Control an electromagnetically induced transparency feature with a microwave field

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ABSTRACT

In this paper we present a theoretical study of the effect of a microwave field on an EIT feature. The EIT feature is associated with the well-known three-level $\Lambda$ type configuration where a pump and probe laser field couples two separate optical transitions. In addition to these two laser fields, there is a microwave field which drives one of the two lower levels of the $\Lambda$ type three-level system to another hyperfine level. The EIT feature is studied as a function of microwave field frequency and intensity. Our results show that the presence of a microwave field can dramatically modify the EIT feature. When microwave is resonant with the hyperfine transition, the EIT feature can be split into two EIT features. When it is off resonant with the hyperfine transition, it causes a frequency shift of the EIT feature, reminiscent of the well-known light shift effect.

Key words: electromagnetically induced transparency; dynamic Stark splitting; light shift

1. INTRODUCTION

Electromagnetically induced transparency (EIT) in its simplest configuration occurs when two laser fields satisfy a two-photon resonance situation in a three-level double resonance configuration [1, 2]. Due to its intriguing physics and potential applications, there have been numerous works extending study of EIT to other more complicated configurations. It has been shown that there are interesting non-linear optics phenomena when an extra laser field is applied to drive one of the three levels associated with an EIT feature to a fourth level forming a four level triple resonance configuration.

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[3-11]. For example, a slow-light six-wave mixing has been observed at low light intensities in a four level atomic system interacting with three laser fields in which there is an EIT feature associated with a coupling and a probing laser interacting with three atomic levels forming a \( \Lambda \) system and there is an extra laser field drives one of the lower levels in \( \Lambda \) system to the fourth level [11]. If the fourth level belongs to the same ground state hyperfine structure as the two lower levels of the \( \Lambda \) three-level system, a microwave (or radio-frequency) field can be used to drive this fourth level to one of the two lower levels, and such a configuration is also a topic of recent studies [12-17]. In these previous studies, the microwave field drives the hyperfine transition that shares a common level with the coupled optical transition. In this paper we consider a different situation where the microwave field drives the hyperfine transition that shares a common level with the probed optical transition. We will show that the EIT feature can be significantly modified by the microwave field and effects observed include EIT dynamic Stark splitting and EIT frequency tuning or ‘light shifting’.

### 2. THEORETICAL CONSIDERATION

We consider a four level atom interacting with two laser and one microwave fields as shown in figure 1. The frequencies of these two laser fields are denoted as \( \omega_1 \) and \( \omega_2 \) and are referred as to coupling and probing field, respectively. Their Rabi intensities are denoted as \( \chi_1 \) and \( \chi_2 \), respectively. The coupling and probing field interacts with \( |2\rangle - |3\rangle \) and \( |1\rangle - |3\rangle \) transition, respectively and thus forms a \( \Lambda \) configuration. In such a \( \Lambda \) configuration, it is well known that the probe laser will experience a decrease in absorption, i.e. EIT, due to the presence of the coupling laser. The microwave field has

![Figure 1: Energy level scheme, (a) in bare state basis where level \( |1\rangle, |2\rangle \) and \( |3\rangle \) interacting with a coupling and a probing laser from a \( \Lambda \) type three-level system leading to EIT. A microwave field is applied to manipulate the EIT feature, (b) in dressed state basis, there are two set \( \Lambda \) type three-level system due to dynamic Stark splitting.](image-url)
a frequency $\omega_3$ and a Rabi frequency $\chi_3$. We are interested in effects of such a microwave field on the EIT when it is applied to a hyperfine transition between one of the two lower levels of the $\Lambda$ three level system to a fourth level $|4\rangle$ and in this paper we consider the situation that the microwave field drives the $|1\rangle - |4\rangle$ transition and the microwave-driven transition shares a common level with the probed transition $|1\rangle - |3\rangle$.

Under the rotating wave approximation, the equations of motion of density matrix can be written as

\[
\begin{align*}
\dot{\rho}_{11} &= i\chi_1 (\rho_{31} - \rho_{13}) + i\chi_3 (\rho_{41} - \rho_{14}) + \Gamma_{31}\rho_{33} + \Gamma_{21}\rho_{22} + \Gamma_{41}\rho_{44} - (\Gamma_{12} + \Gamma_{14})\rho_{11} \\
\dot{\rho}_{22} &= i\chi_1 (\rho_{32} - \rho_{23}) + \Gamma_{32}\rho_{33} + \Gamma_{12}\rho_{11} - \Gamma_{21}\rho_{22} \\
\dot{\rho}_{33} &= -i\chi_2 (\rho_{31} - \rho_{13}) - i\chi_4 (\rho_{32} - \rho_{23}) - (\Gamma_{32} + \Gamma_{31} + \Gamma_{34})\rho_{33} \\
\dot{\rho}_{44} &= -i\chi_3 (\rho_{41} - \rho_{14}) + \Gamma_{41}\rho_{44} + \Gamma_{34}\rho_{33} - \Gamma_{41}\rho_{44} \\
\dot{\rho}_{43} &= -d_{43}\rho_{43} + i\chi_3\rho_{33} - i\chi_2\rho_{41} - i\chi_1\rho_{42} \\
\dot{\rho}_{42} &= -d_{42}\rho_{42} + i\chi_3\rho_{32} - i\chi_1\rho_{43} \\
\dot{\rho}_{41} &= -d_{41}\rho_{41} - i\chi_2\rho_{31} - i\chi_3\rho_{44} - \rho_{11} \\
\dot{\rho}_{32} &= -d_{32}\rho_{32} + i\chi_2\rho_{31} - i\chi_1\rho_{33} + \rho_{22} \\
\dot{\rho}_{31} &= -d_{31}\rho_{31} + i\chi_1\rho_{31} + i\chi_3\rho_{34} - i\chi_2\rho_{33} - \rho_{11} \\
\dot{\rho}_{21} &= -d_{21}\rho_{21} + i\chi_1\rho_{31} - i\chi_2\rho_{23} - i\chi_3\rho_{24}
\end{align*}
\]

where complex detunings are defined as

\[
\begin{align*}
d_{43} &= i(\Delta_2 + \Delta_3) + \gamma_{43} \\
d_{42} &= i(\Delta_2 + \Delta_3 - \Delta_1) + \gamma_{42} \\
d_{41} &= i\Delta_3 + \gamma_{41} \\
d_{32} &= -i\Delta_1 + \gamma_{32}
\end{align*}
\]
\[ d_{31} = -i\Delta_2 + \gamma_{31}, \quad d_{21} = i(\Delta_1 - \Delta_2) + \gamma_{21} \]

And pump, probe and microwave field detunings are defined as
\[ \Delta_1 = \omega_1 - \omega_{32}, \quad \Delta_2 = \omega_2 - \omega_{31}, \quad \Delta_3 = \omega_3 - \omega_{14} \]
\[ \Gamma_{ij} \] is the population relaxation rate and \[ \gamma_{ij} \] is the coherence relaxation rate.

To calculate the absorption profiles of the laser field \( \omega_2 \) probing the \(|1> - |3>\) transition, we derive a steady state solution for \( \rho_{31} \). As we are interested in the effects of the microwave field on the EIT feature, it is sufficient to consider only weak probe field and for this case the steady state solution can be derived perturbatively to the first order of probe field Rabi intensity \( \chi_2 \). The absorption profiles of the probing field can be obtained by plotting the imaginary part of coherence term \( \rho_{31} \) as a function of probe detuning \( \Delta_2 \) and the results are presented in the following section.

3. RESULTS AND DISCUSSION

In this section we present the result of numerical calculation. To simplify the presentation, the relevant parameters are all normalized to the excited state population relaxation rate \( \Gamma_{31} = 1 \). The branching ratios of population decay from excited level \(|3>\) to ground state sub-levels \(|i>\) (\(i = 1, 2, 4\)) can affect the optical pumping process, and hence the absorption strength. However, this will not change the characteristics of the microwave induced EIT splitting pattern and therefore an equal branching ratio is assumed, \( \Gamma_{31} = \Gamma_{32} = \Gamma_{34} \). Also without losing generality, \( \Gamma_{21} = \Gamma_{12} = \Gamma_{14} = \Gamma_{41} \) is assumed for the decay rates between hyperfine transitions. It is also known that the ration of the sub-levels decay rate to that of the excited level can vary over a large range for different atomic systems. In this paper a ratio of \( \frac{\Gamma_{21}}{\Gamma_{31}} = 10^{-4} \) is used, which is convenient for illustrating EIT features. The Rabi frequencies and detunings \( \chi_1, \chi_2, \chi_3, \Delta_1, \Delta_2 \) and \( \Delta_3 \) are also normalized to \( \Gamma_{31} \).

Figure 2 shows the absorption profiles for the following situations: (i) both coupling laser and microwave driving field are absent (solid line), (ii) in the presence of a resonant coupling field only, \( \chi_1 = 0.5 \) (dashed line) and (iii) in the presence of both coupling laser and microwave field, \( \chi_1 = 0.5, \chi_3 = 1 \) (dotted line). Curve (i) gives a normal absorption profiles and is presented here for the purpose of comparison. In the absence of microwave field, the system becomes the well-studied A three level configuration. The most noticeable effect of a coupling laser is seen to induce a sharp EIT feature which lies in the center of the absorption profile for a resonant coupling field satisfying a two-photon resonance condition.
Apart from that, there is also change in the overall absorption strength due to optical pumping effect, which is not of interest in this paper. When a microwave field is introduced resonant with $|1\rangle - |4\rangle$ transition, the most interesting characteristic is the splitting of the EIT feature into a doublet as shown in curve (iii). Apart from the doublet splitting, there are again changes in the overall absorption strength due to the fact that the microwave field will perturb the optical pumping process, which is not main interest of this paper, and this population redistribution process will not be discussed further in this paper. Increasing the microwave field intensity results in an increase of the separation of the EIT doublet in a linear fashion, whose magnitude are found to be equal to the microwave field Rabi frequency as shown in figure 3.

![Absorption spectrum](image)

**Figure 2:** Absorption spectrum for the situations (i) both coupling laser and microwave field are absent, (ii) in the presence of a resonant coupling laser, (iii) in the presence of both coupling laser and microwave field.

It is well known that a strong driving field can significantly alter spectral properties of a real transition between two atomic levels. For example, the resonant fluorescence of a strongly driven two level atom has a triplet structure due to the dynamic Stark splitting, often referred to as the Mollow spectrum in the literature, and when such a strongly driven two level atom is probed to a third level, the dynamic Stark effect gives rise to a doublet structure, often referred to as the...
Autler-Townes spectrum in the literature [18-20]. It is seen that there is a one-to-one correlation between the splitting of the EIT feature and that of an Autler-Townes splitting and thus it is straightforward to relate the EIT splitting to the dynamic Stark effect.

The effect of microwave field detuning while keeping the coupling laser field resonant with the optical transition is shown in figure 4. As can be seen, both the relative intensity and spectral position of the EIT features are functions of the microwave detuning. As the frequency of the microwave field is moved off resonance, one of the components gains intensity and moves continuously toward the central position while the other component loses intensity and moves further away from the central position. The spectral position of two EIT components are given by $\frac{1}{2} (\Omega_{1} + \Delta_1)$ and $\frac{1}{2} (\Omega_{3} - \Delta_3)$, respectively, and the EIT doublet splitting is given by the generalized microwave Rabi frequency: $\Omega_3 = \sqrt{\Delta_3^2 + \chi_3^2}$. At large microwave detuning, one of the components has a negligible intensity, while the other component will have an intensity close to that of the original EIT and its position is shifted from the central position as a quadratic function of microwave Rabi frequency, reminiscent of light shifting [21].

Figure 3: Absorption spectrum showing a linear EIT dynamic Stark splitting as a function of microwave field intensity
In studying the strong interaction of a two level atom with an electromagnetic field, it is often convenient, both physically and mathematically, to introduce the dressed state picture [22] which allows one to gain more physical insight into the problem. In dressed state picture, the two level atom and the driving field are treated as a coupled global ‘atom+field’ system and the dressed states are the eigenstates of this global ‘atom+field’ system within the rotating wave approximation. If taking two lower hyperfine levels, |1> and |4>, and the microwave driving field as the global ‘atom+field’ system, then dressed state is given by:

\[ |A, n\rangle = \cos \theta |1, n\rangle + \sin \theta |4, n+1\rangle \quad \text{and} \quad |B, n\rangle = -\sin \theta |1, n\rangle + \cos \theta |4, n+1\rangle \]

where \( \theta \), given by \( \tan 2\theta = \frac{\chi}{\Delta} \), describes the wave function mixing due to the interaction.

The dynamic Stark splitting observed in two level atom can be conveniently viewed as arising from the transition within the dressed state doublets. The dressed state picture is found to be valuable in the present study. In the present study the parameters used in calculation, both coupling and probing lasers are weak with respect to the optical linewidth while the microwave field is strong with respect to the hyperfine transition linewidth, and the dressed state energy level scheme is

Figure 4: Absorption spectrum showing EIT dynamic Stark splitting and light shift as a function of microwave field detuning
shown in figure 1(b) with the dressed state obtained by considering the two hyperfine levels and microwave field as a global system. The Rabi frequency of the microwave field is large with respect to the hyperfine transition but small with respect to the optical transition, therefore the dressed state doublet is embedded within the optical linewidth. Then the probing laser is scanned through the $|1\rangle - |3\rangle$ transition there will be two situations where the coupling and probing laser fields satisfy a two-photon resonance condition and this results in two EIT features.

4. CONCLUSION

In this paper we presented a theoretical study of the nonlinear behaviors of an EIT feature subjected to a microwave driving field. This is demonstrated using the well known $\Lambda$ three level atom and the microwave drives a transition which shares a common level with the probed transition. The occurrence of the doublet splitting and frequency ‘shifting’ of the EIT feature reminiscences of the Autler-Townes doublet observed for a driven two level transition and is related to the dynamic Stark splitting. The configuration treated here can be found in many real atomic systems and thus the results will have practical implication for the potential application of EIT. For example, a microwave field can be used to open more than one EIT windows. Also by controlling the microwave field intensity and detuning we can continuously vary the spectral position of the EIOT window, thus realize EIT frequency tuning.

REFERENCES


