Autler-Townes effect in a strongly driven electromagnetically induced transparency resonance

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In this paper we study the nonlinear behavior of an electromagnetically induced transparency (EIT) resonance subject to a coherent driving field. The EIT is associated with a Λ three-level system where two hyperfine levels within an electronic ground state are coupled to a common excited state level by a coupling field and a probe field. In addition there is an radio-frequency (rf) field driving a hyperfine transition within the ground state. The paper contrasts two different situations. In one case the rf-driven transition shares a common level with the probed transition and in the second case it shares a common level with the coupled transition. In both cases the EIT resonance is split into a doublet and the characteristics of the EIT doublet are determined by the strength and frequency of the rf-driving field. The doublet splitting originates from the rf-field induced dynamic Stark effect and has close analogy with the Autler-Townes effect observed in three-level pump-probe spectroscopy study. The situation changes when the rf field is strong and the two cases are very different. One is analogous to two Λ three-level systems with EIT resonance associated with each. The other corresponds to a doubly driven three-level system with rf-field-induced electromagnetically induced absorption resonance. The two situations are modeled using numerical solutions of the relevant equation of motion of density matrix. In addition a physical account of their behaviors is given in terms of a dressed state picture.

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I. INTRODUCTION

When an atomic system is prepared in a coherent superposition state, under suitable conditions, electromagnetically induced transparency (EIT) can be observed where the atomic coherence cancels or reduces absorption [1]. The atomic coherence can be induced by electromagnetic fields driving atomic transitions and a three-level atom interacting with two laser fields is the simplest situation for investigating EIT resonance. The early studies relevant to this situation include measurements by groups in Pisa [2] and in Rochester [3], where the atomic coherence effect was observed as a decrease in fluorescence intensity and terms such as “dark resonance” and “coherent population trapping” were introduced. EIT resonance was subsequently measured in absorption by a group at Stanford [4] and since then there has been growing interest in the topic [5–8]. This interest is due not only to the fascinating physics involving quantum interference but also to the fact that there are many potential applications such as lasing without inversion [9–13], slow light and quantum information storage [14–16].

In this paper we wish to address a more complex situation and that is how an EIT resonance itself responds to a coherent driving field. The specific situation we investigate is an EIT resonance associated with a Λ three-level system consisting of an upper level and two lower hyperfine levels. The upper level is coupled to the two lower hyperfine levels by a coupling field and a probe field. We assume that there is an additional low lying hyperfine level and the interest is in applying a radio-frequency (rf) field resonance with a hyperfine transition between this additional level and one of the two lower levels of the original Λ three-level system. This additional rf field provides important additional flexibility for adjusting resonance frequency, depth and dispersion of the EIT. The present work is motivated by recent experimental study where a sharp EIT resonance was observed in a Λ three-level system consisting of the spin-levels of a nitrogen-vacancy color center in diamond [8] and the splitting of this EIT resonance was observed when one of the hyperfine transitions was driven as described above [17]. The observation was interpreted as dynamic Stark splitting of the EIT resonance similar to an Autler-Townes splitting [18] of an atomic transition. Such effects are of great interest and suggest new possibilities for manipulating and controlling EIT resonances. In this paper we present a theoretical study of the experimental observations [19]. The experimental situation is more complicated involving multiple levels, wave function mixing due to level anticrossing and optical pumping associated with the Raman-Heterodyne detection technique. A theoretical treatment including all the details, if not impossible, will surely cloud the analysis of the underlying physics of the EIT splitting. Therefore, we prefer in the theoretical treatments to present a calculation for a simple model that can account for the major characteristics of the observed effect. The detailed account of the experimental data can be obtained by making allowance for multiple levels and inhomogeneous broadening and will be presented elsewhere [20].

There have been numerous works examining the effect of an additional coherent field on an EIT resonance. These works extend the study of EIT to a more complex configuration and provide a way of manipulating the EIT resonance. Broadly speaking, these studies can be grouped into two types. In one case the additional field is a laser field driving an optical transition in various configurations, such as double

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Λ, Π, and tripod schemes [21–24] and in the second case the additional field is a rf (or microwave) field driving a hyperfine transition [17,25,26]. Of particular interest is the second case, as the rf (or microwave) source is more readily available and easier to control in comparison with an extra laser field, and this is the situation considered in this paper. There is another relevant experimental observation reported recently using cold ^{87}Rb atoms where the magnetic dipole transition within the ground state hyperfine levels lies in the microwave spectral region [25]. However, the maximum power of the microwave field is limited due to experimental difficulties and only a single experimental trace is presented. As the microwave field is not strong enough to give a well separated doublet, the microwave field appears to only induce a sharp absorption peak in the EIT resonance and this feature is discussed in terms of multiphoton quantum interference [25]. Other relevant study includes the observation of sharp electromagnetically induced absorption within the EIT window and interaction of dark resonances due to a microwave field driving a magnetic dipole transition [26].

II. THEORY

In this work we consider a four-level atom with a triplet ground state $|1\rangle$, $|2\rangle$, and $|3\rangle$ and an excited state $|4\rangle$ interacting with two lasers and one rf field as shown in Fig. 1. A laser of fixed frequency (ω_c) interacts with the $|3\rangle\rightarrow|4\rangle$ transition and is referred to as the coupling field. The absorption spectrum is obtained by scanning the frequency (ω_p) of the second laser, referred to as the probe field, through the $|1\rangle\rightarrow|4\rangle$ transition. The Rabi frequencies of the coupling field and probe field are denoted as Ω_c and Ω_p, respectively. This forms a Λ three-level system and it is well known that the presence of both coupling and probe fields induces a two-photon coherence between the $|1\rangle\rightarrow|3\rangle$ hyperfine transition and leads to a reduced absorption of the probe field, known as EIT. The new aspect of the present work is the introduction of an extra coherent field, which drives a hyperfine transition between one of the two lower levels of the above Λ three-level system to another hyperfine level $|2\rangle$. This additional level $|2\rangle$ is also in the ground state hyperfine structure therefore, the extra field is an rf field with a frequency $\omega_{\rm rf}$ and a Rabi frequency $\Omega_{\rm rf}$. We consider two situations: (a) the rf field drives the $|1\rangle\rightarrow|2\rangle$ transition sharing a common level with the probed transition [see Fig. 1(a)] and (b) the rf field drives the $|2\rangle\rightarrow|3\rangle$ transition sharing a common level with the coupled transition [see Fig. 1(b)].

For the case where the rf-driven transition shares a common level with the probed transition as shown in Fig. 1(a), the density matrix equation of motion can be written as

$$\dot{\rho}_{11}=i\chi_{rf}(\rho_{21}-\rho_{12})+i\chi_p(\rho_{41}-\rho_{14})+W_{41}\rho_{44}+\Gamma(\rho_{22}-\rho_{11})+\Gamma(\rho_{33}-\rho_{11}), \tag{1a}$$

$$\dot{\rho}_{22}=-i\chi_{rf}(\rho_{21}-\rho_{12})+W_{42}\rho_{44}-\Gamma(\rho_{22}-\rho_{11})+\Gamma(\rho_{33}-\rho_{22}), \tag{1b}$$

$$\dot{\rho}_{33}=i\chi_c(\rho_{43}-\rho_{34})+W_{43}\rho_{44}-\Gamma(\rho_{33}-\rho_{22})-\Gamma(\rho_{33}-\rho_{11}), \tag{1c}$$

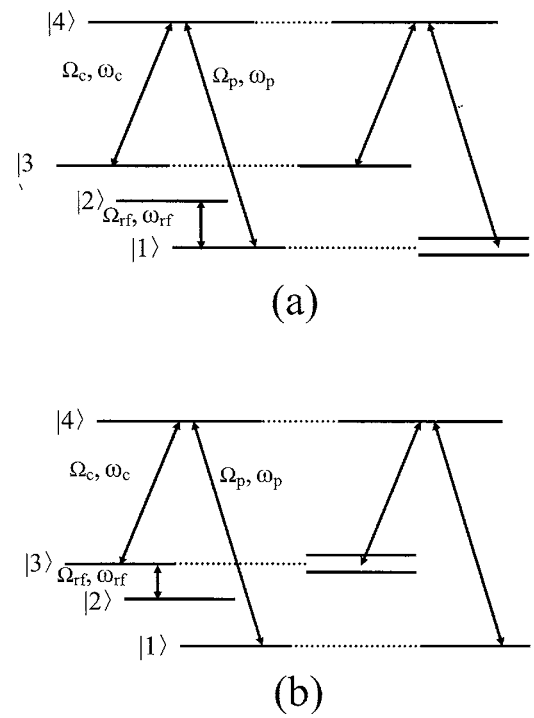

FIG. 1. Energy level scheme for case (a) and (b). In the bare state picture, a coupling laser (frequency ω_c and Rabi frequency Ω_c) interacts with the $|3\rangle\rightarrow|4\rangle$ transition and a probe laser (frequency ω_p and Rabi frequency Ω_p) interacts with the $|1\rangle\rightarrow|4\rangle$ transition, forming a Λ three-level system and giving rise to an EIT resonance. An rf field (frequency $\omega_{\rm rf}$ and Rabi frequency $\Omega_{\rm rf}$) drives a hyperfine transition and splits the EIT resonance. Two situations are considered: (a) the rf-driven transition shares a common level with the probed transition and (b) the rf-driven transition shares a common level with the coupled transition. In the dressed state picture, the EIT double splitting occurs due to the fact that there are two occasions where the coupling and probe laser satisfy a two-photon resonance condition and give rise to two EIT resonances.

$$\dot{\rho}_{44}=-i\chi_p(\rho_{41}-\rho_{14})-i\chi_c(\rho_{43}-\rho_{34})-W_4\rho_{44}, \tag{1d}$$

$$\dot{\rho}_{21}=d_{21}\rho_{21}-i\chi_{rf}(\rho_{22}-\rho_{11})-i\chi_p\rho_{24}, \tag{1e}$$

$$\dot{\rho}_{31}=d_{31}\rho_{31}+i\chi_c\rho_{41}-i\chi_{rf}\rho_{32}-i\chi_p\rho_{34}, \tag{1f}$$

$$\dot{\rho}_{32}=d_{32}\rho_{32}+i\chi_c\rho_{42}-i\chi_{rf}\rho_{31}, \tag{1g}$$

$$\dot{\rho}_{41}=d_{41}\rho_{41}-i\chi_p(\rho_{44}-\rho_{11})+i\chi_c\rho_{31}-i\chi_{rf}\rho_{42}, \tag{1h}$$

$$\dot{\rho}_{42}=d_{42}\rho_{42}+i\chi_p\rho_{12}+i\chi_c\rho_{32}-i\chi_{rf}\rho_{41}, \tag{1i}$$

$$\dot{\rho}_{43}=d_{43}\rho_{43}+i\chi_p\rho_{13}-i\chi_c(\rho_{44}-\rho_{33}), \tag{1j}$$

where the parameters χ_c, χ_p, and $\chi_{\rm rf}$ are introduced for convenience and are equal to half the Rabi frequencies ($\chi_c=\Omega_c/2$, $\chi_p=\Omega_p/2$, and $\chi_{\rm rf}=\Omega_{\rm rf}/2$). $d_{ij}=i\delta_{ij}-\gamma_{ij}$ are complex detunings and the detunings δ_{ij} are given by

$$\delta_{21}=\omega_{rf}-\omega_{21},\quad \delta_{41}=\omega_p-\omega_{41},\quad \delta_{43}=\omega_c-\omega_{43},$$

$$\delta_{31}=\delta_{41}-\delta_{43},\quad \delta_{42}=\delta_{41}-\delta_{21},\quad \delta_{32}=\delta_{41}-\delta_{43}-\delta_{21}.$$

We denote by W_{4i} the population relaxation rate from excited state level $|4\rangle$ to ground state level $|i\rangle$ ($i=1, 2, 3$) and $W_4 = W_{41}+W_{42}+W_{43}$. We denote by Γ the population relaxation rate between the hyperfine levels and for simplicity we have assumed the population relaxation rates between different hyperfine levels have the same value. The coherence relaxation rate between level $|i\rangle$ and $|j\rangle$ is denoted by γ_{ij}. The absorption signal of the probe laser ω_p probing the $|1\rangle \rightarrow |4\rangle$ transition is proportional to the imaginary part of ρ_{41}. As we are interested in effects of the rf driving field on the EIT resonance, it is sufficient to consider a weak probe field case and the first order steady state solution for ρ_{41} can be written as

$$\rho_{41}^{(1)}=\frac{\chi_p}{D}[i(d_{31}d_{32}d_{42}+\chi_c^2 d_{31}+\chi_{\rm rf}^2 d_{42})(\rho_{44}^{(0)}-\rho_{11}^{(0)})+\chi_{\rm rf}(d_{31}d_{32}+\chi_{\rm rf}^2-\chi_c^2)\rho_{12}^{(0)}+\chi_c(d_{32}d_{42}+\chi_c^2-\chi_{\rm rf}^2)\rho_{34}^{(0)}], \quad (2)$$

where

$$D=d_{31}d_{32}d_{41}d_{42}+\chi_c^2(d_{31}d_{41}+d_{32}d_{42})+\chi_{rf}^2(d_{31}d_{32}+d_{41}d_{42})+(\chi_{rf}^2-\chi_c^2)^2.$$

The zero order solution is given in Appendix A.

For the case where the rf-driven transition shares a common level with the coupled transition as shown in Fig. 1(b), the density matrix equation of motion can be written as

$$\dot{\rho}_{11}=i\chi_p(\rho_{41}-\rho_{14})+W_{41}\rho_{44}+\Gamma(\rho_{22}-\rho_{11})+\Gamma(\rho_{33}-\rho_{11}), \quad (3a)$$

$$\dot{\rho}_{22}=i\chi_{rf}(\rho_{32}-\rho_{23})+W_{42}\rho_{44}-\Gamma(\rho_{22}-\rho_{11})+\Gamma(\rho_{33}-\rho_{22}), \quad (3b)$$

$$\dot{\rho}_{33}=-i\chi_{rf}(\rho_{32}-\rho_{23})+i\chi_c(\rho_{43}-\rho_{34})+W_{43}\rho_{44}-\Gamma(\rho_{33}-\rho_{22})-\Gamma(\rho_{33}-\rho_{11}), \quad (3c)$$

$$\dot{\rho}_{44}=-i\chi_p(\rho_{41}-\rho_{14})-i\chi_c(\rho_{43}-\rho_{34})-W_4\rho_{44}, \quad (3d)$$

$$\dot{\rho}_{21}=d_{21}\rho_{21}+i\chi_{rf}\rho_{31}-i\chi_p\rho_{24}, \quad (3e)$$

$$\dot{\rho}_{31}=d_{31}\rho_{31}+i\chi_c\rho_{41}+i\chi_{rf}\rho_{21}-i\chi_p\rho_{34}, \quad (3f)$$

$$\dot{\rho}_{32}=d_{32}\rho_{32}+i\chi_c\rho_{42}-i\chi_{rf}(\rho_{33}-\rho_{22}), \quad (3g)$$

$$\dot{\rho}_{41}=d_{41}\rho_{41}-i\chi_p(\rho_{44}-\rho_{11})+i\chi_c\rho_{31}, \quad (3h)$$

$$\dot{\rho}_{42}=d_{42}\rho_{42}+i\chi_p\rho_{12}+i\chi_c\rho_{32}-i\chi_{rf}\rho_{43}, \quad (3i)$$

$$\dot{\rho}_{43}=d_{43}\rho_{43}+i\chi_p\rho_{13}-i\chi_{rf}\rho_{42}-i\chi_c(\rho_{44}-\rho_{33}). \quad (3j)$$

The notations used here have the same definitions as in case (a) with the exception of the definitions of the detunings δ_{ij} which are given by

$$\delta_{41}=\omega_p-\omega_{41},\quad \delta_{43}=\omega_c-\omega_{43},\quad \delta_{32}=\omega_{rf}-\omega_{32},$$

$$\delta_{31}=\delta_{41}-\delta_{43}\quad \delta_{42}=\delta_{43}+\delta_{32},\quad \delta_{21}=\delta_{41}-\delta_{32}-\delta_{43}.$$

The first order steady state solution for ρ_{41} can be written as

$$\rho_{41}^{(1)}=\chi_p\frac{i(d_{21}d_{31}+\chi_{rf}^2)(\rho_{44}^{(0)}-\rho_{11}^{(0)})-i\chi_c\chi_{rf}\rho_{24}^{(0)}+\chi_c d_{21}\rho_{34}^{(0)}}{d_{21}d_{31}d_{41}+\chi_c^2 d_{21}+\chi_{rf}^2 d_{41}}, \quad (4)$$

where the zero order solution is given in Appendix B.

Having obtained the above solutions, the absorption profile of the probe field ω_p probing the $|1\rangle \rightarrow |4\rangle$ transition can be obtained by plotting $\mathrm{Im}[\rho_{41}^{(1)}]$ as a function of probe detuning $\delta_{41}=\omega_p-\omega_{41}$. In the following section we present the results of numerical calculations.

III. RESULTS AND DISCUSSIONS

In this section we present the results of the numerical calculation for two configurations shown in Figs. 1(a) and 1(b). They are referred to as case (a) where the rf-driven transition shares a common level with the probed transition and case (b) where the rf-driven transition shares a common level with the coupled transition. To simplify the presentation, the parameters are normalized to the excited state decay rate W_4 and the following simplifications are made. The branching ratios of the population decay from level $|4\rangle$ to different ground state sublevels $|i\rangle$ ($i=1,2,3$) may have different values and this will affect the optical pumping process, and hence the absorption signal strength. However, this will not change the characteristics of the rf-induced EIT splitting pattern and for simplicity we assume $W_{41}=W_{42}=W_{43}=W_4/3$. In normal physical systems the hyperfine transition decay rates are much smaller than that of the excited state, and in this paper a ratio of $\Gamma/W_4=10^{-4}$ is used. The Rabi frequencies (Ω_p, Ω_c, and $\Omega_{\rm rf}$) and the detunings δ_{ij} are also normalized to W_4.

The probe field absorption profiles are shown in Fig. 2 for the following situations: (i) in the absence of both coupling field and rf driving field ($\Omega_c=\Omega_{\rm rf}=0$), (ii) in the presence of a coupling field only ($\Omega_c=0.2, \Omega_{\rm rf}=0$), and (iii) in the presence of both coupling field and rf driving field ($\Omega_c=\Omega_{\rm rf}=0.2$). Curve (i) corresponds to a normal absorption profile and is presented for the purpose of comparison. With only coupling field applied, case (a) and (b) become identical and correspond to a Λ three-level configuration. The result is shown in curve (ii) and it can be seen that a resonant coupling field induces an EIT resonance in the center of the absorption profile. The overall absorption strength also changes as a result of the optical pumping. When an rf field is applied, the most interesting effect is the doublet splitting of the EIT resonance as shown in curve (iii). Figure 3 shows how this EIT splitting varies as a function of the strength of the rf field. It splits linearly with the strength of the rf field, and the magnitude of the splitting is equal to the rf field Rabi frequency ($\Omega_{\rm rf}$). It is well known that a strong driving field can significantly modify the spectral properties of a real transition between two atomic levels, and the doublet splitting of an absorption line by a strong driving field is known as dynamic Stark effect or Autler-Townes effect [18]. There is a

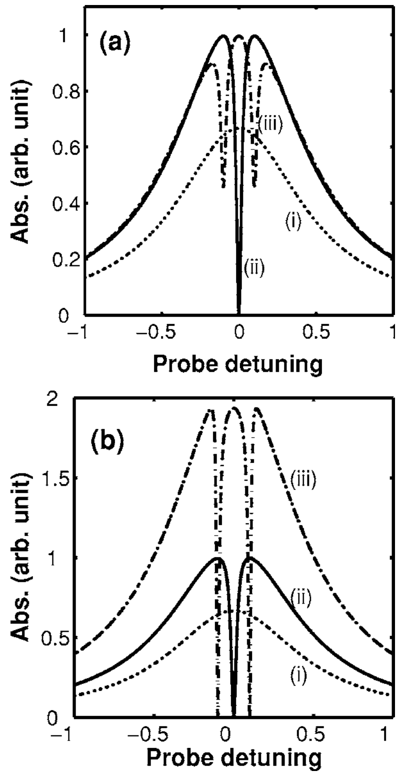

FIG. 2. Absorption of the probe laser. Curve (i) gives a normal absorption spectrum when both coupling field and rf field are absent ($\Omega_c=\Omega_{rf}=0$). Curve (ii) shows an EIT resonance when a coupling field is applied resonantly with the $|3\rangle \rightarrow |4\rangle$ transition ($\Omega_c=0.2$). Curve (iii) shows splitting of an EIT resonance when both coupling field and rf field are applied ($\Omega_c=\Omega_{rf}=0.2$). In case (a) the rf field is resonant with the $|1\rangle \rightarrow |2\rangle$ transition and in case (b) the rf field is resonant with the $|2\rangle \rightarrow |3\rangle$ transition. The probe detuning has been normalized to W_4.

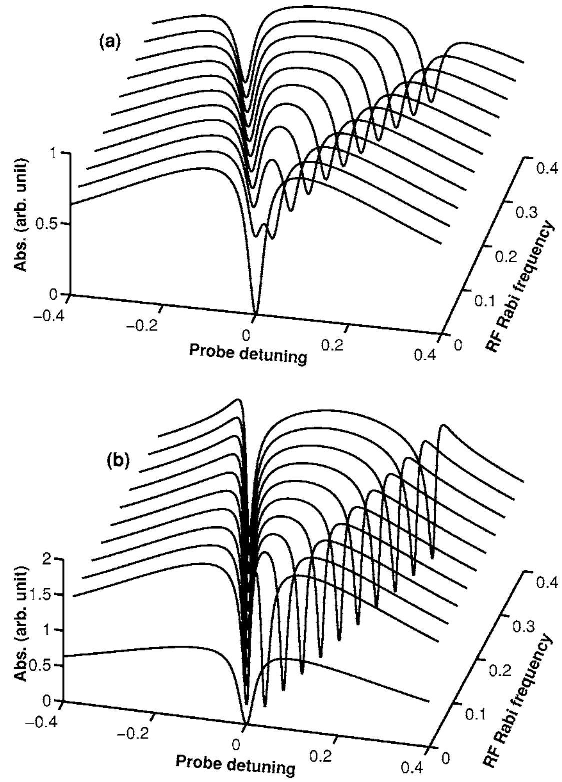

FIG. 3. Absorption of the probe laser showing a linear EIT splitting as a function of rf field Rabi frequency. The rf field is resonant with the $|1\rangle \rightarrow |2\rangle$ transition for case (a) and with the $|2\rangle \rightarrow |3\rangle$ transition for case (b). The coupling field is resonant with the $|3\rangle \rightarrow |4\rangle$ transition and has a Rabi frequency $\Omega_c=0.2$. The probe detuning and rf Rabi frequency have been normalized to W_4.

one-to-one correlation between the splitting of an EIT resonance and the dynamic Stark splitting of a strongly driven transition. Thus it is straightforward to relate the EIT splitting to the dynamic Stark effect and in this paper this EIT splitting is referred to as EIT Autler-Townes splitting.

When treating a strong photon-atom interaction, it is often convenient to introduce the dressed state picture [27,28], which allows us to gain more physical insight. In a dressed state picture a two-level atom and a driving field are treated as a coupled "atom+field" system and the energy levels of the dressed state form a ladder of doublets. The Autler-Townes doublet can be viewed as arising from transitions between dressed state doublets to a third level. For the parameters used in the present study, the coupling field is weak with respect to the optical linewidth whereas the rf field is strong with respect to the hyperfine linewidth. The dressed state can be obtained by simply considering the two hyperfine levels and the rf field as a coupled "atom+field" system, and resultant dressed state levels are shown in Fig. 1. For case (a) the dressed state doublet is associated with the lower level of the probed transition while for case (b) the dressed state doublet is associated with the lower level of the coupled transition. EIT resonances occur when the coupling field and the probe field satisfy a two-photon resonance condition. In both cases there are two occasions satisfying this condition giving rise to EIT doublet.

It is also interesting to note that although there is a common splitting of the EIT resonance for both cases, the effect of the rf field on the EIT resonance exhibits a noticeable difference in terms of the depth of the EIT features, their line shapes as well as the overall absorption. In case (a), the level splitting occurs in the lower level of the probed transition and consequently two transitions are probed. Therefore there are effectively two overlapping Λ three-level systems resulting in two EIT resonances having approximately half transparency. Each EIT feature corresponds to a resonant coupling case and therefore the features have symmetric spectral-hole-like line shape. In case (b), the level splitting occurs in the lower level of the coupled transition. The coupling field interacts with two transitions simultaneously and gives rise to two EIT resonances. The level splitting also introduces a detuning in two coupled transitions, and as rf field strength is increased there is an increased asymmetry in both EIT component. There is also a difference in the overall absorption due to the fact that the optical pumping process is influenced differently by the rf field for case (a) and (b). Without the rf field, the coupling field pumps population out of level $|3\rangle$ and distributes populations equally between sublevels $|1\rangle$ and $|2\rangle$. When an rf field is applied on the $|1\rangle \rightarrow |2\rangle$ transition, there is little change in the populations and

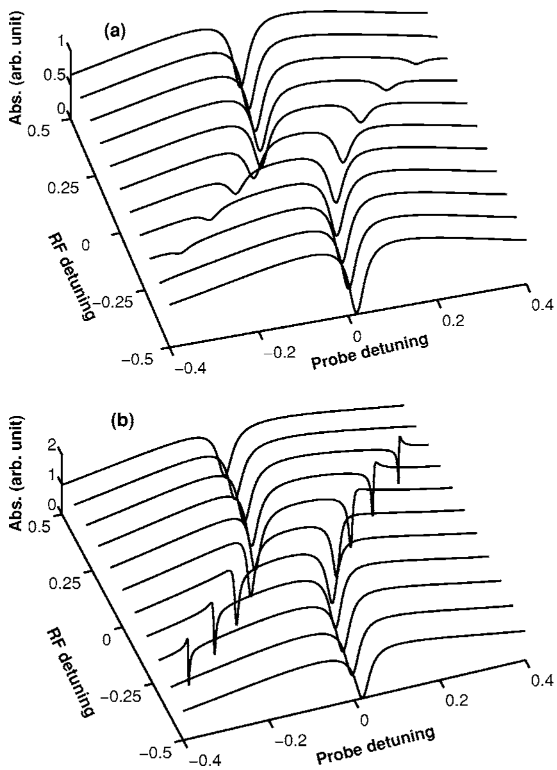

FIG. 4. Absorption of the probe laser showing EIT splitting as a function of rf field detuning for case (a) and (b). The coupling field is resonant with the $|3\rangle \rightarrow |4\rangle$ transition and has a Rabi frequency $\Omega_c = 0.2$. The rf field has a Rabi frequency $\Omega_{rf} = 0.2$. The probe detuning and rf detuning have been normalized to W_4.

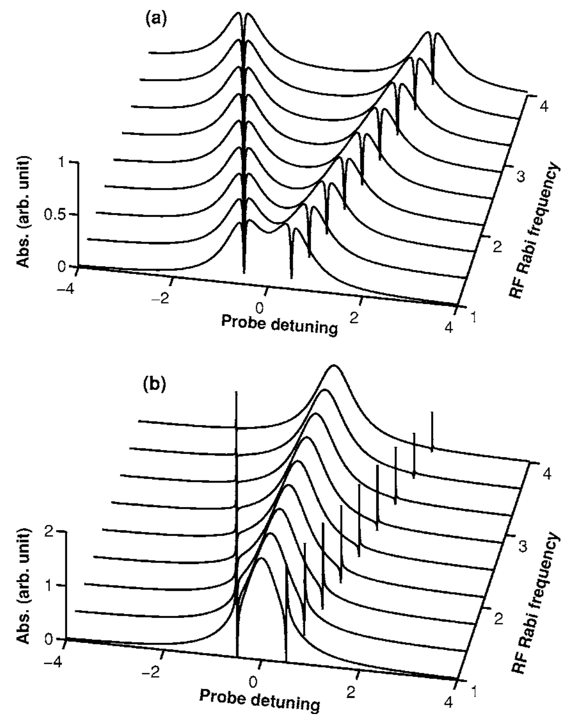

FIG. 5. Absorption of the probe laser for the situation where the rf field Rabi frequency is comparable to or larger than the optical linewidth. The rf field is resonant with the $|1\rangle \rightarrow |2\rangle$ transition for case (a) and with the $|2\rangle \rightarrow |3\rangle$ transition for case (b). The coupling field is resonant with the $|3\rangle \rightarrow |4\rangle$ transition and has a Rabi frequency $\Omega_c = 0.2$. The probe detuning and rf Rabi frequency have been normalized to W_4.

hence little change in the overall absorption. When the rf field is applied to the $|2\rangle \rightarrow |3\rangle$ transition, the rf field repumps populations from level $|2\rangle$ to level $|3\rangle$ and the combined effect of the coupling field and rf field is to transfer population to level $|1\rangle$ resulting in an increase in the overall absorption.

Figure 4 shows the effect of rf field detuning. As can be seen, the rf field detuning affects both the relative intensity and the spectral position of the EIT doublet. At large rf field detuning there is only one dominant EIT component slightly shifted away from the original position. As the rf field frequency is tuned toward the hyperfine resonance, this dominant EIT resonance loses its intensity and is shifted away from the center, reminiscent of the light shift effect [29]. At the same time the other EIT component gains intensity and moves towards the original position. When the rf field is resonant with the hyperfine transition, two EIT components become symmetric in terms of relative intensity and spectral position. As expected, the overall behavior is symmetric, when the rf field frequency continues to be tuned through the hyperfine transition. This behavior is a direct consequence of the anti-crossing behavior of the ground state levels dressed with the rf photons.

The characteristic of the EIT resonance subject to an rf driving field has a parallel in a strongly driven two-level atom. Being induced by hyperfine coherence and associated with quantum interference, the fundamental processes involved are very different and yet the interesting similarity in the nonlinear response to a strong driving field suggests that a coherent field can modify an EIT resonance in a similar way in which it modifies an atomic transition. The configurations considered here can be found in many real atomic systems and thus the results have important implication for the practical applications of EIT. For example, an rf field can be used to open more than one EIT window. Also, by controlling the rf field intensity and detuning we can continuously vary the spectral position of the EIT window, thus performing fine frequency tuning of the EIT resonance.

Up to now our discussion has been restricted to situations where the coupling field intensity used in the calculation is weak with respect to the optical linewidth, which ensures a narrow EIT resonance. The rf field strength is strong with respect to the hyperfine linewidth to give an EIT splitting but weak with respect to the optical linewidth so that the dressed state doublet structure can be viewed as embedded within the optical transition. However our solutions are applicable to arbitrarily strong coupling fields and rf fields. For the completeness of the discussion, in what follows we will present results for arbitrarily strong coupling fields and rf fields.

Figure 5 illustrates the case when the rf field Rabi frequency is large with respect to the optical linewidth under the condition that the coupling field as well as the rf field are resonant. It is seen that previously similar EIT doublet splittings are now very different for case (a) and (b). In case (a), when the rf field Rabi frequency is comparable to or larger than the optical linewidth, the dynamic Stark splitting asso-

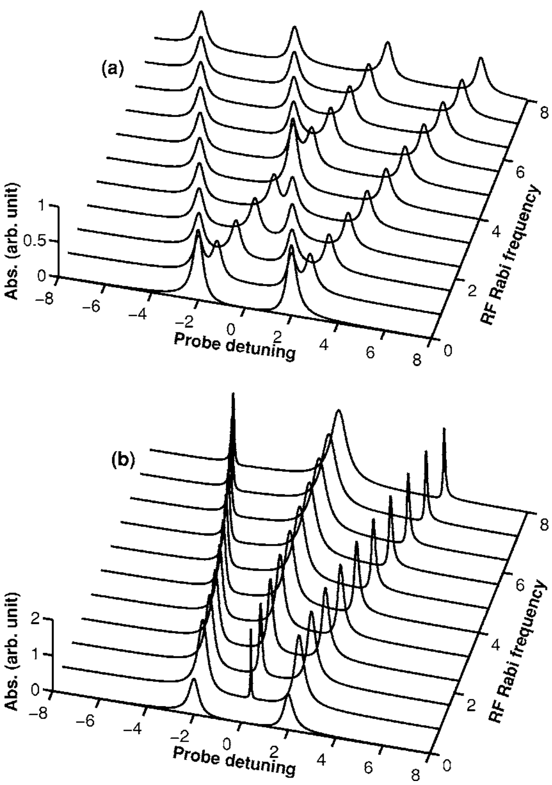

FIG. 6. Absorption of the probe laser for the situation where both coupling field and rf field Rabi frequencies are comparable to or larger than the optical linewidth. The rf field is resonant with the $|1\rangle \rightarrow |2\rangle$ transition for case (a) and with the $|2\rangle \rightarrow |3\rangle$ transition for case (b). The coupling field is resonant with the $|3\rangle \rightarrow |4\rangle$ transition and has the Rabi frequency $\Omega_c = 4$. The probe detuning and rf Rabi frequency have been normalized to W_4.

ciated with the rf field is large enough to give rise to two absorption peaks. This doublet is in fact just an example of the Autler-Townes effect. Meanwhile the levels associated with the coupling field are unaffected by the rf field, and thus the coupling field remains in a resonant situation. This leads to an EIT resonance in the center of each Autler-Townes component. Whereas in case (b), the dynamic Stark splitting is associated with the coupled transition, as the rf Rabi strength increases, the detunings between the coupling field and the two dressed state transitions also increase. This results in a change-over from two electromagnetically induced transparency (EIT) features to two sharp electromagnetically induced absorption (EIA) features.

Finally, we present results for the situation where the coupling field is also strong, that is, the coupling field Rabi frequency is also comparable to or larger than the optical linewidth. Figures 6(a) and 6(b) shows the absorption responses for case (a) and (b), respectively. In both cases the sharp EIT resonance is power broadened and evolves into an Autler-Townes doublet. In case (a), the effect of the rf field is seen to cause a further splitting in each of the dynamic Stark components and gives rise to a four peak absorption profile. As the coupling field and the rf field drive two separate transitions, there are two independent driven two-level systems. In a simplified dressed state description it can be considered that the coupling field gives rise to a splitting of the upper level whereas the rf field causes a splitting of the lowest sublevel. The transitions between these two dressed state doublets lead to a four line pattern spectrum as shown in Fig. 6(a). The behavior when the rf field drives a transition sharing a common level with the coupled transition is very different as shown in Fig. 6(b). In this situation the rf driving field induces a new absorption component at the center of the EIT window, which is similar to that discussed in Ref. [30] and is referred to as absorption within an EIT window. When the rf field Rabi frequency is smaller than that of the coupling field, this new spectral component has a very narrow linewidth corresponding to the hyperfine transition linewidth and the two original Autler-Townes features have a linewidth corresponding to the optical linewidth. As the rf field intensity increases, the central component becomes power broadened and approaches the optical linewidth while the two original Autler-Townes components become narrower and approach the hyperfine transition linewidth, similar to the situation discussed in Refs. [21,31]. The dressed state levels of such a doubly driven three-level atom form a triplet. This results in a three line absorption profile [31].

IV. CONCLUSIONS

In this paper we have presented a theoretical study of the nonlinear behavior of an EIT resonance subject to an rf driving field. This is demonstrated using an EIT resonance associated with a Λ three-level atom, and two different configurations are considered where the rf-driven transition shares a common level with either the probed or coupled transition. With modest rf field strengths both cases exhibit a splitting and frequency shift of the EIT resonance reminiscent of an Autler-Townes splitting for a driven two-level atom. Being induced by hyperfine coherence and associated with quantum interference, the processes involved are different and yet the interesting similarity shows that a coherent driving field can modify the properties of an EIT resonance in a similar way that it modifies the properties of an atomic transition. Both configurations can be found in many real atomic systems and thus the results have practical implication for the potential applications of EIT. For example, an rf driving field can be used to open more than one EIT window and by controlling the rf driving field intensity and frequency we can continuously vary the spectral position of the EIT window, thus performing EIT frequency tuning. The two cases, although similar at modest rf field strengths, become very different at high rf field strengths. The differences are illustrated by numerical calculation and explained in terms of a dressed state model. In the strong fields limit, one configuration corresponds to two independent driven two-level systems and the other corresponds to a doubly driven three-level system.

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APPENDIX A: ZERO ORDER SOLUTION FOR CONFIGURATION WHERE THE rf-DRIVEN TRANSITION SHARES A COMMON LEVEL WITH THE PROBED TRANSITION AS SHOWN IN FIG. 1(a)

To zero order of χ_p, the steady state solution can be obtained by letting $\chi_p=0$ in Eqs. (1), and the solution can be written as

$$\rho_{31}^{(0)}=\rho_{32}^{(0)}=\rho_{41}^{(0)}=\rho_{42}^{(0)}=0, \tag{A1}$$

$$\rho_{21}^{(0)}=\frac{i\chi_{rf}}{d_{21}}(\rho_{22}^{(0)}-\rho_{11}^{(0)}), \tag{A2}$$

$$\rho_{43}^{(0)}=\frac{i\chi_{c}}{d_{43}}(\rho_{44}^{(0)}-\rho_{33}^{(0)}), \tag{A3}$$

$$\rho_{11}^{(0)}=\frac{b(W_{42}-\Gamma)(\Gamma-a)+b(W_{41}-\Gamma)(2\Gamma-a)-\Gamma(2b-W_4)(2a-3\Gamma)}{(2a-3\Gamma)[3W_4\Gamma-b(W_{41}+W_{42})-4b\Gamma]}, \tag{A4}$$

$$\rho_{22}^{(0)}=\frac{b(W_{41}-\Gamma)(\Gamma-a)+b(W_{42}-\Gamma)(2\Gamma-a)-\Gamma(2b-W_4)(2a-3\Gamma)}{(2a-3\Gamma)[3W_4\Gamma-b(W_{41}+W_{42})-4b\Gamma]}, \tag{A5}$$

$$\rho_{44}^{(0)}=\frac{-b\Gamma}{3W_4\Gamma-b(W_{41}+W_{42})-4b\Gamma}, \tag{A6}$$

$$\rho_{33}^{(0)}=1-\rho_{11}^{(0)}-\rho_{22}^{(0)}-\rho_{44}^{(0)}, \tag{A7}$$

where $a=(\chi_{\mathrm{rf}}^2/d_{21}d_{21}^*)(d_{21}+d_{21}^*)$ and $b=(\chi_c^2/d_{43}d_{43}^*)(d_{43}+d_{43}^*)$.

APPENDIX B: ZERO-ORDER SOLUTION FOR CONFIGURATION WHERE THE rf-DRIVEN TRANSITION SHARES A COMMON LEVEL WITH THE COUPLED TRANSITION AS SHOWN IN FIG. 1(b)

The zero order solution is obtained by letting $\chi_p=0$ in Eqs. (3) and can be written as

$$\rho_{31}^{(0)}=\rho_{21}^{(0)}=\rho_{41}^{(0)}=0, \tag{B1}$$

$$\rho_{22}^{(0)}=\frac{\Gamma}{M}[4\chi_c^2\mathrm{Re}\,Y_{43}(2\chi_{rf}^2\mathrm{Re}\,Z_{32}+\Gamma-W_{42})+(2\chi_c^2\mathrm{Re}\,Z_{43}-W_4)(3\Gamma-4\chi_{rf}^2\mathrm{Re}\,Y_{32})-2\chi_c^2\mathrm{Re}\,Y_{43}(2\Gamma+W_{41})], \tag{B2}$$

$$\rho_{33}^{(0)}=\frac{\Gamma}{M}[(2\chi_c^2\mathrm{Re}\,Z_{43}-W_4)(4\chi_{rf}^2\mathrm{Re}\,X_{32}+3\Gamma)+2\chi_c^2\mathrm{Re}\,X_{43}(2\Gamma+W_{41})-4\chi_c^2\mathrm{Re}\,X_{43}(2\chi_{rf}^2\mathrm{Re}\,Z_{32}+\Gamma-W_{42})], \tag{B3}$$

$$\rho_{44}^{(0)}=\frac{\Gamma}{M}[6\Gamma\chi_c^2(\mathrm{Re}\,Y_{43}-\mathrm{Re}\,X_{43})+8\chi_c^2\chi_{rf}^2\mathrm{Re}\,X_{43}\mathrm{Re}\,Y_{32}-4\chi_c^2\mathrm{Re}\,Y_{43}(2\chi_{rf}^2\mathrm{Re}\,X_{32}+3\Gamma)], \tag{B4}$$

$$\rho_{11}^{(0)}=1-\rho_{22}^{(0)}-\rho_{33}^{(0)}-\rho_{44}^{(0)}, \tag{B5}$$

$$\rho_{32}^{(0)}=i\chi_{rf}(X_{32}\rho_{22}^{(0)}+Y_{32}\rho_{33}^{(0)}+Z_{32}\rho_{44}^{(0)}), \tag{B6}$$

$$\rho_{42}^{(0)}=\chi_{rf}\chi_c(X_{42}\rho_{22}^{(0)}+Y_{42}\rho_{33}^{(0)}+Z_{42}\rho_{44}^{(0)}), \tag{B7}$$

$$\rho_{43}^{(0)}=i\chi_c(X_{43}\rho_{22}^{(0)}+Y_{43}\rho_{33}^{(0)}+Z_{43}\rho_{44}^{(0)}), \tag{B8}$$

where

$$X_{32}=-\frac{d_{42}d_{43}+\chi_{rf}^2}{d_{32}d_{42}d_{43}+\chi_{rf}^2d_{32}+\chi_c^2d_{43}},$$

$$Y_{32}=\frac{d_{42}d_{43}+\chi_{rf}^2-\chi_c^2}{d_{32}d_{42}d_{43}+\chi_{rf}^2d_{32}+\chi_c^2d_{43}},$$

$$Z_{32}=\frac{\chi_c^2}{d_{32}d_{42}d_{43}+\chi_{rf}^2d_{32}+\chi_c^2d_{43}},$$

$$X_{42}=-\frac{d_{43}}{d_{32}d_{42}d_{43}+\chi_{rf}^2d_{32}+\chi_c^2d_{43}},$$

$$Y_{42}=\frac{d_{43}+d_{32}}{d_{32}d_{42}d_{43}+\chi_{rf}^2d_{32}+\chi_c^2d_{43}},$$

$$Z_{42}=-\frac{d_{32}}{d_{32}d_{42}d_{43}+\chi_{rf}^2d_{32}+\chi_c^2d_{43}},$$

$$X_{43}=-\frac{\chi_{rf}^2}{d_{32}d_{42}d_{43}+\chi_{rf}^2d_{32}+\chi_c^2d_{43}},$$

$$Y_{43} = \frac{\chi_{rf}^2 - d_{32}d_{42} - \chi_c^2}{d_{32}d_{42}d_{43} + \chi_{rf}^2 d_{32} + \chi_c^2 d_{43}},$$

$$Z_{43} = \frac{d_{32}d_{42} + \chi_c^2}{d_{32}d_{42}d_{43} + \chi_{rf}^2 d_{32} + \chi_c^2 d_{43}},$$

$$\begin{aligned} M = {} & 6\Gamma\chi_c^2(\mathrm{Re}\,Y_{43} - \mathrm{Re}\,X_{43})(2\chi_{rf}^2\mathrm{Re}\,Z_{32} + \Gamma - W_{42}) \\ & + 3\Gamma(2\chi_c^2\mathrm{Re}\,Z_{43} - W_4)(2\chi_{rf}^2\mathrm{Re}\,X_{32} + 3\Gamma - 2\chi_{rf}^2\mathrm{Re}\,Y_{32}) \\ & + 4\chi_c^2\chi_{\mathrm{rf}}^2\mathrm{Re}\,X_{43}\mathrm{Re}\,Y_{32}(2\Gamma + W_{41}) - 2\chi_c^2\mathrm{Re}\,Y_{43}(2\Gamma + W_{41}) \\ & \times(2\chi_{rf}^2\mathrm{Re}\,X_{32} + 3\Gamma). \end{aligned}$$

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