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Controlling spontaneous emission in a driven M-type atom by low-frequency coherence

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ABSTRACT

We have studied the spontaneous emission behaviour in a five-level M-type atom driven by two optical fields of high frequencies and a microwave field of low-frequency. In absence of non-orthogonal decaying pathways, due to microwave field induced low-frequency coherence, the present model produces the emission spectrum resembling that of a three-level system controlled by the effect of vacuum induced decay-interference. For particular sets of values of the Rabi frequencies of the resonant coherent fields, the system exhibits quantum interference induced switching effect. By using this model, we have shown that the phenomenon of narrowing can be induced in the emission peaks without any detuning and phase control of the coherent fields. With the increase in the value of the Rabi frequency of the microwave field, this feature will be accompanied by the peak-compression and -repulsion effect. When the coherent fields are far from resonance, the appearance of the single-photon and the two-photon peaks in the emission spectrum can be easily controlled by changing the value of the Rabi frequency of the microwave field. We have shown the appearance of multiple dark regions in the emission line shape for equal as well as unequal decay rates of two emission pathways. Other interesting phenomena like elimination, enhancement and suppression of spectral line are also explored in various resonant and non-resonant cases.

1. Introduction

In the recent years, there has been considerable interest to study the modification of spontaneous emission in multi-level atoms [1–7]. The control of spontaneous emission based on atomic coherence and quantum interference has attracted much attention, because of its potential applications in lasing without inversion [8,9], high-precision spectroscopy and magnetometry [10], transparent high-index material [11], quantum information and computing [12,13]. In three-level folded-type atoms lying in free space, the coherence (named as vacuum induced coherence (VIC)) can be generated by the vacuum-field induced interaction between two adjacent decay channels of non-orthogonal dipole transition moments [14]. Use of this phenomenon of decay-interference in various multilevel schemes leads to the optical effects like probe transparency, gain with, or without population inversions, phase-dependent line shapes [15]. Effect of VIC has been studied in three-level [16] and four-level [17,18] schemes to exhibit the features like spectral narrowing, enhancement and elimination of spectral line, cancellation of fluorescence within the emission line shape. These spectral features can be further controlled on switching into a five-level scheme [19] incorporating the effect of VIC. It has been pointed out that the phenomenon of quantum coherence similar to VIC could be achieved in the dressed state picture of a coherently driven atom [20] without any requirement of non-orthogonality of the dipole moments. Paspalakis et al. [4] has shown how the equivalent effect of VIC can be induced in the emission spectrum of a V-type atom for variation of relative phase between the control and the pump fields acting on the atom. The effect of this field induced quantum interference has been employed to the recent study of spontaneous emission in various four-level [6,7,21–23] and five-level [24] atomic systems to investigate the similar phenomena as produced by the effect of VIC. By considering the usefulness of dynamic control of spontaneous emission without invoking the effect of VIC, we intend to study

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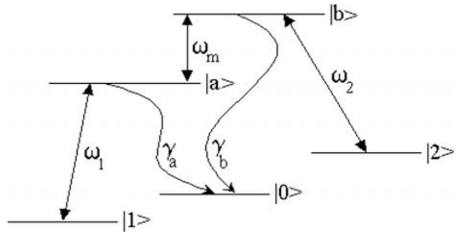

Fig. 1. Schematic diagram of a five-level *M*-type system interacting with three coherent fields designated by their frequencies ω_1, ω_2 and ω_m in the bare-state picture. γ_a and γ_b represent the spontaneous decay rates of the excited levels $|a\rangle$ and $|b\rangle$. The frequency separation between the upper levels is assumed as $2\omega_0$ (not shown in figure).

the emission spectrum in a five-level atom guided by the low-frequency coherence induced by a microwave field.

On following the fabrication of the earlier models based on the open-system approach, in this work we put forward a different five-level atomic system having *M*-type level-configuration (shown in Fig. 1). Our model incorporates two coherent optical fields in the outer transitions. As in the inner transitions the dipole-transition moments corresponding to the spontaneous decay pathways are orthogonal, the phenomenon of VIC cannot occur in the system. In absence of VIC, the upper levels are coupled by a microwave field which can produce strong dynamically induced coherence between them. To realize the effect of this low-frequency coherence in our model, we consider the situation when the atom is initially placed in level $|a\rangle$ (Fig. 1). If no optical fields act in the side wings, then it is obvious that the transition pathway $|a\rangle - |0\rangle$ will interact with the other transition pathway $|a\rangle - |b\rangle - |0\rangle$. As a result of this interaction, there will be dynamically induced coupling between the emission channels. We have shown that unlike the decay-interference effect produced by VIC, the effect of this dynamically induced interaction is constructive in our model. In comparison to the *M*-type models used in the earlier works [13,25] for other purposes, with the inclusion of all coherent fields in our model, the field induced interference effects in two associative Λ-systems of the model are coupled by the low-frequency coherence introduced by the microwave field. In a different perspective of the present model, we observe that the spectral components originated from the Rabi-splitting effect induced by the optical fields will further experience the dynamic stark splitting effect created by the microwave field. This phenomenon has been exploited to obtain multiple-peaked spectrum in our model. Thus, the mechanism of spontaneous emission control underlying this model differs from the process included in the other five-level model prescribed by Li et al. [24].

It should be pointed out that by using this model with the particular choice of parameters involved in the system, one can achieve all the spectral properties as obtained previously in the inverted *Y*-type [22] and a four-level Λ-type schemes [23] as these schemes are coherently embedded in the present model. To clarify this statement we mention that with the exclusion of the transition pathways $|b\rangle - |0\rangle$ and $|b\rangle - |2\rangle$, the present model reduces to the inverted *Y*-type model, whereas for exclusion of the transition pathways $|a\rangle - |0\rangle$ and $|b\rangle - |2\rangle$, the present model can be regarded to be a four-level Λ-type scheme. Similar spectral properties of emission as reported by Li et al. [24] in other five-level model, can also be achievable in the present model at typical dynamic conditions. For proper choice of Rabi frequencies and the detuning parameters of the coherent fields involved in the system, we have found many interesting results which are specific to this model. In comparison to the previous models, to highlight the distinctive features obtained in this model, we briefly discuss the following points.

(i) If the field $E(\omega_1)$ is switched on and the field $E(\omega_2)$ is switched off, the resonant evolution of the spectrum shows sharp quenching of emission at the line centers of two emission channels. Instead of the field $E(\omega_2)$, if the field $E(\omega_1)$ is switched off, in the emission channel $|a\rangle - |0\rangle$, a highly enhanced and sharp peak replaces the dark line arising from the quenching of emission. Thus, if the operating conditions of the optical fields are reversed, the optical property of fluorescence in one emission channel reverses its character in such a manner that we can realize the occurrence of quantum interference induced switching response in our model.

(ii) We have studied the influence of the Rabi frequency of the microwave field on the evolution of eight-peaked spectrum arising from the superposition of the fluorescence due to the pathways $|a\rangle - |0\rangle$ and $|b\rangle - |0\rangle$. For each and every relaxation pathway, we obtain four peaks as a combination of two outer and two inner peaks. At higher values of Rabi frequency of the microwave field, two outer peaks move away from the central position of the emission pathway, while two inner peaks shift towards the central position with simultaneous narrowing induced in their profiles. The more the inner peaks come closer, the more will be the peaks narrowed. This spectral feature arising from the opposite shifting of two sets of peaks in any of two emission channels is attributed to the phenomenon of peak-compression and -repulsion effect which is not similar to that investigated by us in the five-level scheme [19] influenced by the effect of VIC. Moreover, it is interesting to see that the resonant evolution of narrow peaks along with the appearance of the peak shifting effect occurs in the emission spectra without any detuning and phase control of the coupling fields.

(iii) By varying the dynamic conditions in the system interacting with three coherent fields, the number of peaks appearing in the emission spectrum can be easily manipulated. In all of the previous four-level [6,7,21–23] and five-level [24] models, the emission spectra are shown when the driving fields are in resonance or near resonance with the atom. By considering the situation of larger detuning of the coupling fields as required for the generation of distinct multi-photon peak in the spectrum [26], we make an effort to study the emission spectra in a variety of conditions where the optical fields as well as the microwave field are significantly detuned out from the condition of resonance. On using this scheme we have shown the explicit appearance of the single-photon and the two-photon peaks whose intensities and line widths can be efficiently controlled by changing the amplitudes and detunings of the coherent fields. Apart from the spectral features mentioned above, the control of fluorescence in two emission channels at different conditions is also associated with the other phenomena like quenching of emission, spectral line suppression, enhancement and narrowing.

2. Theoretical formulation

We consider a five-level *M*-type atom interacting with three coherent fields $E(\omega_1), E(\omega_2)$ and $E(\omega_m)$ of frequencies ω_1, ω_2 and ω_m, respectively. The coherent fields with the Rabi frequencies R_1, R_2 and R_m resonantly couple the transitions $|a\rangle \leftrightarrow |1\rangle$ of frequency ω_{a1}, $|b\rangle \leftrightarrow |2\rangle$ of frequency ω_{b2} and $|a\rangle \leftrightarrow |b\rangle$ of frequency ω_{ba}, respectively. The system relaxes from the upper levels $|a\rangle$ and $|b\rangle$ to the lower level $|0\rangle$ via the interactions with the same vacuum-field modes. The interaction picture Hamiltonian in the dipole and rotating-wave approximation is given by