FM SPECTROSCOPY OF NONLINEAR MAGNETO-OPTICAL RESONANCES

V. Baryshev
FGUP "VNIIFTRI", Mendeleevo, Moscow Region, 141570, Russian Federation
Email :barychev@aspnet.ru

Abstract: The experiments on the detection of nonlinear magneto-optical transitions in the Hanle configuration on D_2 line of Cs atom by means of FM spectroscopy are presented. The error signals corresponding to the sub-natural electromagnetically induced absorption resonances in cesium vapor cell without buffer gas are most prominent on the cycling $F_g = 4 - F_e = 5$ transition and capable to be utilized for diode laser frequency stabilization, for example. The EIA error signal superimposed on the saturated absorption error signal becomes apparent when the last one corresponds to the dispersion component of the photo-detector beat signal formed by the frequency modulated probe radiation.

INTRODUCTION

Such phenomena as electromagnetically induced transparency and absorption (EIT and EIA) [1, 2] with their feature of suppressed or increased absorption on sub-natural resonant transitions are of great interest in the area of high-resolution laser spectroscopy. These effects have shown the capacity for application in metrology of compact microwave frequency standards and atomic magnetometers as well. Since the contrast of such resonances can be just of a few percent [1], application of highly sensitive detection technique might be useful to resolve them. FM spectroscopy method [3] satisfies fully that demand. For instance, it has been recently reported on FM spectroscopy of coherent population trapping (CPT) resonances in Cs vapor [4, 5]. In combination with reduced light shift, the capacity of extremely high-speed laser frequency tuning given by FM sideband technique can promise further improvement of short-term stability of frequency standards utilizing CPT clock transitions.

The EIT and EIA resonances in saturated vapor can be obtained in the experimental configuration when the atom in the ground state is excited by bi-chromatic laser radiation [6, 7] or in the Hanle configuration when nonlinear resonance appears in the traveling light wave absorption which depends on the static magnetic field value.

In this brief report, the experiments on the detection of nonlinear magneto-optical transitions on D_2 line of Cs atom by means of FM spectroscopy are presented. First, single traveling light wave passed through the magnetically shielded cesium cell without buffer gas placed into magnetic field directed on the light beam (Hanle configuration). EIT or EIA resonances were observed at any point within Doppler-broadened profile of cesium D_2 absorption line when the magnetic field strength was modulated around zero value. Apparently this effect in such experimental configuration, in the cell without buffer gas does not have much practical meaning (for laser frequency control, for example).

To get the error signals corresponding to these magneto-optical transitions, the narrow atomic velocity groups responsible for formation of the sub-Doppler resonances were selected by means of saturated absorption spectroscopy.

EXPERIMENTAL SETUP AND RESULTS

In [7], the experimental observation of nonlinear magneto-optical effects in cesium vapor showed the reduced absorption features near the cycling transition. Their appearance has been explained as consequence of two-photon interference effects within V-type three-level atomic systems. The results were obtained when two collinear optical waves, coupling the same ground hyperfine level to a common exited state, were of mutually perpendicular linear polarizations. The weak uniform magnetic field parallel to the direction of laser beams was applied to the cell. Curve A in Fig. 1 shows the probe beam transmission signal as a function of probe detuning for the case when the coupling laser frequency was set nearly resonant with $6S_{1.2}$(F=4)–$6P_{3.2}$ (F'=5) cycling transition. This curve demonstrates non-Lorentzian dispersion-like line shapes of three resonances superimposed on Doppler profile with prominent non-absorptive central part in the vicinity where laser fields frequency difference gets close to zero. Two weak resonances marked with bars are located approximately in 250 and 450 MHz away from central strong resonance. All three resonances were considered as the result of combined contribution of optical pumping and two-photon absorption processes for different atomic velocity groups.

At present, the EIA effect on the closed transitions F $\rightarrow$ F' (where F и F' are the total angular momentum of the atom in the ground and excited states) is explained as a spontaneous transfer of the Zeeman coherence from the exited to the ground state [2]. The theorists, authors of [2], reported recently that the sign of the nonlinear magneto-optical resonances (EIT or EIA) on the cycling transition F=1$\rightarrow$ F'=1 in the field of the two counter-running waves depends strongly on the mutual orientation of their polarizations. It seems, the magneto-optical phenomena in the atomic vapors has not been studied entirely yet, and they still attract so much attention.

In the presented experiments, when saturation absorption is employed, saturating and probe laser beams were of the same (parallel) linear polarization. The experimental set-up is shown in Fig. 1. Grating stabilized external cavity diode laser (ECDL) in the Littrow configuration provided tunable single-frequency input radiation at 851nm. The AOM-RN [4, 5] single pass output consisted of three beams corresponding to the carrier ω and to the sidebands of ±1st diffraction order at frequencies $\omega \pm \Omega$. It was used as a probe beam for saturated absorption spectroscopy in a magnetically shielded cesium vapor cell at room temperature and was focused on a fast photo-detector PD1. Small part of the probe light was deflected by glass plate on photo-detector PD2 for monitoring the absorption.

The rf beat was detected by the heterodyne detection using double-balanced mixer, which produced dc signal, obtained when the laser frequency is scanned across Doppler broadened profile of cesium D_2 absorption line and coincides with the optical transition frequencies $6S_{1/2}$, F = 4 – $6P_{3/2}$, F' = 3, 4, 5. These signals served as the error signals for ECDL servo system. A Cesium cell is magnetically shielded. The longitudinal shielding factor is about 20, and the transversal one is 400. The longitudinal magnetic field is produced be the solenoid coil placed inside magnetic shield cylinder with end caps.

A particular attention will be paid to the EIA resonances on the cycling transition $6S_{1/2}$, F = 4 – $6P_{3/2}$, F' = 5, where the optical pumping effect is excluded. Fig. 3 shows the diagram of the electromagnetically induced transitions and the magnetic sublevels structure. In a longitudinal magnetic field with induction value B, the $6S_{1/2}$, F=4 ground state splits into nine magnetic sublevels shifted at a rate of $\gamma B m_4$ where γ = 0.35 MHz/Gauss and m_4 is magnetic quantum number [8].

Fig. 4 shows an error signal and PD2 transmission signal (with corresponding to EIA central peak) obtained in the Hanle configuration, when AOM-RN output, presenting probe radiation, passed through the Cs cell at the absence of the saturating beam. The AOM-RN modulation frequency was 27.4 MHz. The ECDL frequency ω was fixed near F = 4 – F' = 5 cycling transition frequency. The ECDL servo-loop was open. The magnetic field strength was modulated symmetrically around zero value by applying ramp voltage to the solenoid coil. The linear absorption of the probe field was about 60%. Power of the probe beam with diameter of 1.5 mm was 0.3 mW. Half width at half maximum of the EIA peak $\Delta B/2$ is about 0.27 Gauss. That corresponds to the shift value of $\gamma B \cong$ 100 kHz. If we assume that a magnetic sublevel m_4=4 is involved into formation of the peak, its half width at half maximum expressed in frequency domain will be about 400 kHz. A full width will of the order of 1 MHz comparable with laser spectrum line-width estimated to be about 1 MHz in free running regime.

In such experimental configuration, with or without saturating beam, EIA or EIT resonances were observed at any point within Doppler-broadened profile of cesium D_2 absorption line. An appearance of EIA strongly related to the cycling and to derived by it crossover resonances. The amplitude of the magneto-optical resonances strongly depends on the pumping effect, therefore the EIA is most prominent in the vicinity near the cycling hyperfine transition.

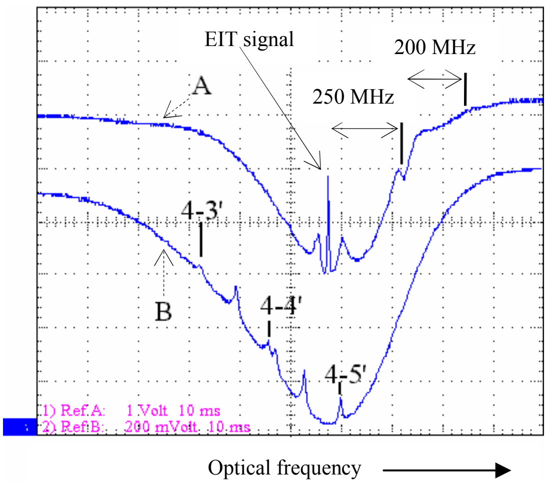

Fig. 1. Probe beam transmission signal (curve A). Curve B – reference saturation absorption signal.

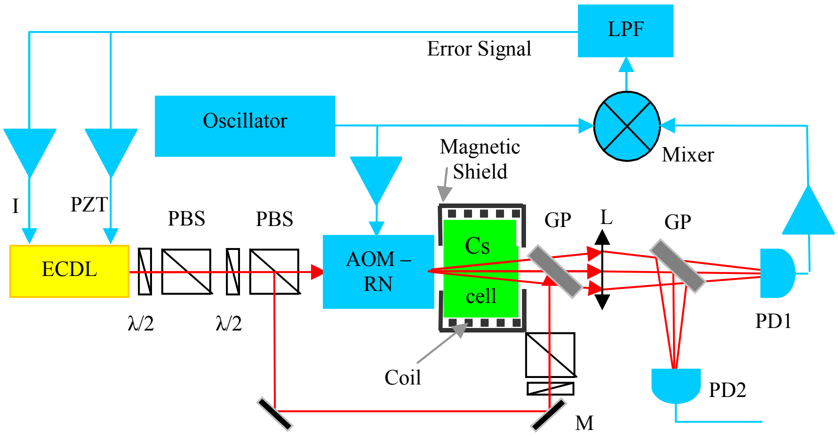

Fig. 2. Experimental setup. ECDL – external cavity diode laser; PZT – piezoelectric transducer; PBS – polarizing beam splitter; M – mirror; AOM-RN – acousto-optic modulator in the Raman-Nath diffraction regime; L – lens; PD – photo-detector; I - injection current; λ/2 – half-wave plate; LPF – low-pass filter; GP – glass plate.

Then, to get the error signals corresponding to the magneto-optical transitions at static magnetic field, the narrow atomic velocity groups responsible for formation of sub-Doppler resonances were selected by means of saturated absorption spectroscopy. It is helpful recall that, according the theory of FM spectroscopy [3], (8) in[4], the expression for the intensity of the light incident on a photo-detector PD1 contains a beat signal at AOM modulation frequency Ω whose in-phase component (cos Ωt) is proportional to the difference in loss experienced by the upper and lower sidebands, whereas the quadrature (sin Ωt) component is proportional to the difference between phase shift experienced by the carrier and the average of the phase shifts experienced by the sidebands. The cosΩt and sinΩt components of the beat signal are directly proportional to the absorption and dispersion, respectively.
A curve *1* in fig. 5,6 shows the error signal corresponding to EIA and superimposed on a dispersion-like saturated absorption error signal corresponding to the cycling F = 4 – F' = 5 transition. The slopes of these two error signals are of different sign, so narrow signal of 5 MHz width, indeed, corresponds to the increased absorption. The EIA error signal superimposed on the saturated absorption error signal becomes apparent when and only when the last one corresponds to the dispersion component of the photo-detector beat signal formed by the frequency modulated probe radiation. In this case the saturating beam is resonant with the same atom as the probe carrier.

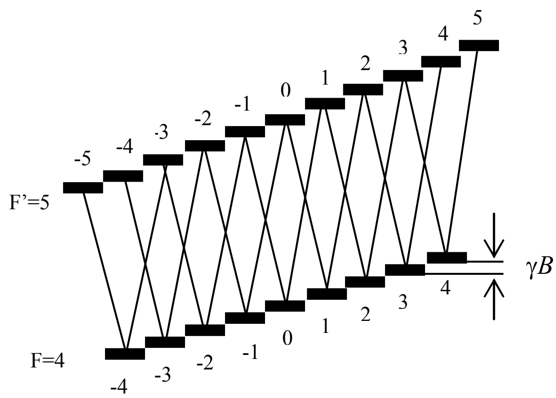

Fig. 3. Diagram of electromagnetically induced transitions

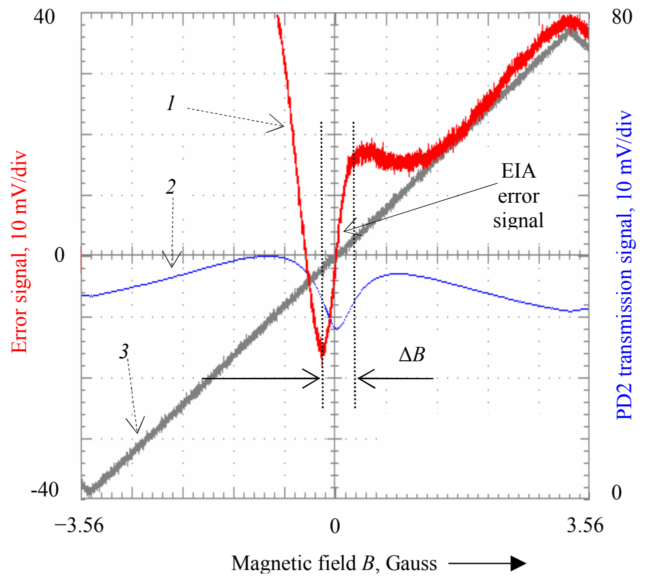

Fig. 4. Error (curve *1*) and PD2 transmission (curve *2*) signals dependence on magnetic field induction value *B*. Curve *3* – ramp voltage reference signal.

The modulation frequency value was 25.8 MHz, the calculated magnetic field value was B = 8.4 Gauss, power of the probe beam P_{pr} = 0.3 mW, saturating beam power P_{sat} = 0.33 mW. The EIA error signal is the result of overlapping of the error signals corresponding to the all possible magneto-optical resonances formed by the split and shifted magnetic sublevels. If we assume that each of them is formed by the pair of magnetic sublevels in the ground state in Λ or *N* type systems [2], the frequency separation $\Delta\omega$ between them should not exceed natural line-width 5 MHz. For B = 8.4 Gauss that value is $\Delta\omega = 2\gamma B \cong$ 5.9 MHz. At magnetic field strength exceeding B = 9-10 Gauss, the EIA error signal disappears. Apparently, the atoms in the narrow velocity group from V_z=0 to $V_z = \Delta\omega\, c/2\omega$ (where V_z is an atom velocity projection on a wave vector direction, c is the light speed) contribute to the EIA error signal.

No such narrow EIA or EIT error signals have been detected on other saturated absorption error signals, probably, due to the pumping and broadening effects.

In conclusion, it has been experimentally demonstrated that the detection of sub-natural magneto-optical resonances by means of FM spectroscopy with AOM-RN as an external phase modulator is possible. The EIA error signal superimposed on the saturated absorption error signal becomes apparent when the last one corresponds to the dispersion component of the photo-detector beat signal formed by the frequency modulated probe radiation.

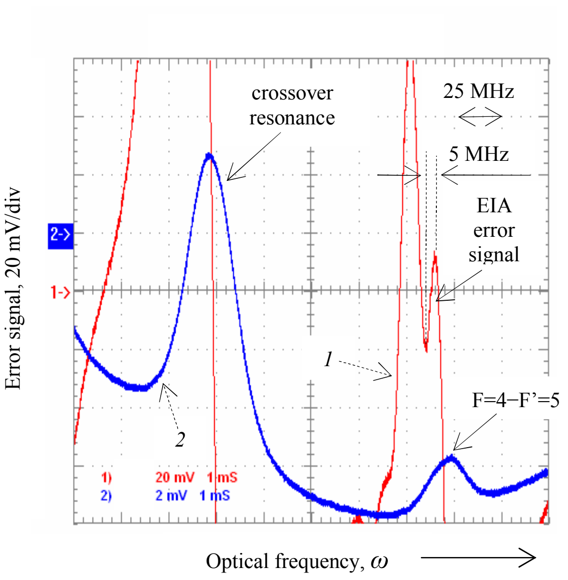

Fig. 5. Error (curve *1*) and PD2 transmission (curve *2*) signals recorded simultaneously.

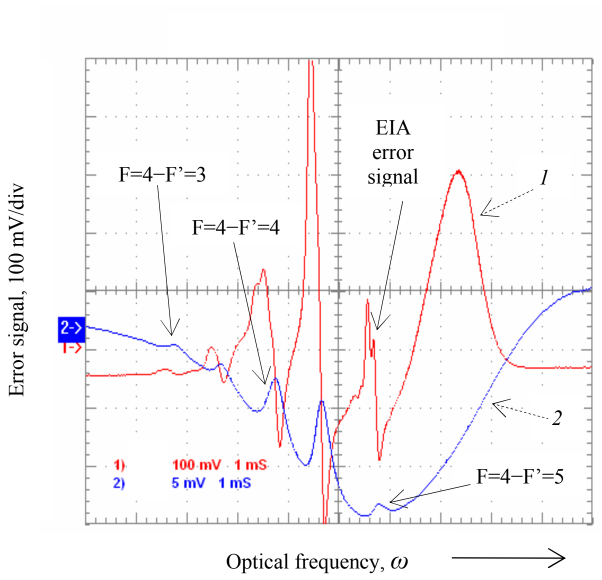

Fig. 6. Error (curve *1*) and PD2 transmission (curve *2*) signals recorded simultaneously.

References

1. A.S. Zibrov and A.B. Matsko, "Induced absorption resonance on the open $F_g=1 \rightarrow F_e=2$ transition of the D_1 line of the ^{87}Rb atom", *JETP Lett*., vol. 82, N. 8, pp. 472-476, 2005.

2. D.V. Brazhnikov, A.V. Taichenachev, A.M. Tumaikin, V.I. Yudin, S.A. Zibrov, Ya.O. Dudin, V.V. Vasil'ev, V.L. Velichansky, "Features of magneto-optical resonances in an elliptically polarized traveling light wave", *JETP Lett*., vol. 83, N. 2, pp. 64-68, 2006.

3. G. Bjorklund, "Frequency-modulation spectroscopy: a new method for measuring weak absorptions and dispersions", *Opt. Lett*., vol. 5, pp. 15-17, 1980.

4. V. Baryshev, V. Epikhin, L. Kopylov, Yu. Domnin, "FM spectroscopy of CPT resonances with AOM operating purely in the Raman-Nath diffraction regime as optic phase modulator. ", *In Proc. of EFTF-IFCS 2009*, pp. 582-586, Besanson, France, 2009;

5. V. Baryshev, V. Epikhin, "Compact AOM Operating Purely in the Raman-Nath Diffraction Regime as Phase Modulator in FM Spectroscopy", in press, (will be published in *Quantum Electronics* in 2010).

6. A Akulshin, S. Barreiro, and A. Lezama*, Phys. Rev. A*, vol. 57, p. 2996, 1998.

7. V. Barychev, V.Pal'chikov, A. De Marchi, "Nonlinear Magneto-Optical Effects in Cesium Vapor", *In Proceedings of the 6-th Symposium on Frequency Standards and Metrology* 2001, University of St. Andrews, Fife, Scotland, pp. 603-605, 2001.

8. Wynands R., Nagel A., Brandt S., Meschede D., and Weis A., *Phys. Rev. A*, vol. 58, №1, pp. 196-203, 1998.