

# Transformation of electromagnetically induced transparency into absorption in a thermal potassium optical cell with spin preserving coating

S Gozzini<sup>1</sup>, A Lucchesini<sup>1</sup>, C Marinelli<sup>2</sup>, L Marmugi<sup>4</sup>, S Gateva<sup>3</sup>, S Tsvetkov<sup>3,4</sup> and S Cartaleva<sup>3</sup>

<sup>1</sup>Istituto Nazionale di Ottica CNR – UOS Pisa, Via Moruzzi 1, 56124 Pisa, Italy

<sup>2</sup>Department of Physical, Geological and Environmental Science, University of Siena, via Roma 56, 53100 Siena, Italy

<sup>3</sup>Emil Djakov Institute of Electronics, Bulgarian Academy of Sciences, 72 Tzarigradsko Chaussee, 1784 Sofia, Bulgaria

<sup>4</sup>INO and Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom

E-mail: stocvet@ie.bas.bg

**Abstract.** We report a new experimental approach where an order of magnitude enhancement of the electromagnetically induced absorption (EIA) resonance contrast, thus making it similar to that of the EIT resonance contrast is observed under the same conditions. The EIA signal results from the interaction of a weak probe beam with a ground state that has been driven by the pump (counter-propagating) beam. Probe absorption spectra are presented where the laser frequency is slowly detuned over the  $D_1$  line of  $^{39}\text{K}$  vapor contained in a cell with a PDMS antirelaxation coating. In addition to the frequency detuning, a magnetic field orthogonal to the laser beams is scanned around zero value at a higher rate. With both laser beams linearly polarized, an EIT resonance is observed. However, changing the pump beam polarization from linear to circular reverses the resonance signal from EIT to EIA.

## 1. Introduction

The phenomenon of electromagnetically induced transparency (EIT) has many applications in laser physics, precision laser spectroscopy, quantum information, all-optical magnetometers, miniaturized atomic clocks, precision measurements of fundamental symmetry, etc. In the fluorescence signal from a vapor cell, the EIT resonance is usually observed as a narrow dip. Consequently, the EIT signal is also called “dark resonance”. One of the most significant and useful features of the EIT resonance is its width, which can be much smaller than the natural line width. Perhaps these resonances are the narrowest ones that can be observed in a cell filled with ‘hot’ atomic vapor (i.e. at room temperature).

The electromagnetically induced absorption (EIA) resonance, a sub-natural-width resonance (“bright resonance”), has applications in an enhancement of the group velocity of the light (“fast” light), four-wave mixing, magnetic field mapping of cold atomic samples. However, the scope of EIA applications is rather small due to some problems that are yet to be solved. So far, the EIA has been

<sup>4</sup> To whom any correspondence should be addressed.



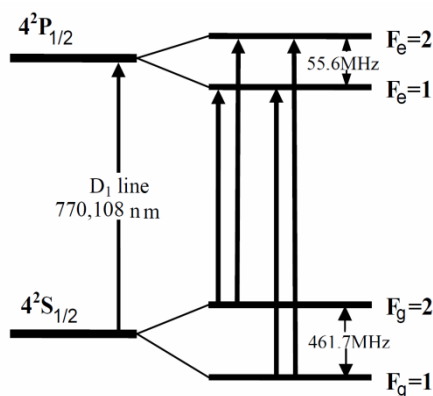
predominantly observed in closed “bright” hf transitions. The most effective methods for sufficient narrowing of the resonance width are based on the usage of a buffer gas or an optical cell with an anti-relaxation coating on the walls. These methods, although demonstrating perfect results with EIT signals, happen to be useless for EIA ones in conventional schemes of resonance observation. The collision process between atoms and buffer gas or cell walls rapidly destroys the EIA signal, or even changes its sign. For a long time, EIA resonances with a good contrast-to-width ratio could not be achieved [1,2].

In this paper, we suggest a new approach to observing EIA signals with a potential for significant (up to an order of magnitude) enhanced resonance contrast. The scheme is based on open hyperfine (hf) transitions of resonance lines in alkali atoms. The scheme proposed allows one to use a cell with anti-relaxation coating of the walls or a buffer gas, in order to improve the resonance properties. In this case, the buffer gas does not lead to destroying the EIA resonance [3] as in regular schemes for EIA observation. In the new scheme, the EIA signal results from the interaction of a low intensity probe beam with the ground atomic state of K ( $D_1$  line) that has been driven in Hanle configuration by a pump laser beam. The pump and probe beams are taken from the same mono-mode laser source and arranged as for the case of saturated absorption (SA) observation [4]. The sign of the coherent resonance (i.e. EIT or EIA) can be controlled by the polarization (linear or circular) of both laser beams.

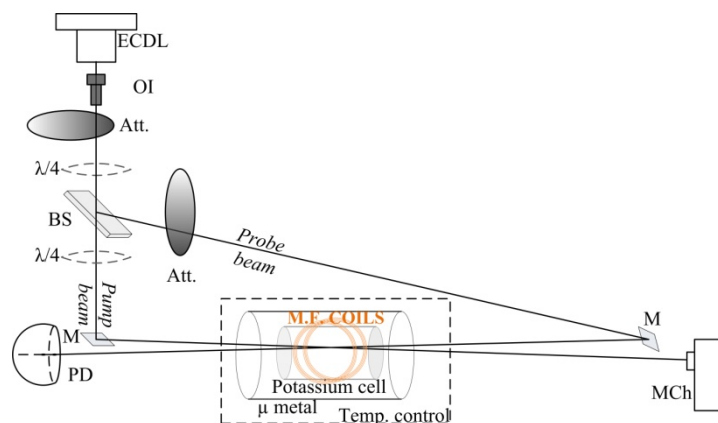
## 2. Experimental results and discussion

### 2.1. $D_1$ line of potassium

The optical cells used in the experiment contained atomic vapor with natural abundance of the two stable isotopes of potassium with mass numbers 39 and 41. The potassium-39 isotope atoms are predominant (93.3%). In figure 1 we show the level diagram of the  $D_1$  line (770.1 nm) of potassium-39. The ground level frequency splitting is smaller than the Doppler width of the optical transitions (0.77 GHz at 300 K). The spectrum of potassium is much less studied than those of Na, Rb, and Cs. Several features distinguish K from the other alkali atoms; in particular, the hf ground-state splitting is smaller than the Doppler width. Thanks to this fact, the hf transitions starting from a single ground level are completely overlapped. Moreover, the hf components from both the ground state levels cannot be spectrally resolved. As a result, the crossover (CO) resonances that involve both ground state levels, being negligible for Cs and Rb and suppressed for Na, are usually dominant for K [5].



**Figure 1.** Energy level diagram and hyperfine transitions of the  $D_1$  line of potassium



**Figure 2.** Experimental setup. ECDC – extended cavity diode laser; OI – optical isolator; PD – photodiode detector, M – mirror, BS – beam splitter, Att – attenuator, MCh – mono-chromator.

## 2.2. Experimental setup

A sketch of the experimental setup is shown in figure 2. The laser beam produced by an extended cavity diode laser (ECDL, Toptica DL 100) is tuned to the  $D_1$  line of potassium (770.1 nm). It is divided in a pump and a probe beams that enter into a PDMS coated optical cell from two opposite directions and overlap inside it. The laser intensities are controlled by two adjustable attenuators in order to obtain the needed power ratio between the pump and probe beams. The polarization of the probe beam is set either linear or close to circular by a  $\lambda/4$  plate placed in both beam arms. The pump beam polarization is linear or close to circular, controlled by a second  $\lambda/4$  plate placed in its beam arm. A heater controls the temperature of the measurement cell. The PDMS coated cell is protected against stray laboratory magnetic fields by a  $\mu$ -metal shield. The cell is situated between two coils in a Helmholtz configuration providing a magnetic field variable around zero value and orthogonal to the laser beam propagating direction. The laser frequency is scanned across the  $D_1$  line spectrum, and the transmission of the probe beam is detected by a photodiode.

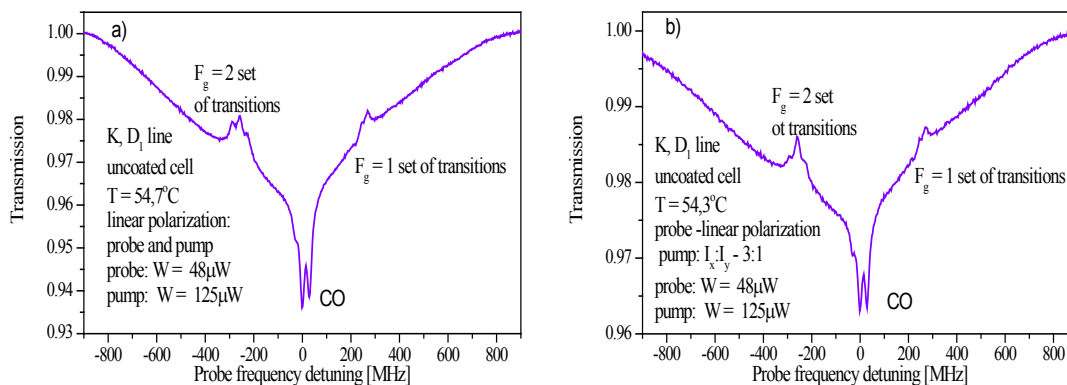
## 2.3. Saturated absorption resonances on the $D_1$ line of K

Transmitted spectra of the probe beam with the SA resonances are shown in figure 3, in case of uncoated optical cell. Three well separated groups of SA resonances can be clearly distinguished.

(i) The first group is formed on the ground state level  $F_g = 2$  set of hf transitions and is situated at the lower frequency part of the transmission profile of the  $D_1$  line. Here, both hf transitions start from the same hf level of the ground state. This group consists of three resonances of reduced absorption. The conventional crossover resonance situated in the middle of the group combines transitions from the same ground level to different excited hf levels. Here the dip in absorption shows that at each resonance the probe beam sees the depleted atomic population of the ground level that is caused by the counter propagating pump beam. The behavior of the crossover resonance produced by the  $F_g = 2$  transitions shows that the resonance peak is influenced by the pump beam polarization, being of higher amplitude in case of elliptically polarized pump beam.

(ii) The second group of SA resonances is due to the  $F_g = 1$  set of transitions and is situated on the higher frequency wing of the absorption profile. Here also, both hf transitions start from the same ground level.

(iii) Between the two groups, a third group of sub-Doppler-width resonances is formed and is identified as a particular CO group, which involves the hf transitions starting from both ground-state levels. The contrast of the resonances belonging to the last group is much larger than that of the previous two groups. Moreover, they are with opposite signs compared to those of the two previous groups. Here, the enhanced absorption resonances combine transitions sharing the same excited hf level, as well as four separate hf transitions that do not share any of the excited or ground hf levels. In this group, the probe beam measures a very strong accumulation of atoms on the ground levels caused



**Figure 3.** Transmission of the probe beam with SA resonances on the  $D_1$  line of K. In this work, the polarization of the probe beam is kept linear, while that of the pump beam is changed: (a) the pump beam is linearly polarized; (b) the pump beam is with elliptical polarization.

by the pump beam, due to the velocity selective hf optical pumping. Such an accumulation is the reason of the saturated resonance sign reversal from reduced to enhanced absorption.

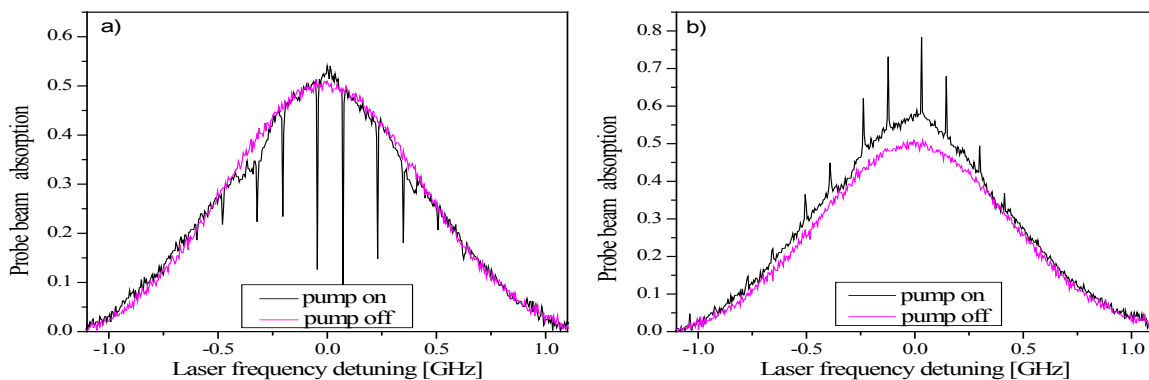
Further discussion of the processes involved shows that the area of the last group of transitions is the most promising for formation of the EIA resonances with a good contrast in a coated cell.

#### 2.4. EIA resonance observation in optical cell with anti-relaxation coating

The EIA resonances in Hanle configuration have been first observed in uncoated optical cells, irradiating Rb vapor by linearly [6] or circularly [7] polarized mono-mode laser light. In the case of a buffered cell containing alkali atoms, the EIA resonance transforms to an EIT one due to the depolarization of excited state resulting from Rb atom collisions with the buffered gas atoms [1].

While in [3] a new method has been theoretically proposed for observing a high-contrast and narrow-width EIA resonances using a buffered gas cell and a single hf transition of alkali atoms in Hanle configuration under counter propagating pump and probe light waves, here we decided to use an anti-relaxation coated optical cell that shows better efficiency for excitation by mono-mode laser light. Moreover, instead of using a single hf transition, in our case the EIA resonance formation takes place in the CO area (figure 3), where all 4 hf transitions contribute to the EIA resonance contrast.

The first experimental result observed by the new experimental approach is illustrated in figure 4. A coated optical cell containing pure K vapor is irradiated by a counter propagating: pump beam and a probe beam of significantly lower intensity. The absorption profile of the probe beam is measured under conditions of slow laser frequency scan and much faster variations around zero value of a magnetic field orthogonal to both laser beams. At low probe beam intensity that is used in our experiment, no Hanle resonance is observed experimentally when the pump beam is switched off. With the pump beam (of a significantly higher intensity) involvement, a Hanle resonance with a very good contrast is observed in the probe beam absorption. In the case of both beam being linearly polarized, EIT resonances are observed with contrast that is more than 70% of the maximal absorption

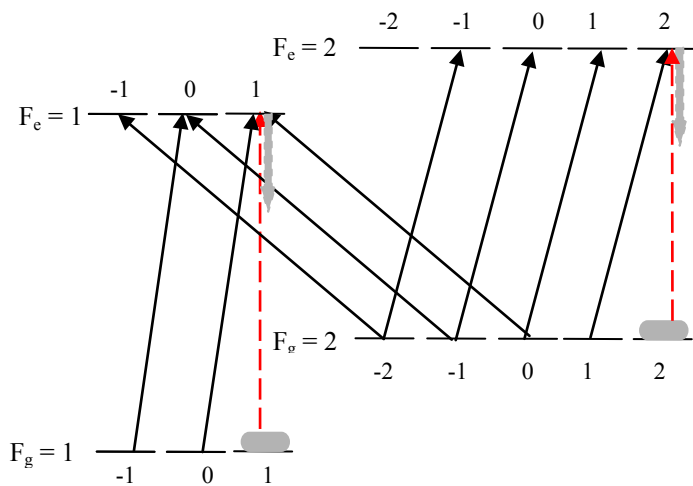


**Figure 4.** EIT (a) and EIA (b) resonances observed by means of scan of the laser frequency over the absorption profile and magnetic field varying around zero value. (a) pump and probe beams are of linear polarization;  $W_{\text{pump}} = 2.92\text{mW}$ ,  $W_{\text{probe}} = 0.98\text{mW}$ ; (b) pump beam is almost circularly polarized (1:1.4), probe beam is linearly polarized;  $W_{\text{pump}} = 2.91\text{mW}$ ,  $W_{\text{probe}} = 0.57\text{mW}$ .

of the D<sub>1</sub> line (figure 4a). When the pump beam polarization is changed to circular, the Hanle resonance sign is reversed and an EIA resonance is demonstrated with a dramatically increased contrast, more than 40% of the atomic absorption (figure 4b). Thus, the new experimental method proposed shows extremely good efficiency of EIA resonance preparation. The resonance width observed is 150 mG. It is enhanced by the low-quality magnetic shielding and not completely homogeneous magnetic field applied.

### 2.5. Discussion of processes involved in EIA resonance observation

Figure 5 illustrates the main hf transitions and processes leading to the EIA resonance formation. When the polarization of the pump beam is circular, the hf transition  $F_g = 1 \rightarrow F_e = 1$  leads to atomic accumulation on the magnetic sublevel  $m = 1$  of the  $F_g = 1$  level. Such an accumulation is provided by the fluorescence from the  $F_e = 1$  Zeeman sublevels. Note that the  $m = 1$  sublevel does not interact with the pump beam, i.e. its population is significant. Both the  $F_g = 2 \rightarrow F_e = 1,2$  transitions produce strong



**Figure 5.** Magnetic sublevels of the potassium  $D_1$  line hf levels and hf transitions involved in the EIA resonance formation. The circularly polarized pump beam is involved in  $\sigma^+$ ,  $F_g = 1 \rightarrow F_e = 1$  and  $F_g = 2 \rightarrow F_e = 1,2$  transitions (black solid arrows) between magnetic sublevels. The linearly polarized probe beam transitions are only shown that are responsible for the EIA resonance observation (red dash arrows).

atomic accumulation on Zeeman sublevel  $m = 2$  of the  $F_g = 2$  that also does not interact with the pump light. It is worth noting that the population of the ground-state magnetic sublevels not interacting with the pump beam is the highest in the case of magnetic field  $B = 0$ , i.e. at the maximum of the Hanle EIA resonance profile that is measured by the lower intensity probe beam. Further on, with the enhancement of the magnetic field value  $B$  in both directions with respect to  $B = 0$ , the atoms accumulated on  $m = 1,2$  ground Zeeman sublevels evolve on the other Zeeman sublevels and the probe beam sees a reduction of atomic population, i.e. the low-absorption wings of the EIA profile.

### 3. Conclusions

A new approach is proposed and demonstrated that provides formation of an EIA resonance with a contrast enhancement by one order of magnitude. Now the EIA and EIT resonances can be of comparable contrast. The new method is experimentally demonstrated in K vapor contained in a coated cell, thus realizing advanced combination of a narrow resonance with its high contrast. The amplitude and the sign (EIT or EIA) of coherent resonances can be easily controlled by the polarization of the involved laser beams. Further work is planned related to the magnetic shielding improvement and providing a homogeneous, orthogonal to the laser beam magnetic field, aimed at a significant resonance narrowing.

This result is expected to contribute significantly to expanding the EIA resonance applications in numerous new important fields.

### Acknowledgements

This work was supported by Marie Curie International Research Staff Exchange Scheme Fellowship within the 7th European Community Framework Program and by the Italian National Research Council and the Bulgarian Academy of Sciences (Program CNR/BAS 2013-2015).

### References

- [1] Andreeva C, Cartaleva S, Dancheva Y, Biancalana V, Burchianti A, Marinelli C, Mariotti E, Moi L and Nasyrov K 2002 *Phys.Rev. A* **66** 012502
- [2] Ho-Jung Kim and Han Seb Moon 2011 *Opt. Express* **19**/1 168

- [3] Brazhnikov D, Taichenachev A, Tumaikin A and Yudin V 2014 *Laser Phys. Lett.* **11** 125702
- [4] Gozzini S, Lucchesini A, Marinelli C, Marmugi L, Gateva S, Tsvetkov S and Cartaleva S 2015 *Proc. SPIE* **9447** 944708
- [5] Bloch D, Ducloy M, Senkov N, Velichansky V and Yudin V 1996 *Las. Phys.* **6** 670–8
- [6] Dancheva Y, Alzetta G, Cartaleva S, Taslakov M, Andreeva Ch 2000 *Opt. Commun.* **178** 103
- [7] Renzoni F, Cartaleva S, Alzetta G and Arimondo E 2001 *Phys.Rev. A* **63** 065401