the system does not exhibit gain for any value of probe detuning. However, incomplete EIT is established at $\Delta_3=0$, as can be seen from the dotted lines of Figs. 3 and 4, due to the interference effect of the drive field [the last term of the numerator of Eq. (13)]. The case

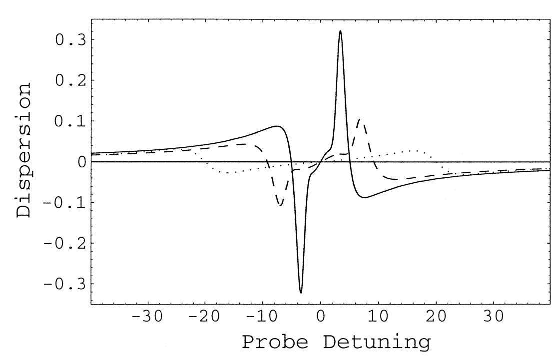

Fig. 4. The steady state results for dispersion $\mathrm{Re}(\sigma_{31})/E$ as a function of the probe detuning Δ_3 for the same parameters as in Fig. 2 but with no incoherent pumping ($R=0$). Dotted curve shows results with $p=0$, dashed curve with $p=0.95$ and finally solid curve with $p=0.99$.

with $p \neq 0$ is far more interesting. The behaviour of the system for small values of p is similar to that for $p = 0$. However, in the case of large values of p, such as $p = 0.95$ (shown as dashed curves in Figs. 3 and 4) on the one hand EIT can be still realized at resonance, but on the other hand in the non-resonant case gain can be created in two symmetric regions centered around zero probe detuning. The gain for lasing realized here, in its maximum value, is approximately eight times larger than the gain in the case when incoherent pumping is present [Fig. 2(b)]. Furthermore, if p is increased to the value $p = 0.99$, as shown by solid curves in Figs. 3 and 4, the gain increases further and becomes approximately twelve times stronger at its maximum value than for the analogous case of incoherent pumping [Fig. 2(c)]. The gain realised here is associated with an unexpected population inversion in the $|3\rangle \leftrightarrow |1\rangle$ transition [13]. So in this case, we obtain lasing *with* inversion. This will be discussed in detail elsewhere. The presence of incoherent pumping leads to less efficient (at least for the maximal values) gain because the necessary induced coherence due to the quantum interference of spontaneous emission will be partially destroyed by the incoherent pumping. Finally, we would like to point out that in both cases with $p \neq 0$, shown in Figs. 3 and 4, the dispersion (Fig. 4) is larger than the absorption (Fig. 3). This leads to the conclusion that enhancement of the index of refraction can also be exhibited by this system at the same time as EIT and lasing with inversion.

4. Conclusions

In this paper we have investigated the effects of coherence created from interference of spontaneous emission from two close lying atomic levels of a V-type atom. In the presence of incoherent pumping, the LWI gain increases with increasing interference. In addition, a transparency can be induced in the medium for specific values of probe detuning. In the absence of incoherent pumping, both EIT and very strong gain can be realized by increasing this interference. At the same time large dispersion, which is accompanied by small absorption is found to exist. In summary, in closed V-type atomic systems the interference in the spontaneous emission from the two closely spaced excited levels can be a useful tool for establishing coherence and can help in the experimental observation of EIT, lasing with or without inversion and enhancement of the index of refraction.

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