Simultaneous coupling of three $\text{hfs}$ components in a cascade scheme of EIT in cold $^{85}\text{Rb}$ atoms

K. Kowalski$^a$, V. Cao Long$^b$, H. Nguyen Viet$^c$, S. Gateva$^d$, M. Głódź$^a$, J. Szonert$^a$

$^a$Institute of Physics, PAS, Al. Lotników 32/46, 02-668 Warsaw, Poland
$^b$Institute of Physics, University of Zielona Góra, Podgórna 50, 65-246 Zielona Góra, Poland
$^c$The Andrzej Sołtan Institute for Nuclear Studies, Hoza 69, 00-681 Warsaw, Poland
$^d$Institute of Electronics, BAS, 72 Tzarigradsko Chaussee, 1784 Sofia, Bulgaria

**A R T I C L E   I N F O**

Article history:
Available online 10 June 2009

PACS:
42.50.–p
42.50.Gy

Keyword:
Optical properties

**A B S T R A C T**

We have investigated multiple windows of electromagnetically induced transparency (EIT) registered in a cascade scheme $5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F = 3) \rightarrow 5D_{5/2}(F = 4, 3, 2)$ of cold $^{85}\text{Rb}$ atoms in a magneto-optical trap (MOT), with a weak probe laser in the first step and with a strong coupling laser in the second step. A structure composed of up to three transparency windows is observed in the spectral profile of the probe absorption, due to a simultaneous coupling of three $F$ components of a dense $\text{hfs}$ structure of a $5D_{5/2}$ state of the $^{85}\text{Rb}$ isotope. The experimental EIT features, as dependent on the coupling beam intensity or on the frequency detuning from the $F = 3 \rightarrow F = 3$ resonance are compared with those theoretically obtained from a five-level model. A coefficient characterizing a relative decrease of absorption at the center of the most prominent EIT peak, plotted versus the coupling beam intensity, is also presented for both the experimental and modeled spectra. A good agreement between theory and experiment is observed. As it is very simple to manipulate the positions, shapes and depths of the EIT features, the present scheme could be of interest, e.g., for the quantum information science.

1. Introduction

The phenomenon of electromagnetically induced transparency (EIT) refers to the reduction of the resonant absorption of a probe laser field on an otherwise optically allowed transition by means of a strong coupling field on a linked transition [1,2]. The two allowed laser field on an otherwise optically allowed transition by means of (EIT) refers to the reduction of the resonant absorption of a probe absorption, due to a simultaneous coupling of three $F$ components of a dense $\text{hfs}$ structure of a $5D_{5/2}$ state of the $^{85}\text{Rb}$ isotope. The experimental EIT features, as dependent on the coupling beam intensity or on the frequency detuning from the $F = 3 \rightarrow F = 3$ resonance are compared with those theoretically obtained from a five-level model. A coefficient characterizing a relative decrease of absorption at the center of the most prominent EIT peak, plotted versus the coupling beam intensity, is also presented for both the experimental and modeled spectra. A good agreement between theory and experiment is observed. As it is very simple to manipulate the positions, shapes and depths of the EIT features, the present scheme could be of interest, e.g., for the quantum information science.

Various materials have been analyzed and applied to study the fundamental properties of EIT and in view of exploring its practical implications. Many investigations concerning EIT have been performed with gas samples (hot [19], cold [20] and ultra cold [7]). More recently the study of EIT and related coherent phenomena has been extended to include solids. EIT in solids was first observed in rare earth doped insulators and used for manipulating light pulses [10,21]. EIT is investigated in semiconductor quantum wells and quantum dots [22–29]. Phenomena related to EIT are also studied in optical fibers [30], silicon ring resonators [31] and photonic crystals [32].

Several excellent reviews on the progress in EIT and other quantum coherence phenomena are available [33–39] giving a deeper insight into the subject and providing lists of original references. A basic EIT scheme (with three levels, two fields and a single peak of enhanced transmission) can be realized to a good approximation by picking out three various atomic levels. However, an interesting aspect of EIT is the possibility of its generalization to a case characterized by multiple transparency windows. One way to produce multiple transparency windows is to engage extra coupling beams (one or more) and extra levels. Such beams could be at optical [40,41] or radio [42] frequencies. Another way is to introduce a dichromatic (or trichromatic etc.) coupling beam at close frequencies detuned from the same level [43,44]. Yet another idea,
implemented in our experiment, is to take advantage of a manifold of close lying atomic levels which could be simultaneously coupled by a single monochromatic coupling beam [45].

In the present work, as in Ref. [45], the cascade configuration of \(^{85}\text{Rb}\) levels with the dense hyperfine structure (hfs) in the uppermost state \(5D_{5/2}\) is selected for analysis. In Fig. 1 a partial scheme of \(^{85}\text{Rb}\) levels and relevant transitions are given. Three groups of allowed transitions \(C_i\) connect the hfs components of the states \(5P_{3/2}\) and \(5D_{5/2}\). The adjacent \(5D_{5/2}(F = \ell)\) hfs sublevels are separated by less than 10 MHz. Therefore, in each \(C_i\) group, the coupling laser beam of sufficient intensity can bind a given \(F\) state with three \(F\) states, simultaneously, but with different detunings and Rabi frequencies. The tuning range of the probe beam, exciting the allowed transitions from the ground state \(5S_{1/2}(F = 3)\) to the \(5P_{3/2}(F')\) states, is marked by a dashed portion of the arrow \(P\). The experiment is performed in a sample of cold \(^{85}\text{Rb}\) atoms produced in a magneto-optical trap (MOT); \(T\) and \(R\) stand for the trapping and repumping transitions of the MOT, respectively.

We have registered distinct multiple EIT windows for each \(C_i\) coupling, as well as in an analogous case of a probe beam exciting the \(F = 2\) sublevel of the ground state to the sublevels of the \(5P_{3/2}\) state. However, aiming at a comparison of our results with those of the work [45], we report in this paper only the spectra referring to the case of \(C_3\) coupling, i.e. the ones corresponding to the process:

\[
5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 3) \rightarrow 5D_{5/2}(F'' = 4, 3, 2).
\]

The presented results examine the dependence of EIT resonances (positions, and amplitudes) on the coupling field parameters (intensity, detuning). The measurements are compared with the results of calculations performed for an idealized five-level model.

### 2. Experiment

The experiment was performed in a gas of cold \(^{85}\text{Rb}\) atoms which were cooled and trapped in a six-beam magneto-optical trap (MOT) built in our laboratory [46]. The setup for EIT measurements [47] is shown in Fig. 2. The cw probe- and coupling-beams from extended-cavity diode lasers (DL1, DL2, respectively, both with a 1 MHz bandwidth) intersected, at an angle of 50°, in the center of a cold atomic cloud. The two beams were of linear and mutually perpendicular polarizations. The probe beam intensity was \(I_p = 100 \text{ W/cm}^2\). The coupling beam intensity varied in the range of \(I_c = 33 \pm 400 \text{ mW/cm}^2\). The coupling laser was tuned into the region of \(5P_{3/2}(F = 3) \rightarrow 5D_{5/2}(F'' = 4, 3, 2)\) resonances (\(\lambda_c = 775.8 \text{ nm}\)). The probe beam (\(\lambda_p = 780 \text{ nm}\)) was scanned across the \(D_2\) line components \(5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F' = 2, 3, 4)\), stepwise with an increment of 300 kHz. The transmission was registered with a photodiode.

An example of the registered spectrum, corresponding to \(I_c = 400 \text{ mW/cm}^2\), is shown in Fig. 3 (black line). The spectrum
taken with the coupling laser off (red line) is also given for reference. As can be seen, when the coupler is on the absorption profile of the probe (absorption A is related to transmission T as A = 1−T), corresponding to the transition F = 3 → F = 3, is broadened and engraved with the EIT features of enhanced transmission due to the hfs components F′ = 4, 3, 2 of the 5D5/2 state. The separations between the spectral features are close to the spacings of these hfs components. Several other spectra have been registered as a function of the probe (absorption) and the strong beam (excitation). As can be seen, when the coupler is on the absorption profile taken with the coupling laser off (red line) is also given for reference (red line). Zero-detuning is chosen arbitrarily.

3. Theory: a five-level model

In order to reproduce and interpret the experimental results, a five-level model with two fields ωp and ωc is applied (Fig. 4), similarly as in Ref. [45]. While the weak probe beam (ωp) excites the transition |1⟩ → |2⟩, the strong beam (ωc) couples the level |2⟩ with the group of three closely spaced levels |4⟩, |3⟩ and |5⟩ separated by δ1 and δ2, respectively. Detunings of the applied fields are given as

\[ \Delta_c = \omega_c - \omega_{23}, \quad \Delta_p = \omega_p - \omega_{21}, \]

(1)

where ω23 and ω21 are the frequencies at resonance.

\[ |1\rangle \rightarrow |2\rangle \rightarrow |3\rangle \rightarrow |4\rangle \rightarrow |5\rangle \]

The levels |i⟩ (i = 1 ... 5) are assigned to the relevant real 85Rb atom levels as follows:

\[ |1\rangle \Rightarrow 5S_{1/2}(F = 3); \quad |2\rangle \Rightarrow 5P_{3/2}(F = 3); \]

\[ |3\rangle \Rightarrow 5D_{5/2}(F′ = 3); \quad |4\rangle \Rightarrow 5D_{5/2}(F′ = 4); \quad |5\rangle \Rightarrow 5D_{5/2}(F′ = 2). \]

The evolution equation for the density operator \( \rho \) [48] for the system of a five-level atom interacting with two laser fields, in dipole- and RWA-approximations, takes the form:

\[ \frac{\partial \rho}{\partial t} = -i [H, \rho] + \Lambda \rho, \]

(2)

where the Hamiltonian \( H \) is the sum of the unperturbed atomic Hamiltonian \( H_{\text{at}} \) and the interaction Hamiltonian \( H_{\text{int}} \).

\[ H = H_{\text{at}} + H_{\text{int}}, \]

(3)

and the term \( \Lambda \rho \) accounts for the relaxation mechanisms of the system.

The Hamiltonians \( H_{\text{at}} \) and \( H_{\text{int}} \), in the basis of the five states, take the form:

\[ H_{\text{at}} = -\hbar \Delta_p \sigma_{32} - \hbar (\Delta_c + \Delta_p) \sigma_{33} - \hbar (\Delta_p + \Delta_c - \delta_1) \sigma_{44} \]

\[ -\hbar (\Delta_p + \Delta_c - \delta_2) \sigma_{55}, \]

(4)

\[ H_{\text{int}} = -\hbar \Omega_{21} \sigma_{21} - \hbar \Omega_{35} \sigma_{35} - \hbar \Omega_{42} \sigma_{42} - \hbar \Omega_{52} \sigma_{52} + \hbar c, \]

(5)

where \( \sigma_{ij} = \langle i | j \rangle \) (i,j = 1 ... 5), \( \Delta_p \) and \( \Delta_c \) are defined as in (1), and respective Rabi frequencies are:

\[ \Omega_p = \Omega_{21} = \mu_{21} E_p / \hbar, \quad \Omega_c = \mu_{22} E_c / \hbar, \]

(6)

with k = 3, 4, 5, and with \( E_p (E_c) \) being the electric field amplitude of the probe (coupling) beam, and \( \mu_\gamma \) respective transition matrix elements. We express \( \Omega_{ij} \) and \( \Omega_{k2} \) by \( \Omega_c \equiv \Omega_{ij} \) as

\[ \Omega_{42} = a_{42} \Omega_c, \quad \Omega_{52} = a_{52} \Omega_c, \]

(7)

where \( a_\gamma \) are relative values:

\[ a_{42} = \frac{\mu_{42}}{\mu_{22}}, \quad a_{52} = \frac{\mu_{52}}{\mu_{32}}, \]

(8)

Eq. (2), written in the form of a set of equations for density matrix elements \( \rho_{ij} = \langle i | j \rangle \) (i,j = 1 ... 5), has been solved numerically by assuming stationary regime (\( d\rho_{ij} / dt = 0 \)) and realistic parameters corresponding to the conditions of our experiment. The density matrix element \( \rho_{21}(\omega_p) \) obtained in this way is related to the absorption coefficient \( \alpha(\omega_p) \) via the (dressed) linear susceptibility \( \chi(\omega_p) \).
\[ \alpha(\omega_p) = k \text{Im}\{\chi(\omega_p)\} = \frac{2\mu_0 N k}{\varepsilon_0 E_p} \text{Im}\{\rho_{21}(\omega_p)\}, \]  

(9)

while the dispersion is related to \( \text{Re}\{\rho_{21}(\omega_p)\} \) [49]. \( N \) is the number density of the cold atoms; \( k = \omega_p/c \) and \( \varepsilon_0 \) is the vacuum permittivity. The experimental transmission spectrum \( T(\omega_p) \) could be related to the numerically calculated \( \rho_{21}(\omega_p) \) by using the formula \( T(\omega_p) = \exp[-\alpha(\omega_p)l] \), where \( l \) is the depth of the medium, and \( \alpha(\omega_p) \) is expressed by \( \text{Im}\{\rho_{21}(\omega_p)\} \) through the relation (9).

**Fig. 5.** Experimental EIT spectra at various intensities \( I_c \) of the coupling field (left column), compared with the corresponding results of calculations (right column). The probe frequency has been scanned across the 5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F = 3) \) transition, while the coupling beam frequency has been detuned by \( \Delta_c \) from the 5P_{3/2}(F = 3) \rightarrow 5D_{5/2}(F = 3) \) transition.
4. Results

Some of the registered spectra and the corresponding numerically calculated spectra are given in Fig. 5 and 6. The dependence of the EIT spectra on the coupling beam intensity \( I_c \), or equivalently on Rabi frequency \( \Omega_c \), is shown in Fig. 5. The left column presents the experimental spectra, while the right column shows numerically simulated results. The probe beam has been scanned across the \( 5S_{1/2}(F = 3) \rightarrow 5P_{3/2}(F = 3) \) transition. The frequency axis represents detuning \( \Delta_p \) from the exact resonance in the absence of the coupling field \( (I_c = 0) \). The coupling beam has been detuned by \( \Delta_c \) from the \( 5P_{3/2}(F = 3) \leftrightarrow 5D_{5/2}(F = 3) \) resonance. Both experimental and assumed in calculations detunings \( \Delta_c \) are given.

In the process of reproducing the experimental spectra by the theoretical ones, a value of an effective Rabi frequency \( \Omega_c \equiv \Omega_{32} \) has been attributed to each spectrum registered at a given intensity \( I_c \). \( \Omega_c \) is effective in a twofold sense. First, assuming a single value of the Rabi frequency for the transition \( 3 \rightarrow 2 \) is inherent to the applied model in view of its simplifications, e.g., the model does not take into account the presence of quasi-degenerate magnetic substates with the quantum numbers \( m_F \). In a real atom, the polarized light is coupled to the \( (F, m_F) \leftrightarrow (F', m_{F'}) \) transitions, and not merely to the \( F \leftrightarrow F' \) transition. Every such coupling is in fact characterized by its own \( \Omega \) value (it should be noted that the probe beam polarization and magnetic states in the first step are disregarded as well [50]). For the same reason, also \( a_{ij} \) values (please see (8)), initially assumed as ratios of respective reduced matrix elements, had to be slightly modified. Second, some idealizations of the experimental conditions have been assumed, e.g., the model does not account for spatial nonuniformity of \( E_c \) in the interaction.

![Experimental EIT spectra](image-url)
region. The values of $\Omega_e$ have been taken to be proportional to $(\text{mean}) E_v$ values, while $E_r$ proportional to $\sqrt{l_c}$, with $l_c$ being mean experimental values. The common proportionality factor has been optimized to obtain the best match of theoretical and experimental EIT features, with regard to the whole series of experimental spectra in Fig. 5. $l_c$ value is given with each registered spectrum and corresponding $\Omega_e$ with each theoretical spectrum.

The agreement between the experimental and simulated narrow EIT features is very good. Still, as can be noticed, the overall width of each calculated absorption profile exceeds such a width of the corresponding experimental absorption profile. It seems that the broadening of the uncoupled resonance of the corresponding experimental absorption profile. It seems that the broadening of the uncoupled resonance $|1\rangle \rightarrow |2\rangle$ (equivalently $F = 3 \rightarrow F = 3$) assumed in the model has been too large. It should be noted, however, that the resonance width used in the theoretical model should be larger than the natural width, e.g., due to the influence of the MOT fields.

Fig. 6 exemplifies the dependence of the EIT spectra on detuning. Experimental (left column) and theoretical (right column) spectra, taken at three different detunings: $\Delta_c = +8$ MHz (top of the figure), $\Delta_c = -2.5$ MHz and $\Delta_c = -10$ MHz, are shown. The spectra have been registered at $l_c = 400$ mW/cm$^2$, corresponding to Rabi frequency $\Omega_c = 7$ MHz. The significant difference with respect to the spectra in Fig. 5, is that the spectra in Fig. 6 have been registered with MOT beams switched off. Other details are similar as described above in the case of Fig. 5. As can be seen, the displaced EIT resonances, observed experimentally, are correctly reproduced by the theory. Some differences, especially in the depths of the transmission windows, could be explained by the measurement procedure details. Unlike in the previous series of experiments, the spectra were registered only within a short period of time after MOT had been (periodically) switched off, and during the rest of the cycle the cold atomic cloud was rebuilt. This lengthened the time needed to register the entire spectrum by a factor of 15. In Fig. 6 the measured EIT features appear shallower than those in Fig. 5 taken at the same $l_c$ value. One of the reasons could be the laser frequency instabilities which accumulate over a longer period of the cycle, resulting in a stronger washout of the spectral details.

In order to characterize the efficiency of EIT we have defined the relative absorption reduction factor:

$$R_A = \frac{A - A_{\text{EIT}}}{A} \times 100\%.$$  \hspace{1cm} (10)

where $A_{\text{EIT}}$ denotes the probe absorption at an EIT peak, while $A$ denotes the probe absorption at the $F = 3 \rightarrow F = 3$ resonance, with the coupler off. The $R_A$ values, determined for the most pronounced EIT feature in the spectra of Fig. 5 (related to the transition $F = 3 \leftrightarrow F = 4$), are plotted in Fig. 7 vs. coupling beam intensity $l_c$.

The theoretical values well reproduce the experimental ones. However, the grounds for such conclusion are weakened by the lack of any experimental points for intensities $l_c$ above 150 mW/cm$^2$ and below 400 mW/cm$^2$ due to technical problems with the coupling laser. It is planned to complement the measurements.

5. Discussion and conclusions

We have experimentally confirmed, in agreement with the results of Ref. [45] that the dense hfs structure of the $^{85}\text{Rb}(5D_{5/2})$ state allows multiple EIT windows to be created in a MOT environment. Multiple narrow transparency windows, as accompanied by steep changes in a refractive index, could serve to slow down the multiple light pulses at close frequencies, which could be useful in applications in the quantum information science. We have shown that the positions, the shape and depth of the windows can be effectively controlled by changing the coupling field intensity and/or detuning.

Our EIT spectra registered as a function of the coupling laser intensity agree well with those obtained as a result of our numerical modeling by using a simple five-level model. A direct comparison with the results of Ref. [45] is not possible, since the conditions of the two experiments are not quite the same and not all details of the applied procedures are clearly stated in [45]; however, the conditions seem to be close enough to justify some conclusions. We have obtained windows of a reduced absorption significantly deeper than those reported in [45], and we have also achieved a better correspondence between the calculated EIT features and those registered experimentally (compare Fig. 5 of this paper with Fig. 5 of Ref. [45]). However, the width of the uncoupled resonance $5S_{1/2}(F = 3) \rightarrow 5P_{1/2}(F = 3)$, used in our calculations as a parameter, is evidently overestimated, unlike in Ref. [45], where it appears slightly underestimated. We have also presented the dependence of coefficient $R_A$ characterizing the relative decrease of absorption (determined for the most pronounced EIT peak) upon the coupling laser intensity. A good agreement between the calculated and experimental $R_A$ values is observed.

Some discrepancies between the model and the experimental observations require a further more detailed analysis, for instance, by extending the model to include semidegenerate Zeeman substrates. Improved control over the experimental parameters (e.g., stability of laser frequencies) is also planned.

Acknowledgements

This work was partially supported by the Polish Ministry of Science and Higher Education grant under Contract No. N202 120 32/3392.

References
