Bulgarian Chemical Communications, Volume 48, Special Issue G (pp. 178-182) 2016

Dark resonances in potassium vapor for absolute measurement of magnetic fields

A. Krasteva[1]*, S. Gateva[1], A. Sargsyan[2], D. Sarkisyan[2], S. Cartaleva[1]

[1]*Institute of Electronics - BAS, 72 Tzarigradsko Chaussee Blvd., 1784 Sofia, Bulgaria*
[2]*Institute for Physical Research, NAS of Armenia, Ashtarak-2, 0203 Armenia*

Received October 10, 2016; Revised November 11, 2016

In this communication, we present a new approach for development of optical magnetometer based on the D_2 line of potassium (K), where the hyperfine transitions are strongly overlapped. Magnetically unshielded, 8-mm-long cell (containing K + 30Torr Ne) is introduced, in order to reduce the gradients influence of laboratory magnetic field B_{lab} to spectral width of Dark Resonances (DRs), which are used for magnetic field (MF) measurement. K vapor is irradiated by the light of frequency-modulated distributed feedback DFB diode laser that results in formation of narrow resonances with reduced absorption, i.e. DRs. Dark Resonance (DR) spectrum is shown as a function of frequency ν. Depending on the value of measured MF, different modulation frequencies f_m can be used. The spectral transition overlapping results in very good signal, non-critical to laser frequency shifts that is not the case with other alkali. The proposed approach can be used for MF measurement produced by different sources, for example of archaeological origin. Moreover, the principle of MF measurement allows development of self-calibrated optical magnetometer with potential for calibrating various commercially available magnetometers that need frequent calibrations.

Keywords: dark resonance, potassium vapor, magnetic field

INTRODUCTION

When an atomic system is prepared in a coherent superposition state, extremely narrow Dark Resonance [1,2] and related Electromagnetically Induced Transparency (EIT) [3] resonance can be observed where the atomic coherence cancels, or reduces, light absorption. The continuously expanding interest in the topic is due not only to the fascinating physics involving quantum coherence but also to the fact that there are many potential applications with relevance both in development of new techniques and devices, and in new scientific approaches to fundamental studies, such as slowing of light [4], quantum information storage [5], frequency standards [6], and precise magnetometers [7].

Resonances based on Dark State phenomenon have been studied mainly in Rb and Cs vapors, due to the availability of conventional diode lasers matching their resonance lines. Different approaches have been utilized for DR observation: most frequently two ground-state levels of alkali atoms are coupled to a common exited level by means of two coherent light fields, provided by laser frequency modulation in the GHz range. For practical applications it is advantageous to reduce the modulation frequency down to the kHz range, coherently coupling Zeeman sub-levels within single ground-state hyperfine (hf) level [8]. In such approach, however, the optical pumping to the ground-state hf level non-interacting with the laser field causes strong losses in the formation of the dark resonance. The hf optical pumping is particularly efficient when using noble-gas-buffered or anti-relaxation coated cells filled with alkali atoms. However, buffered and coated cells introduce real advantage and are used very often because they provide long-living ground-state coherence.

In this work we report experimental observation of sub-natural-width DR on the D_2 line of K vapor, demonstrating its application for development of simple experimental approach for magnetic field measurement based on the self-calibration of magnetic field value. The method is tested by laboratory magnetic field measurement. Potassium D_1 and D_2 lines provide the possibility to overcome the problem with the hf optical pumping because in this case the ground-level frequency difference (of 461.8MHz) is much less than the Doppler width of optical transition (about 800MHz). Thus, the overlapping of the Doppler profiles of the transitions, starting from both ground-state hf levels

* To whom all correspondence should be sent:
E-mail: anna0kr0stz@gmail.com

can provide the re-population of the resonantly exited by the light ground hf level [9], hence to enhance significantly the efficiency of the DR preparation.

EXPERIMENTAL SETUP AND METHOD FOR MAGNETIC FIELD MEASUREMENT

First the experimental setup shown in Fig.1 is briefly described. The frequency ν of the radiation of a mono-mode distributed feedback diode laser (λ=766.7nm, 2MHz bandwidth) is modulated at constant frequency f_m by means of a signal generator that modulates the diode laser current. The laser frequency modulation transforms the single-frequency laser field into a multi-frequency output, with frequency separation between the adjacent components equal to the modulation frequency f_m. There is a complete optical coherence between the components of the multi-frequency light. The laser beam is circularly polarized by a quarter-wave (λ/4) plate and directed to an optical cell containing K vapor, buffered by 30 Torr of Ne.

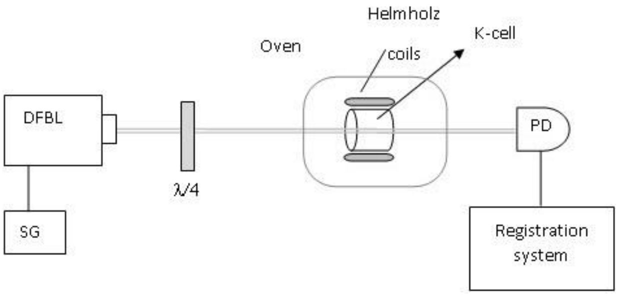

Fig. 1. Experimental set-up diagram: DFBL - distributed feedback laser, SG – signal generator, λ/4 - quarter-wave plate, PD - Photo-Detector.

In our experiment, 8-mm-long optical cell is introduced, in order to reduce the gradients influence of laboratory MF $\mathbf{B}_{lab}$ to spectral width of DRs, as the measurements are performed in magnetically unshielded environment. A pair of Helmholtz coils is situated around the K-cells in a way to produce magnetic field $\mathbf{B}_{coil}$ orthogonal to the laser beam propagating direction. The applied magnetic field $\mathbf{B}_{coil}$ is continuously varied in two opposite directions crossing the $\mathbf{B}_{coil} = 0$ value. A photo-detector (PD) is used for registering the signal of the transmitted thought the K cell laser light.

The laser modulation frequency f_m is kept constant but the magnetic field value is swept in a large interval around $\mathbf{B}_{coil} = 0$. If in laboratory MF $\mathbf{B}_{lab}$ K atoms are irradiated by the light modulated at constant frequency and their absorption is registered versus an orthogonal to the laser beam summary MF $\mathbf{B} = \mathbf{B}_{lab} + \mathbf{B}_{coil}$, several sub-natural-width dark resonances will be observed: (i) at $\mathbf{B} = 0$ (Hanle resonance), (ii) at MF determined by the laser modulation frequency ($\pm 1^{st}$ resonances) and (iii) at its harmonics ($\pm 2^{nd}$, $\pm 3^{rd}$, … resonances). Generally, two types of DRs are observed. The first type is the DR centered at $\mathbf{B} = 0$, where the Zeeman sublevels belonging to single hyperfine ground levels are degenerate, i.e. of the same energy. The resonance, centered at zero MF is related to the well-known Hanle resonance, which is obtained without any modulation of the light but only scanning the magnetic field around $\mathbf{B} = 0$ value.

Enhancing magnetic field, first two resonances occur on either side of the MF scan, centered at the field values creating Larmour precession of the magnetic moments with frequency ν_L that is equal to laser modulation frequency, i.e. $\nu_L = f_m$. With the MF scanned in the two opposite directions, the side resonances appear at positions symmetrical to B = 0. In this way, the known laser modulation frequency, provided by the SG can be used as a precise measure of the magnetic field value.

RESULTS AND DISCUSSION

Spectroscopy of K is different from those of Rb and Cs, due to the small spacing of its ground-state hyperfine energy levels. In particular, the ground-state hyperfine splitting in K is much less than the Doppler width of hyperfine transition profiles, and hence only summary absorption profile can be seen on each of the D_1 and D_2 lines of K. The energy levels and hyperfine transitions involved in the D_2 line (λ = 766.7 nm) of K are shown in Fig. 2a. It can be seen that the Doppler profiles of the two groups of hyperfine transitions starting from the ground levels F = 1 and F = 2 suffer strong overlapping due to the 800MHz Doppler width of each F → F' hyperfine transition presented in Fig.2a. From the other hand, such overlapping is advantageous for performing coherent spectroscopy based on excitation of ground-state hyperfine levels, providing the repopulation of the resonantly excited ground hyperfine level [9]. It should be stressed that both groups of hyperfine transitions, each starting from single ground state (F = 1 or F = 2) level are completely overlapped. Due to this fact, the formation of the DR is discussed only for the F = 2 → F' = 2 hyperfine transition. Fig. 2b illustrates the formation of 4 three-level Λ systems, based on Zeeman sub-levels of the F = 2 hyperfine level.

Starting from the left to the right, the first Λ system shows simultaneous excitations of two ground Zeeman sub-levels (F = 2, m_F = -2 and F = 2, m_F = -1) to a common exited Zeeman sub-level (F' = 2, $m_{F'}$ = -1). The two radiations forming the Λ system should be properly polarized to allow transitions to the level F' = 2, $m_{F'}$ = -1 of the excited state. In the example reported in Fig. 2b, the first radiation is of σ type, while the second one is π polarized light. It is easily to see that in the same way the following 3 pairs of Zeeman sub-levels of the ground state with Δm= ±1 can be connected by Λ systems to respective excited Zeeman sub-levels. Note that all four pairs of ground state levels contribute to formation of single DR, due to the equal energy difference between the two ground Zeeman sub-

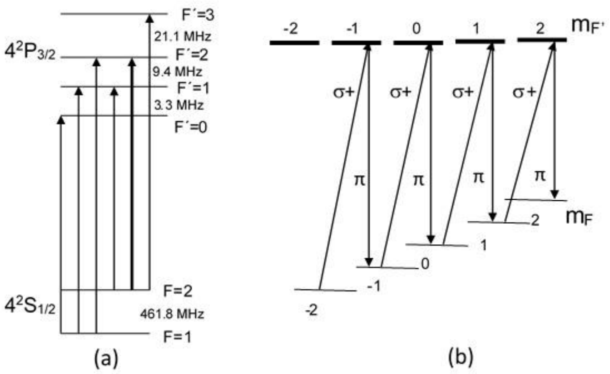

Fig. 2. (a) Energy level diagram of the $4^2S_{1/2} \rightarrow 4^2P_{3/2}$ transitions (D_2 line) of ^{39}K. (b) Simplified energy level diagram. Zeeman splitting of the F = 2 level is only shown because the F' = 2 level splitting is much less than its spectral width.

levels. The two optical frequency fields needed for the simultaneous excitation of the Zeeman sub-levels are produced by means of modulating the current of the diode laser at the frequency difference between the two optical transitions. Optical sidebands of the emission line of the diode are produced with a constant phase relationship between all components. The matching of the energy distance between Zeeman sublevels and the optical frequencies differences is obtained by changing the Zeeman splitting applying the above discussed scanned MF. If a wide scanning of the magnetic field is performed, several Dark Resonances can be observed.

In Fig. 3 the experimentally measured DR spectrum is shown, where the laser light frequency is tuned to the D_2 line absorption profile and it is modulated at the fixed frequency f_m = 200 kHz. The transmitted power is measured with a photodiode and the signal is recorded by a digital oscilloscope.

Scanning MF around **B** = 0, whenever the splitting of Zeeman sub-levels of the ground state matches the frequency difference of a pair of the components of laser spectrum, a Λ chain is created (see fig.2b) and a narrow DR is observed. In Fig. 3, besides the signal at B = 0 (0^{th} dip), two pairs of DR dips in the absorption signal appear. They can be related to the sidebands with frequency separations of modulation frequency f_m and $2f_m$ that exist in the spectrum of the diode laser. It is worth noting that the n^{th} DR is not in simple correspondence with the n^{th} sideband, e.g. the 2^{nd} DR is due to the presence of the 0^{th} and 2^{nd} sidebands, but it may originate also due to the presence of 1^{st} and -1^{st} ones. The highest order of the DR gives information about the most distant pair of sidebands, having a suitably high power.

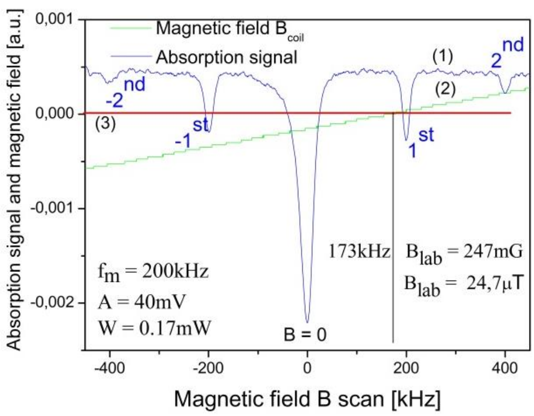

Fig. 3. Dark resonances in K vapor absorption measured as a function of magnetic field B, scanned around B = 0. The measured stray magnetic field in laboratory is: B_{lab} = 24.7μT.

It should be pointed out that very good signal-to-noise, narrow dark resonances are observed for modulation frequency much smaller than the width of the laser line. Hence, the spectral profiles of the two fields producing the dark state are strongly overlapped. In the case of coherent population trapping at Zeeman sublevels of different ground-state hyperfine levels, the modulation frequency is in the GHz region that is several orders of magnitude larger than the laser line width. In Fig. 3, the DR spectrum is shown as a function of frequency ν. In our experiment the DR spectrum is measured as a function of magnetic field B_{coil}, which is not calibrated preliminary. In our case, the absolute calibration of the coil can be done using the presented in Fig. 3 DR spectrum. Measuring the zero point of the coil current (see curve 2, Fig. 3) and using the related to D_2 line equation ν[kHz]=7B[μT] [10] that is determined from the Zeeman splitting of ground levels, the absolute value of MF B can be deduced. In order to determine the B_{lab} magnetic field (that is the final goal in this work), only the $B_{coil} = 0$ point at $\nu = 173kHz$ has to be used, i.e. the crossing point of line 3 with line 2 (Fig.3). This results in a measured value of $B_{lab} = 24.7\mu T$. Depending on the value of the measured MF, different frequencies f_m can be used.

In order to test the proposed approach for measurement of absolute value of MF without magnetic shielding of the optical cell, several different modulation frequencies of diode laser current are used in the experiment under the same laboratory environment. In Fig. 4, the DR spectrum is shown for $f_m = 100kHz$, $W = 0.2mW$ and the same amplitude of modulation. It can be seen that here the measured $B_{lab} = 24.8\mu T$, which is in agreement with the result shown in Fig. 3. The magnetic field measurements, based on the new approach are also supported by an independent measurement using different magnetometer.

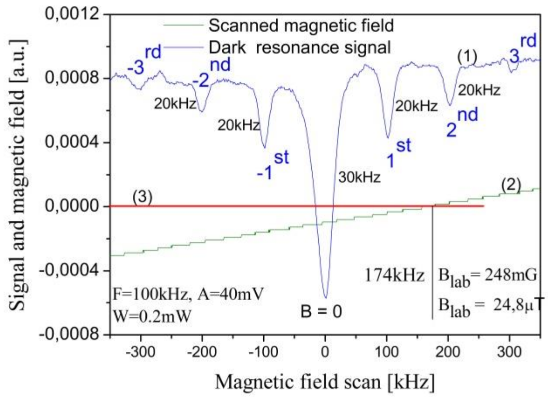

Fig.4. DR spectrum: $B_{lab} = 24.8\mu T$.

Comparing Fig. 3 and Fig. 4, one can conclude that in case of lower modulation frequency, two more DRs ($\pm 3^{rd}$) are observed, due to more effective modulation of the laser current. It can be seen that the spectral width of observed DRs is well below the natural width (6.2 MHz) of optical transitions, on the first resonance line in K. The DR width is mainly determined by the spectral width of the ground-state energy levels. Mainly, the strong DR narrowing is a result of two factors. The first one is the protection against spin relaxation collision with the cell-walls, provided by the used buffer gas in the optical cell. At the same time, the overlapping of the Doppler broadened profiles of the hyperfine levels in K causes a great reduction of the optical pumping, producing great performance and strong signal/noise improvement for both types of DRs. This is not the case when using other alkalis, where the poor or absent overlapping of the hyperfine optical transitions causes a more efficient optical pumping, which depletes the populations available for the DR preparation.

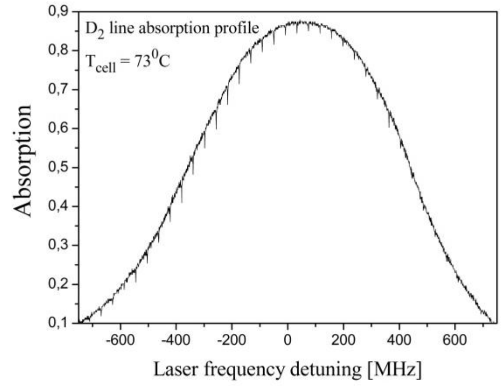

Fig. 5. Double scan: laser frequency slow detuning across the D_2 line and magnetic field faster modulation around B = 0.

Another advantage of K also results from the optical transition profiles overlapping. A double scan of the laser frequency, that is performed by a slow scan of the laser current and faster variations of MF around $\mathbf{B} = 0$ allows measurement of the DR contrast over the entire D_2 line profile. In this case no kHz modulation is applied to the current. A double scan applied for the absorption profile measurement of D_2 line with Hanle type resonances is shown in Fig.5. It can be seen that the DRs are registered in very large region of the absorption profile. Hence, due to the strong overlapping of D_2 line hyperfine transitions there is no need of precise fixing of laser current, in order to observe a DR with good amplitude. This is not the case of DR observed in Cs buffered by noble gas, where the narrow resonance exists in a narrow region on the slope of absorption profile.

CONCLUSION

The presented experimental study show important advantages of using K-atoms, for DR-based methodology applied to absolute MF measurement. At the same time, the significant reduction of the optical cell longitudinal dimension and the overlapping of the Doppler broadened profiles of the hyperfine transitions cause a great reduction of the optical pumping, producing efficiency improvements both in the Λ and in the Hanle configurations and relatively narrow DR, less influenced by the laboratory MF gradients. The proposed approach can be used for the measurement of magnetic fields that are produced from different sources. Moreover, the principle of

MF measurement allows development of self-calibrated optical magnetometer with potential for calibration various portable magnetometers that are commercially available but need regular calibration for absolute magnetic field measurements.

Acknowledgement: *A. Krasteva and S. Gateva personally acknowledged the program for support of the young scientists in BAS for funding within grant DFNP-188/2016.*

REFERENCES

1. G. Alzetta, A. Gozzini, L. Moi, and G. Orriols, *Nuovo Cimento* **36**, 5-20 (1976).
2. E. Arimondo, G. Orriols, *Lett. Nuovo Cimento*, **17**, 333 (1976); E.Arimondo, *Prog.Opt.* , **35**, 257 (1996).
3. L. Hau, S. Harris, Z. Dutton, C. Behroozi, *Nature*, (London) **397**, 594 (1999).
4. A. Zibrov, M. Lukin, M. O. Scully, *Phys.Rev.Lett.*, **83**, 4049 (1999).
5. A. Zibrov, A. Matsko, O. Kocharovskaya, Y. Rostovtsev, G. Welch, M. O. Scully, *Phys.Rev.Lett.*, **88**, 103601 (2002).
6. S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, J. Kitching, L.-A. Liew, et al., *Appl. Phys. Lett.*, **85,** 1460 (2004)
7. D. Budker and M. Romalis, *Nature Physics*, **3,** 227 (2007).
8. Ch. Andreeva, G. Bevilacqua, V. Biancalana, S. Cartaleva, Y. Dancheva, T. Karaulanov, C. Marinelli, E. Mariotti and L. Moi, *Appl. Phys. B*, **76**, 667 (2003).
9. K. Nasyrov, S. Gozzini, A. Lucchesini, C. Marinelli, S. Gateva, S. Cartaleva, and L. Marmugi, *Phys. Rev. A*, Vol.**92**, 043803, (2015).
10. S. Gozzini, S. Cartaleva, D. Slavov, L. Marmugia, A. Lucchesini, *Proc. SPIE* , **7027**, 70270K (2008).

ТЪМНИ РЕЗОНАНСИ В ПАРИ НА КАЛИЯ ЗА АБСОЛЮТНО ИЗМЕРВАНЕ НА МАГНИТНИ ПОЛЕТА

А. Кръстева[1]*, С. Гатева[1], А. Саргсиан[2], Д. Саркисиан[2], С. Карталева[1]

[1]*Институт по електроника, Българска академия на науките, бул. „Цариградско шосе“ 72, 1784 София, България*

[2]*Институт по Физика, Национална академия на науките на Армения, 0203 Ащарак-2, Армения*

Постъпила на 10 октомври 2016 г.; коригирана на 11 ноември, 2016 г.

(Резюме)

В това съобщение предстяваме нов подход за развитие на оптичен магнитометър базиран на D_2 линията на калия (K), където срвъх фините преходи са силно препокрити. Магнитно неекранирана 8-мм клетка съдържаща K и 30Torr Ne е използвана с цел да се намали влиянието на градиентите на лабораторното магнитно поле B_{lab} върху спектралната ширина на тъмните резонанси, които са използвани за измерването на магнитното поле. Парите на K са облъчени със светлината на честотно моделиран диоден лазер с разпределена обратба връзка, което води до формирането на тесни резонанси на намалено поглъщане, тоест тъмни резонанси. Спектъра на тъмните резонанси е изследван като функция на честотата ν. Взависимост от стойността на магнитното поле, различни честоти на модулация f_m могат да бъдат използвани. Препокриването на спектралните преходи води до много добър сигнал, некритичен от отместването на лазерната честота, какъвто не е случая при другите алкални пари. Предложения подход може да бъде използван за измерване на магнитно поле предизвикано от различни източници. Освен това, принципа на магнитното измерване позволява развитие на самокалибриращ оптичен магнитометър с потенциал за калибриране на различни налични в търговската мрежа магнитометри.