Study of the splitting of electromagnetically induced transparency resonance in strong magnetic field using Rb nano-thin cell

R Mirzoyan, A Sargsyan, A S. Sarkisyan, D Sarkisyan

Institute for Physical Research, NAS of Armenia, Ashtarak, 0203, Armenia

E-mail: rafayelm@gmail.com

Abstract. Recently we have obtained the high-contrast electromagnetically induced transparency resonance on $^{85}\text{Rb}$ and $^{87}\text{Rb}$ D$_1$ line in nanometric-thin cell of $L=\lambda=794$ nm thickness. In present work we exploit the 40% contrast of EIT resonance to study its splitting in a very wide range of B-field covering, for the first time, 1 – 1700 G region. Experimental results are fully consistent with the developed theoretical model.

1. Introduction

The continuous interest in coherent processes of electromagnetically induced transparency (EIT) is caused by relative simplicity of forming ultra-narrow optical resonances with a width of less than 1 kHz, several orders of magnitude below the natural linewidth of atomic transitions. The EIT has already found practical applications in a variety of fields such as laser cooling, quantum information, optical magnetometry, laser spectroscopy, etc [1-4]. EIT resonance occurs particularly in a $\Lambda$-system with two long-living states and one excited state coupled by two laser fields, and displays a strong reduction in absorption where a maximum is expected in the absence of the coupling laser field. Results of the study of EIT-resonance splitting in a relatively low magnetic field (< 40 G) are presented in Refs. [3,5-9,11].

Recently we have reported the observation of a high contrast EIT resonance on D$_1$ line of $^{85}\text{Rb}$ and $^{87}\text{Rb}$ in the wavelength-thickness nanometric thin cell (NTC), $L=\lambda=794$ nm. A remarkable result is that reduction of the cell thickness by 4 orders from conventional centimeter-scale cell to the NTC does not deteriorate formation of a sharp EIT resonance with up to 40 % contrast defined as the ratio of EIT amplitude to the height of the peak absorption shoulders [5]. It is important to note that extremely small thickness of NTC facilitates application of a strong B-field of well-defined strength by use of conventional permanent magnets, which otherwise behave as inhomogeneous magnetic field source.

In the paper we present, for the first time, the results of studies on EIT resonance splitting in an extended range of magnetic field, from 1 G to 1700 G.
2. Experimental

2.1. Design of the nanometric thin cell

The NTC with a thickness smoothly variable in the range between 50 nm and 3 μm is similar to those described in Refs. [10,11]. Rectangular 25 x 30 mm, 2-mm-thick windows were made of monocrystalline sapphire (Al₂O₃) with the C-axis perpendicular to the window surface, which significantly reduces the birefringence. Surfaces of the sapphire windows are thoroughly polished (surface roughness ~ 5 nm). A 3 μm-thick platinum strip is placed between the windows in the lower part to form a wedge-shaped gap between the inner surfaces of the NTC. The side extension arm of NTC is filled with a natural mixture of Rb isotopes containing $^{85}$Rb (72%) and $^{87}$Rb (28%).

2.2. Experimental setup

The experimental arrangement for studying the EIT is shown in Fig. 1. Two independent narrow-band (~ 1 MHz) cw extended-cavity diode lasers (ECDL) are used to form EIT resonance. One of the lasers operates at a fixed frequency $\nu_C$ (coupling laser), while the frequency $\nu_P$ of the other laser (probe laser) is tuneable. The two laser beams of 1 mm diameter having orthogonal linear polarizations are superimposed by the Glan prism $G_1$ and are incident on NTC. Faraday isolators (1) are used in order to prevent the optical feedback. Part of the probe radiation is branched into the reference NTC with thickness $L = \lambda$ where frequency reference (FR) signal is formed. Velocity selective optical pumping (VSOP) process resulting in appearance of narrow resonances in the NTC transmission spectrum located at atomic transitions was used to form the reference spectrum [11]. The radiations signals are detected by photodiodes 3 followed by operational amplifiers and are displayed on a Tektronix TDS2014B four-channel digital oscilloscope 4. Part of the coupling-laser radiation at the frequency $\nu_C$ is sent to a frequency stabilization system (FS) described in [12]. Prism $G_2$ blocks the coupling laser so that only the probe radiation is detected.

![Figure 1. Sketch of the experimental setup. (1) Faraday isolators, $G_1,2$ - Glan prisms, (2) auxiliary NTC of $L = \lambda$, (3) photodiodes, (4) oscilloscope; (5) permanent ring magnets (for details, see text).](image1)

![Figure 2. $^{87}$Rb D₁ line. EIT resonance of 40% contrast and 30 MHz linewidth. NTC thickness is $L = \lambda = 794$ nm.](image2)

System of Helmholtz coils (not shown in Fig. 1) is used to apply a longitudinal magnetic field of relatively small strength 1 - 200 G measured by a calibrated Hall gauge. Among the advantages of NTC is the possibility to apply much stronger magnetic fields using widely available strong permanent...
ring magnets (PRMs) [13]. In spite of their $B$-field strong non-homogeneity (in our case it can reach 150 G/mm), the variation of $B$ inside atomic vapor column is by several orders less than the applied $B$ value thanks to small thickness of the NTC (794 nm).

2.3. Experimental results

In Ref. [14] it was shown that for a conventional centimetre-scale cell the excitation of the Rb D$_1$ line results in greater EIT resonance contrast as compared to that for D$_2$ line. We confirm that this statement is correct also in the case of NTC, and for D$_1$ line we succeeded to obtain $\approx 40\%$ EIT contrast (as is shown in Fig.2), which is $\approx 8$ times larger than the EIT contrast observed earlier for D$_2$ line [11]. The coupling and probe laser powers are 25 mW and 0.02 mW, correspondingly. The EIT linewidth is 30 MHz FWHM. Decreasing of the coupling laser power results in reduction of both the linewidth and contrast of EIT resonance (for some applications small EIT width is important).

Energy levels of $^{87}$Rb D$_1$ line involved in EIT process are shown in Fig. 3. The coupling laser frequency is resonant with 2 → 2' transition, while the probe laser frequency is scanned across 1 → 1',2' transitions.

Since $\nu_p - \nu_C = \{ E (F_g=2, m_F) - E (F_g=1, m_F) \}/\hbar$, the number of EIT components depends on the Zeeman splitting of the ground levels $F_g=1,2$ described by quantum number $m_F$ and presented in Fig. 4. Only three EIT components out of seven possible $\Lambda$-systems are seen for $B < 300$ G EIT components marked by the same symbol (circle, square or rectangle) have the same frequency, i.e. $\nu_6 \approx \nu_7$; $\nu_1 \approx \nu_2$; $\nu_3 \approx \nu_4 \approx \nu_5$.

All the possible hyperfine Zeeman transitions are calculated as a function of $B$ [3,15]:

\begin{align}
E (F=2,m_F) &= \hbar \nu_{hf} [1 - 1/8 + 1/2(1+m_F \times x + x^2)^{1/2} ]^{''} (m_F=2), \\
E (F=2,-2) &= \hbar \nu_{hf} (3/8 - x/2), \\
E (F=1,m_F) &= \hbar \nu_{hf} [1 - 1/8 - 1/2(1+m_F \times x + x^2)^{1/2} ],
\end{align}

(1) (2) (3)
where \( x = 2\mu_B B / \nu_{\text{HFS}} \), \( \mu_B \) being the Bohr magneton and \( \nu_{\text{HFS}} = 6835 \text{ MHz} \).

As is shown in Ref. [11], measuring the splitting of EIT resonances formed on Rb D\textsubscript{2} line in NTC with Rb vapor thickness \( L = \lambda = 794 \text{ nm} \), one can determine the applied magnetic field. However, due to small contrast of EIT resonance it is impossible to detect the splitting at smaller values of \( L \). The use of D\textsubscript{1} excitation allows to enhance the EIT contrast thus making possible detection of splitting at \( L = \lambda \), when longitudinal (\( \mathbf{B} \parallel \mathbf{k} \)) magnetic field \( B = 5.3 \text{ G} \) is applied to NTC, as presented in Fig. 5. Here \( P_C = 2 \text{ mW} \), \( P_P = 0.02 \text{ mW} \); the side-arm temperature, which determines the Rb atomic vapor density inside the NTC is 120 \( ^\circ \text{C} \), while the temperature at the windows is kept 20 degrees higher). Three resolved EIT components are seen as it is expected, with frequency separation \( 1.4 \text{ MHz/G} \times 5.3 \text{ G} \approx 7.4 \text{ MHz} \) [11]. The Gaussian fitting gives 6.5 MHz linewidth of the components.

So-called “\( \lambda \)-Zeeman technique” (LZT) is introduced in Ref. [13] to investigate atomic transitions in magnetic field. For this technique, Rb atoms are confined in NTC of thickness \( L = \lambda \). Narrow (30 - 35 MHz) VSOP resonances are produced in transmission spectrum by a single beam, and they are split into several components in a magnetic field, with frequency positions and transition probabilities depending on \( B \)-field. As it is seen from Fig. 5, the EIT resonance splitting provides 5-fold better spectral resolution, than that obtained by LZT [13].

Figure 6 shows EIT components, when 280 G longitudinal magnetic field is applied to NTC with \( P_C = 27 \text{ mW} \), and \( P_P = 0.1 \text{ mW} \). Values of the frequency shifts: \( a_1 \), \( a_2 \) and \( a_3 \) are equal to 399, 356 and 44 MHz, correspondingly. The labels denote corresponding transitions shown in Figures 4, 8. Some broadening of EIT components is caused by non-zero detuning value of the coupling laser frequency from the corresponding intermediate level (see below).

Figure 7 shows three EIT components, when \( B = 596 \text{ G} \) longitudinal magnetic field is applied (upper curve). The lower curve shows frequency reference spectrum. It is interesting to note, that in the case of a good adjustment of the coupling and probe beams at the conventional NTC 2 (Fig.2), an EIT resonance appears in the reference spectrum, which is narrower than VSOP resonance presented in the frequency reference spectrum when the coupling is not well adjusted.
Fig. 8 presents frequency shifts of the EIT components as a function of magnetic field (zero shift means the initial frequency position of EIT resonance when \( B = 0 \)). Quantum numbers of the ground levels involved in formation of EIT components labeled 1-7 are shown in Fig.4. Solid lines are plotted using equations (1)-(3); black dots present experimental results. As it is seen, the theory well describes the results of measurements.

By measuring the frequency shift between EIT component and the reference it is possible to determine either homogeneous or non-homogeneous magnetic field \( B \) in the range of \( 1 \sim 1700 \) G.

Although in the case of strong \( B \)-field six EIT components are expected to exist in the probe radiation spectrum (the components labeled 4 and 5 have the same frequency even at high \( B \)-field), however for \( B > 700 \) G only components 3 and 6 remain (this is mainly caused by the increase of coupling laser frequency detuning from the corresponding intermediate level). The EIT component 3 blue-shifted for high \( B \)-field is formed involving two ground states \( F_g=1, m_F=0 \) and \( F_g=2, m_F=0 \), while for formation of the red-shifted component 6 two other ground states \( F_g=1, m_F=-1 \) and \( F_g=2, m_F=-1 \) are responsible.

It is important that the amplitude of EIT component in the case of NTC strongly depends on the detuning \( \Delta \) of the coupling laser frequency from the appropriate intermediate hyperfine Zeeman sublevel. As it is demonstrated in [5], when the coupling laser frequency is detuned from the corresponding atomic transition by \( \Delta > 50 \) MHz, the EIT contrast (amplitude) strongly reduces, while the linewidth strongly increases. This causes additional broadening of the EIT components presented in Figures 6, 7, and in some cases the profile can be dispersive, as it is for EIT 3 shown in Fig. 7. The \( B \)-field dependence of coupling frequency detuning \( \Delta \) from the atomic level \( F_e=2, m_F=+1 \) is shown in Fig. 9 for EIT component labeled 3 (for this EIT component \( F_g=2, m_F=0 \rightarrow F_e=2, m_F=+1 \) transition is involved). As it is seen, for \( B > 1700 \) G the coupling laser detuning \( \Delta \) exceeds 100 MHz, that is why the component 3 is detectable only when \( B < 1700 \) G.

We should note that the amplitudes of EIT components strongly depend also on the probability of the atomic transitions forming the \( \Lambda \)-system (see Fig. 3). It is well known that external magnetic field
Figure 9. The coupling frequency detuning $\Delta$ from the atomic level $F_e=2 \ m_F= +1$ vs $B$-field for the component 3.

causes strong modification of atomic transition probability [13,16]. Consequently, there are two important conditions, which assure existence of EIT component in very strong magnetic field: i) a small value of the coupling laser frequency detuning $\Delta$; ii) high probabilities of atomic transitions involved in the $\Lambda$-system formation. Choosing appropriate detuning of the coupling laser frequency in order to achieve $\Delta = 0$, it will be possible to realize selective addressing of the amplitudes increase for separate EIT components at any value of a $B$-field. Well resolved EIT components can be used for optical magnetometry with local nanometric spatial resolution.

Acknowledgement
The authors are grateful for the ANSEF Opt-2428 support. R.M. acknowledges the support from the NFSAT, NAS RA and CRDF (grant no. ECSP-10-10 GRSP).

References
[1] G. Alzetta, A. Gozzini, L. Moi, G. Orriols: Nuovo Cimento Soc. Ital. Fis., B. 36, 5 (1976).
[2] E. Arimondo : Progress in Optics edited by E. Wolf (Elsevier, Amsterdam) 35, 257 (1996).
[3] R. Wynands, A. Nagel: Appl. Phys. B: Lasers Opt. 68, 1 (1999).
[4] M. Fleischhauer, A. Imamoglu, and J. P. Marangos: Rev. Mod. Phys. 77, 633 (2005).
[5] A. Sargsyan, Y. Pashayan-Leroy, C. Leroy, R.Mirzoyan, A.Papoyan, D. Sarkisyan, Applied Physics B. Lasers and Optics, V.105, pp. 767–774 (2011).
[6] X. Wei, J. Wu, G. Sun, Z. Shao, Z. Kang, Y. Jiang, J-Y.Gao, Phys. Rev. A 72, 0238061 (2005).
[7] S. M. Iftiquar and V. Natarajan, Phys. Rev. A 79, 013808 (2009).
[8] G. Katsoprinakis, D. Petrosyan and I. K. Kominis, Phys. Rev.Lett. 97, 230801 (2006)
[9] V. I. Yudin, A. V. Taichenachev, Y. O. Dudin, et al, Phys. Rev. A 82, 033807 (2010)
[10] D. Sarkisyan, D. Bloch, A. Papoyan, and M. Ducloy, Opt. Commun. 200, 201 (2001).
[11] A. Sargsyan, D. Sarkisyan, and A. Papoyan, Phys. Rev. A 73, 033803 (2006).
[12] A. Sargsyan, A. V. Papoyan, D. Sarkisyan, A. Weis, Eur. Phys. J. Appl. Phys. 48, 20701 (2009).
[13] A. Sargsyan, G. Hakhumyan, A. Papoyan, et al, Appl. Phys. Lett. 93, 021119 (2008).
[14] M Stähler, R. Wynands, S. Knappe, J. Kitching, L. Hollberg, A. Taichenachev, V. Yudin, Optics Lett. 27, 1472 (2002).
[15] K. Motomura and M. Mitsunaga, JOSA, 19, 2456-2460 (2002).
[16] G. Hakhumyan, C. Leroy, et al, Optics Communications, 284 , 4007–4012 (2011).