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Periodically modulated dark states

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ABSTRACT

Phenomena of electromagnetically induced transparency (PEIT) may be interpreted by the Autler–Townes Splitting (ATS), where the coupled states are split by the coupling laser field, or by the quantum destructive interference (QDI), where the atomic phases caused by the coupling laser and the probe laser field cancel. We propose modulated experiments to explore the PEIT in an alternative way by periodically modulating the coupling and the probe fields in a Λ-type three-level system initially in a dark state. Our analytical and numerical results rule out the ATS interpretation and show that the QDI interpretation is more appropriate for the modulated experiments. Interestingly, dark state persists in the double-modulation situation where control and probe fields never occur simultaneously, which is significant difference from the traditional dark state condition. The proposed experiments are readily implemented in atomic gases, artificial atoms in superconducting quantum devices, or three-level meta-atoms in meta-materials.

1. Introduction

Phenomena of electromagnetically induced transparency exists in a wide variety of physical systems, such as atomic gases [1–3], artificial atoms in superconducting quantum circuits [4,5], quantum dots [6], optomechanics [7], and three-level meta-atoms in meta-materials [8,9]. Important applications of EIT include the slow light experiments [10–13], quantum memory [14,15], precision measurements [16,17]. However, the theoretical interpretations of the PEIT has not been unified [18,19]. Among these many explanations, two theories, the ATS [20,21] and the QDI [22], are often quoted.

According to the ATS theory, the strong coupling field causes a large splitting between the doublet structure in the absorption profile and the probe field is unabsorbed in the space within the doublet [23,24]. Alternatively, the QDI theory considers that the quantum destructive interference of two or many transition paths results in the atomic transparency [25]. The difference between the ATS and the QDI theory has also been investigated [26–28]. The common conclusion is that the ATS (QDI) dominates if the coupling field is strong (weak), compared to the decay of the three-level system. A crossover exists in between [29,30], where both theories do not work well. Therefore, new experiments are demanded in order to unambiguously discern the two theories.

By periodically switching on and off the coupling and/or the probe field, we may distinguish the two theories in a different manner. In fact, switching on suddenly the coupling field in a Λ-type three-level system shows unusual transient gain features [31]. Moreover, modulated two-level systems often exhibit quite different dynamics, compared with the free evolution [32]. For example, the decoherence of a two-level qubit is strongly suppressed by periodically rotating the qubit [33–35]. We thus expect different dynamics of the three-level system by modulating the coupling and/or the probe field.

A key feature of the modulation in the three-level system is that the ATS disappears if the coupling field is off, as shown in Fig. 1. The probe field is then absorbed and PEIT should disappear according to the ATS theory (see also Table 1). However, the phases induced by the coupling field and the probe field may cancel even if the two fields are not simultaneously on. The PEIT might occur according to the QDI theory.

In this paper, we put forward two modulated dark states experiments. We investigate the absorption of a Λ-type three-level system [36] driven by periodically modulated coupling and probe fields. By comparing the analytical and numerical results with the ATS and QDI's predictions, we expect to distinguish these two theories in the modulated dark states experiments. We also carry out numerical calculations of the modulated dark states under real experimental conditions, i.e., nonzero decay and mixed initial state, and show that it is practical to realize the proposed modulated dark states experiments with current techniques.

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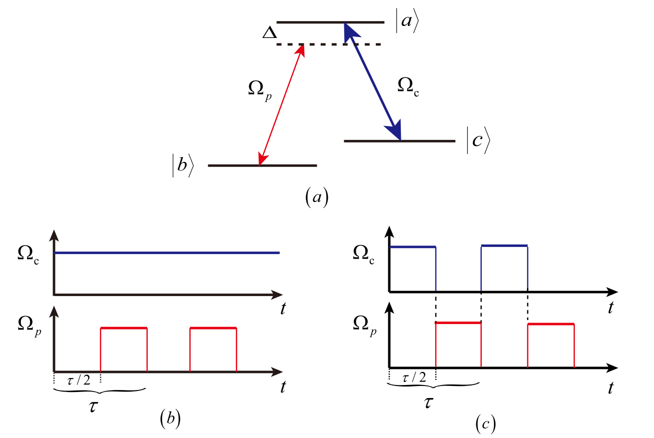

Fig. 1. (Color online.) Schematic of modulated dark state in a Λ-type three-level atom. (a) Levels of the atom, the resonant coupling field Ω_c, and the probe field Ω_p with a detuning Δ. (b) Pulse sequence of the lasers for single-modulation, where only the probe field is modulated, and (c) double-modulation, where both the coupling and the probe fields are modulated complementarily.

The paper is organized as follows. In Sec. 2, we describe the proposed experiment by modulating the coupling and the probe laser field in a Λ-type three-level atom. The main analytical and numerical results for various modulation situations are presented in Sec. 3. We also discuss the validity of the interpretations of the ATS and the QDI for the proposed experiments. We draw our conclusion in Sec. 4.

2. Modulation in a Λ-type three-level system

We consider a Λ-type three-level atom shown in Fig. 1(a). A strong laser resonantly couples the ground state $|c\rangle$ and the excited state $|a\rangle$ with a Rabi frequency Ω_c. A second laser couples the state $|b\rangle$ and $|a\rangle$ with a Rabi frequency Ω_p and a detuning Δ. The transition between states $|b\rangle$ and $|c\rangle$ is forbidden.

For a standard dark state system, the coupling and the probe lasers are on simultaneously [1,12]. The Hamiltonian of such a system is

$$H = H_0 - \frac{1}{2}(\Omega_p|a\rangle\langle b| + \Omega_c|a\rangle\langle c| + h.c.)$$

where $H_0 = (\Delta/2)(|a\rangle\langle a| - |b\rangle\langle b| + |c\rangle\langle c|)$. We have set $\hbar = 1$ and adopted the rotating wave approximation [37]. Since the initial state is a dark state at $\Delta = 0$,

$$|\Psi(0)\rangle = \frac{\Omega_c|b\rangle - \Omega_p|c\rangle}{\sqrt{\Omega_p^2 + \Omega_c^2}}, \tag{1}$$

the atomic gases are transparent for the probe laser due to the existence of the coupling laser.

We focus on two modulation situations: (I) single-modulation where only the probe field is switched on and off periodically and (II) double-modulation where both the coupling and the probe fields are switched complementarily. In the single-modulation situation as shown in Fig. 1(b), the time-dependent system Hamiltonian is

$$H_I = \begin{cases} H_1, & t \in [n\tau, (n+\frac{1}{2})\tau] \\ H_2, & t \in [(n+\frac{1}{2})\tau, (n+1)\tau] \end{cases} \tag{2}$$

where

$$H_1 = H_0 - \frac{1}{2}(\Omega_c|a\rangle\langle c| + h.c.),$$

$$H_2 = H_0 - \frac{1}{2}(\Omega_p|a\rangle\langle b| + \Omega_c|a\rangle\langle c| + h.c.)$$

Table 1
Predictions from the ATS and QDI theories for the Λ-type three-level system in the two modulation situations. Our analytical and numerical result confirm the QDI predictions.

	Single-mod.	Double-mod.
ATS	PEIT	No PEIT
QDI	No PEIT	PEIT

with τ denoting the cycle period and $n = 0, 1, 2, \cdots$. In the double-modulation situation as shown in Fig. 1(c), the system Hamiltonian is similar to the single-modulation one,

$$H_{II} = \begin{cases} H_1, & t \in [n\tau, (n+\frac{1}{2})\tau] \\ H_2, & t \in [(n+\frac{1}{2})\tau, (n+1)\tau] \end{cases} \tag{3}$$

where

$$H_1 = H_0 - \frac{1}{2}(\Omega_c|a\rangle\langle c| + h.c.),$$

$$H_2 = H_0 - \frac{1}{2}(\Omega_p|a\rangle\langle b| + h.c.).$$

The modulated dark state experiments proposed here are actually readily realized in many three-level systems, such as atomic gases [2,11], artificial atoms in superconducting quantum circuits [30,38], three-level meta-atoms in meta-materials [9,39,40]. For atomic gases, the Rabi frequency for an atom driven by a strong laser can reach 10^9 Hz. The detuning Δ is adjustable and ranges from 10 Hz to 10^9 Hz. The pulse period τ relates to the laser repetition rate and the smallest τ is about 10 ns [41]. For such systems, the limits $\Delta\tau \ll 1$ and $\Omega_{c,p}\tau \ll 1$ are feasible.

3. Results and discussions

For a no-modulation system, both the ATS theory and the QDI theory can interpret the transparency observed in atomic gases [1,18,20]. While in the two modulated dark states systems, as shown in Table 1 the ATS induced by the coupling field occurs in the single-modulation situation but is absent in the double-modulation situation when the probe field is on. According to the ATS theory, the three-level system would only exhibit PEIT in the single-modulation situation. On the contrary, the QDI exists and the PEIT appears only in the double-modulation situation. By observing the absorption of the atom in the two modulation situations, we are able to clearly verify the validity of the ATS and the QDI theories.

The initial state in all situations is set as a dark state, Eq. (1). We will calculate the fidelity of the system defined as

$$F(t) = |\langle\Psi(0)|\Psi(t)\rangle|^2 \tag{4}$$

and the absorption between the states $|b\rangle$ and $|a\rangle$, which is proportional to the imaginary part of the off-diagonal element of the density matrix $\rho(t)$

$$\mathrm{Im}(\chi) \propto \mathrm{Im}(\rho_{ab}). \tag{5}$$

3.1. Situation I: single-modulation

In the single-modulation situation, the time evolution operator for a period is

$$U(\tau) = e^{-i\tau H_2/2}e^{-i\tau H_1/2} = e^{-i\tau H_{\mathrm{eff}}}. \tag{6}$$

By employing the Baker–Campbell–Hausdorff formula [42] we obtain

$$H_{\mathrm{eff}} \approx \frac{1}{2}(H_1 + H_2) - \frac{i\tau}{8}[H_2, H_1] - \frac{\tau^2}{96}[H_2 - H_1, [H_2, H_1]]. \tag{7}$$

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