Temporal evolution of coherence resonances in degenerate two level atoms

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Abstract

We study the temporal evolution of coherence resonances of Electromagnetically Induced Transparency (EIT) and Electromagnetically Induced Absorption (EIA) in pump-probe spectroscopy of degenerate two level atoms. Two complementary theoretical approaches were used: simplified models, leading to analytical expressions for the time dependence of the transient probe absorption and a realistic numerical calculation where the Zeeman degeneracy is fully accounted for. Both treatments are in qualitative agreement with the transient probe absorption for the ^{85}Rb D_2 line in an atomic beam experiment.

Introduction

The interaction of an atomic system with mutually coherent optical waves can lead to quantum coherent effects. One particular example of such effects is Electromagnetically Induced Transparency (EIT), where the absorption of a probe field can be reduced, even eliminated, by the action of a pumping field[1]. When the two fields satisfies a two-photon (Raman) resonance condition a coherent superposition of the atomic states that do not interact with light is created. Such superposition is called a dark state, and Coherent Population Trapping (CPT) takes place[2]. The stationary and transient properties of EIT have been explored by many authors in simple

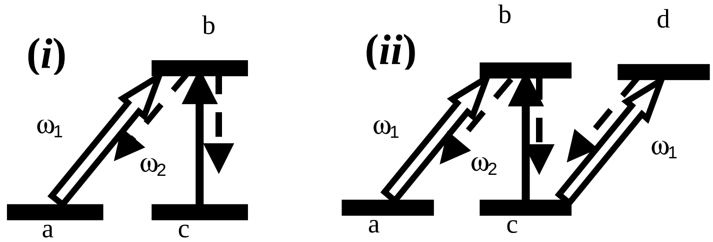

Figure 1: Model systems for EIT (*i*) and EIA (*ii*) coherence resonances. ω_1 and ω_2 are the pump and probe frequencies, respectively. Dashed lines indicate spontaneous emission decay channels.

model systems. It was demonstrated that the characteristic time for EIT is proportional to the square of the pumping field Rabi frequency Ω_1 divided by the excited state relaxation time Γ[3].

Another kind of coherence resonance corresponds Electromagnetically Induced Absorption (EIA). Here, the absorption of a probe field is increased in presence of a coupling wave[4]. Although similar to EIT in many features, except for the sign, EIA cannot be associated with any coherent superposition of states. EIA was first observed in degenerate two level system (DTLS) illuminated by a resonant pump and the probe was scanned around the same transition. When the two fields satisfies a two-photon (Raman) resonance condition there is an increase of absorption. It was established that EIA is a consequence of the transfer of coherence generated from the excited to the lower state by spontaneous emission[5].. In this work we present the first study of the temporal evolution of the EIA resonance and put in evidence similarities and differences with EIT.

Simple Models

A three level Λ system is the simplest model for EIT. The level scheme is shown in Figure 1(*i*). A pump field couples the levels *a* and *b* and a low intensity probe connect the *b* and *c* levels. Following a perturbative analysis to first order in the probe, the Optical Bloch Equations (OBE) can be integrated in time giving the no linear probe absorption:

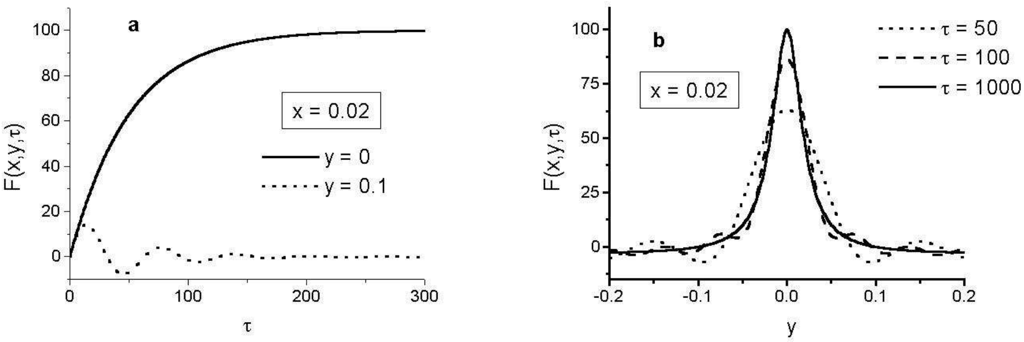

Figure 2: Plot of the function *F(x,y,τ)* evaluated for *x=0.02*. (a) τ dependence for fixed *y*. (b) *y* dependence for fixed τ.

$$\Delta\alpha_\Lambda(t) = -KF(\beta/\Gamma, \delta/\Gamma, \Gamma\tau)$$

$$F(x,y,\tau) = \mathrm{Re}\left[\frac{1-\exp(-(x-iy)\tau)}{\left(\frac{1}{2}-iy\right)(x-iy)}\right]$$

where K is a constant that depends on the intensity of both fields, δ is the detuning between the two fields and

$$\beta = \frac{2\Omega_1^2}{\Gamma}$$

defines the characteristic time of the resonance. This function presents the most important features of EIT transient behavior. For long times $F(x,y,\infty)$ is a Lorentzian function of y with width $2x$. For short times, it presents a central peak of width $\sim 4\pi/\tau$ and oscillating wings of period $\sim 2\pi/\tau$. For fixed x and y the absorption is a damped oscillation with frequency $y/2\pi$ and damping rate β. A plot of F is shown in Figure 2. The simplest model for EIA is a *N* four level system, as seen in Figure 1 (*ii*). The pump field couples the *a-b* and *c-d* transitions, while the probe couples the *c-b* one, and the three transitions have relative dipole matrix elements *A*, *B* and 1. To the first order in the probe, the absorption is given by

$$\Delta\alpha_N(t) = -\frac{K'}{\left(\frac{\Gamma}{2}\right)^2+\delta^2} + K'\frac{A^2}{\Gamma^2}F(\beta'/\Gamma, \delta/\Gamma, \Gamma\tau)$$

$$\beta' = 2\frac{\Omega_1^2}{\Gamma}\left(1-|A|^2\right)$$

The first term presents the effect of saturation of the *c-d* transition caused by the pump and the second term shows the EIA resonance. We note that the spectral and temporal behavior is similar to the EIT case, except for the sign inversion and the narrowing factor $\left(1-|A|^2\right)$ for the damping rate and stationary spectral width. As a consequence EIA will be slower than EIT in its evolution.

Realistic Models

We consider two degenerate levels of angular momentum F_g and F_e in interaction with two fields. The optical Bloch equations (OBE) are given by

$$\frac{\partial\rho}{\partial t} = \frac{-i}{\hbar}[H,\rho] - \frac{\Gamma}{2}\{P_e,\rho\} + \Gamma\sum_{q=-1,0,1} Q_{ge}^q \rho Q_{eg}^q$$

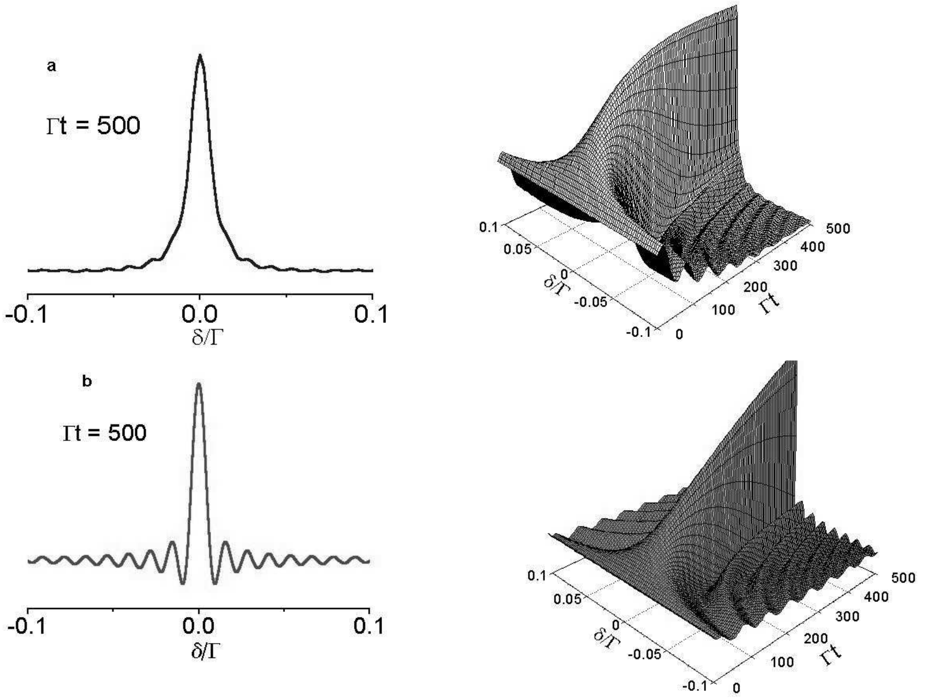

Figure 3: Calculated temporal and spectral dependence of the no linear probe absorption for two closed transitions. (a) $F_g=1\rightarrow F_e=0$, the vertical axes indicates transparency. (b) $F_g=2\rightarrow F_e=3$ transition, the vertical axes indicates absorption.

where *H* is the total Hamiltonian, $Q_{ge}^{q}=\frac{\sqrt{2F_e+1}}{\langle F_g\|D\|F_e\rangle}D_{ge}^{q}$ and P_e is the projector on the excited state. It can be seen that the condition to the occurrence of EIA is $0 < F_g < F_e$. The OBE are first solved with no probe field to all orders after what the coupling with the probe is included as a perturbation. The results is shown in Figure 3. For a given interaction time the EIT is very close to its stationary state, but the EIA curve still present strong oscillations. The main features of the simple model calculation are reproduced by the numerical results. Once again, the EIA evolution is slower and the corresponding resonances narrower.

Experiment

We have studied the temporal evolution of the probe absorption for the two closed transitions of the D_2 line of

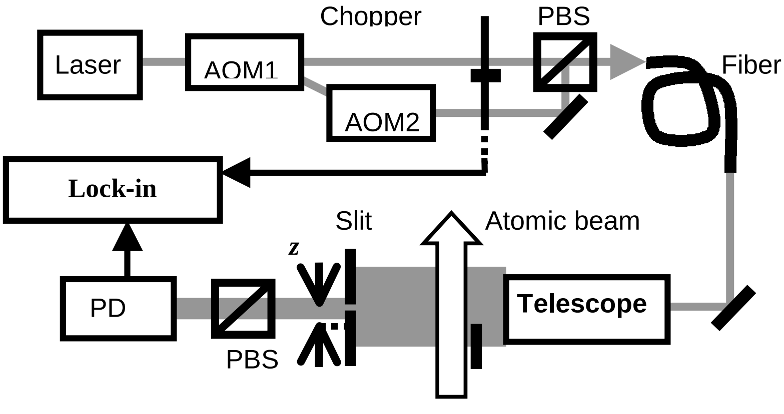

Figure 4: Experimental setup for the atomic beam experiment. PBS: polarizing beam splitter. AOM: acousto-optical modulator. PD: photodiode.

^{85}Rb, namely $5S_{1/2}(F=2)\rightarrow 5S_{3/2}(F'=1)$ that presents EIT and $5S_{1/2}(F=3)\rightarrow 5S_{3/2}(F'=4)$ that presents EIA. The experiment was done in a rubidium atomic beam. A moving slit after the interaction zone select atoms with different interaction times. The pump and probe fields having linear and orthogonal polarizations are obtained from the same diode laser using two acousto-optic modulators (AOM). The probe frequency is scanned by a tunable rf source that controls one of the AOMs. In order to detect only the no linear contribution of the signal, a two-frequency modulation was used. The pump and probe are mechanically modulated with frequencies f_1 and f_2 while a lock-in amplifier analyze the sum frequency ($f_1 + f_2$).

The results are shown in Figure 5, where we see the evolution in time of the EIT and EIA resonances. A good qualitative agreement is observed between the theoretical predictions and the experimental observations. The EIT resonance rapidly reaches its stationary state while the EIA resonances exhibit a much slower behavior. During the whole measurement time interval the EIA presents a continuous narrowing while the line spectra is clearly not Lorentzian.

Conclusions

We have presented the temporal evolution of the EIA coherence resonance and compared with that of EIT. The results provided by the analysis of the simple models and the numeric calculations are in good agreement with an experiment done in an atomic beam. We have seen that the EIT resonance reaches its stationary state in a shorter time than EIA. Because the existence of a dark state its characteristic time is just an optical pump time. In the

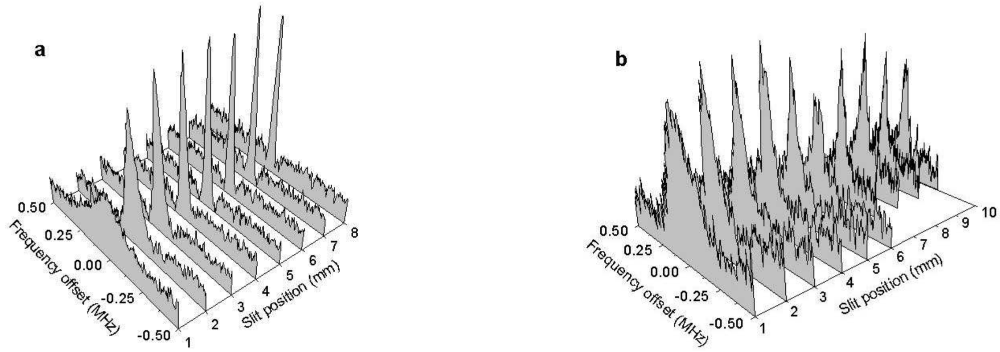

Figure 5:Experimental no linear probe absorption spectra at different positions of the movable slit. (a) $5S_{1/2}(F=3)\rightarrow 5S_{1/2}(F=4)$ transition, the vertical axes indicates absorption. (b) $5S_{1/2}(F=2)\rightarrow 5S_{1/2}(F=1)$ transition, the vertical axes indicates transparency.

EIA case, a narrowing factor appearing in the probe absorption transient equation makes its evolution shorter and the stationary spectra narrower.

Acknowledgments

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