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All-Optical Magnetometer Based on Resonant Excitation of Rubidium Atoms by Frequency Modulated Diode Laser Light

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Magnetic field and its gradient measurements based on coherent population trapping resonances at the D_1 line of ^{87}Rb are performed by means of coupling two ground-state Zeeman sublevels belonging to different hyperfine levels to a common excited state. Two coherent laser fields with frequency difference of 6.8 GHz are used. They are produced by direct current modulation of a diode laser. The resonance splitting and broadening caused by the applied magnetic field is measured by scanning the laser modulation frequency around the ground-state hyperfine frequency.

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1. Introduction

Optical magnetometers become nowadays among the most sensitive magnetometers [1]. Their potential is demonstrated in an increasing number of applications ranging from geophysical through space applications to the test of fundamental symmetries. Recently, the effect of coherent population trapping (CPT) has been used to develop an all-optical sensor with the aim of application for magnetic field (MF) measurement with good absolute accuracy, high spatial resolution and wide dynamic range [2]. CPT-resonances can be prepared in different configurations. The principal scheme consists of coupling two ground states of an atomic system to a common excited state using two phase coherent optical components.

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In this communication we present our results on building a practical CPT--based optical magnetometer. The CPT resonances are obtained by coupling two Zeeman sub-levels from the two different hyperfine ground-state levels of ^{87}Rb. In order to realize such a coupling, two phase-locked optical frequencies with the difference corresponding to energy separation between the ground levels are required. These optical components are provided by modulation of the diode laser current at frequency around 3.4 GHz equal to the half of the hyperfine splitting of ^{87}Rb. In this way, different orders of side bands separated by the modulation frequency are created in the laser spectrum. The magnetometer performance is studied depending on the light parameters and the index of modulation. The influence of the MF direction, gradient and 50 Hz noise are also discussed.

2. Experimental results and discussion

A portable magnetometer, based on the CPT phenomenon is designed and built in the Institute of Electronics (Fig. 1). The 795 nm (10 mW power) emission from a temperature controlled Fabry–Perot laser diode was circularly polarized and directed to a glass cell containing atomic vapor of ^{87}Rb with 20 Torr Ne buffer gas added. The diode current is modulated at 3.417 GHz using voltage controlled oscillator (VCO). The VCO spectral linewidth is about 3 kHz at 3 dB. Its output power is amplified to about 200 mW at 1 dB and coupled to the laser through a directional coupler. Additionally, the VCO frequency is appropriately swept (about 3 MHz) around the central modulation frequency in order to detect the CPT resonance splitting due to the measured MF. On the sweeping voltage of the VCO input a 0.8 kHz sinusoidal modulation is imposed, in order to apply

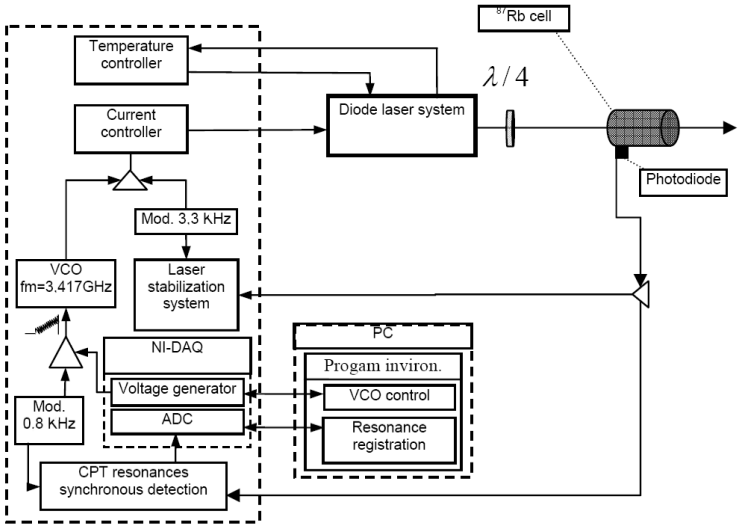

Fig. 1. The CPT based magnetometer diagram.

consequent synchronous detection technique. The VCO input parameters are controlled using PC software programmed AD/DA converters. The laser frequency was stabilized to the maximum of the Doppler profile of the fluorescence spectrum at ^{87}Rb D_1 line additionally modulating the laser current at 3.3 kHz. The fluorescence signal is collected by a photodiode. The photodiode signal is amplified and split to the stabilization system and the input of the synchronous detection. The output signal of the synchronous detector obtained after demodulation at 0.8 kHz is recorded.

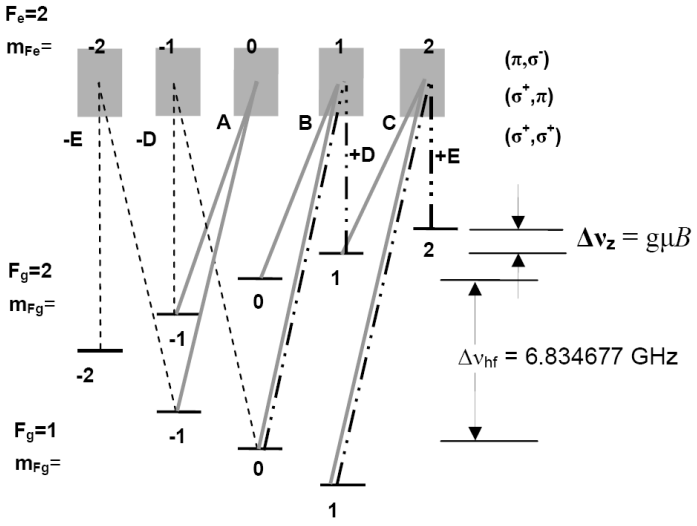

Fig. 2. Involved energy level scheme of ^{87}Rb D_1 line and possible Λ-scheme formation depending on the light polarization.

In Fig. 2, the energy level diagram of ^{87}Rb D_1 line is presented. Because of the opposite sign of the ground-state hyperfine-level g-factors, their Zeeman sublevels split antisymmetrically. In the general case of elliptically polarized laser light [3], 7 Λ-schemes can be formed leading to observation of 7 CPT resonances. Circularly polarized light (σ^+) allows the formation of the A, B and C Λ-schemes only. However, introducing some ellipticity, the light polarization can be represented by a sum of σ^+, σ^-, and π components, responsible for the appearance of two new pairs ($\pm D$ and $\pm E$) of Λ-schemes. The energy-level-frequency-difference shift $\Delta\nu_i$ between the Zeeman ground-state levels of the considered Λ-schemes can be expressed as follows: $\Delta\nu_i = F_i - F_0 = K_i\Delta\nu_z$, where F_0 corresponds to half of the Rb "clock" transition frequency $\Delta\nu_{\rm hf}$ (accounting for all the perturbation on its value). The frequency $\Delta\nu_{\rm hf}/2$ equals to the modulation frequency needed for the resonance formation on the "B" Λ-scheme. F_i is the modulation frequency at which the considered CPT resonance "i" is centered; $\Delta\nu_z = g\mu B$ is the Zeeman splitting between two sublevels with $\Delta m = 1$ (g and μ being the hyperfine levels

TABLE

Frequency shift of the CPT resonances due to the magnetic field

i	A	B	C	$+D$	$+E$	$-D$	$-E$
$\Delta\nu_i = K_i\Delta\nu_z$	$-2\Delta\nu_z$	0	$2\Delta\nu_z$	$\Delta\nu_z$	$3\Delta\nu_z$	$-\Delta\nu_z$	$-3\Delta\nu_z$

g-factor and Bohr magneton, respectively). B is the measured MF. $K_i\Delta\nu_z$ are presented in Table for each Λ-scheme.

Therefore for the magnetic field B we have

$$B = \frac{\Delta\nu_i}{K_i g\mu} = \frac{F_i - F_0}{K_i g\mu}.$$

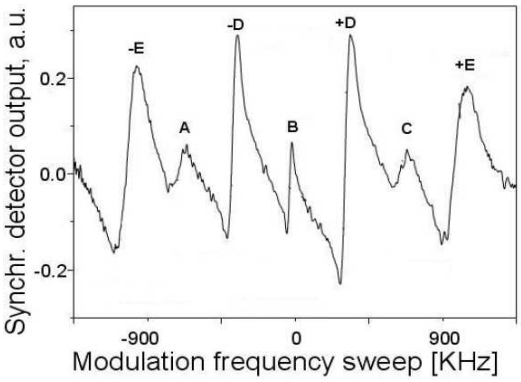

Fig. 3. Experimentally obtained 7 CPT resonances in MF of $(453 \pm 4) \times 10^{-7}$ T.

Figure 3 shows the experimentally obtained CPT resonance splitting (by the laboratory + Earth MFs) into 7 components, when irradiating the Rb cell with elliptically polarized light. The labels describe the corresponding Λ-schemes. Using the relations presented in Table, the MF value (of $(453 \pm 4) \times 10^{-7}$ T) is derived from the modulation frequency difference between each pair of the resonances.

As it can be seen from Fig. 3, the widths of different resonances are different. The higher the order of the resonance (compared to "B" resonance) the more sensitive is to the MF, as well as to its gradient. Therefore the "E" resonances are much broader than the "B" resonance. Comparing the CPT resonance width with this of the unaffected by the MF (in linear to the field approximation) resonance "B", we can estimate the MF gradient δB_i as well

$$\delta B_i = \frac{\delta\nu_i - \delta\nu_B}{K_i g\mu}.$$

Here $\delta\nu_i$ is the "i"-resonace width and $\delta\nu_B$ is the "B"-resonance width.

We propose to determine the MF gradient using also a mathematical fitting procedure. It consists of the following steps: First we apply chi-squared fit to "B"-resonance assuming that the CPT resonance shape is Lorentzian. Then for

each of the resonances we synthesize a fitting which is a sum of n-copies ($n = 5$ in our first approximation) of the "B"-resonance fitting. Each of these n-copies has the same shape but different amplitude and shift one to the other. The obtained set of fitting resonances (Fig. 4, L_1, L_2, L_3, L_4, and L_5) allows us to determine the MF gradient (in our case: 90×10^{-7} T over a volume of 1 cm^2) from the frequency interval between the first (L_1) and the last (L_5) in the set. The physics behind this procedure relies on the possibility to divide in several areas (with different MFs imposed) the volume (1 cm^2) from which the fluorescence is collected. One advantage of the approach proposed is that the obtained MF gradient value is not dependent on the way we determine the resonance width. Applying this procedure to each of the magnetically sensitive CPT resonances we obtain the average value for the scanning period.

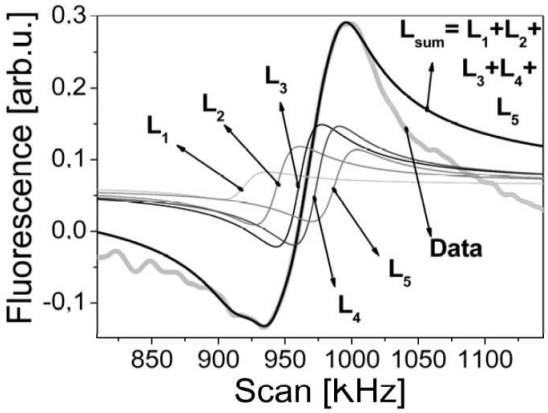

Fig. 4. Illustration of magnetic field gradient deduction.

The described approach for MF measurement allows measuring the scalar value of the MF because the CPT resonance position is determined by the Zeeman sublevels splitting. The resonance broadening is mainly due to the MF gradients. However, in the presence of alternating MF component, depending on its frequency and amplitude the resonances broaden additionally [4]. Therefore the obtained δB_i value should be interpreted as a complex result of the MF gradient and the presence of alternating MF.

Other source of resonance broadening is the modulation of laser current. Three different harmonic oscillations are used to control the laser optical frequency appropriately: 3.3 kHz for laser frequency stabilization, 0.8 kHz for the synchronous detection of CPT resonances and 3.4 GHz for preparing the laser optical spectrum. The most important point is related to the spectral purity of the GHz-generator directly reflecting to the purity of the optical spectrum of the laser radiation. In our case this is the factor limiting the resonance width and therefore the resolution of the magnetometer. This factor stresses on the importance of a high-quality GHz VCO in the approach presented here.

Optimization of the modulation index $I_{\rm m}$ is also a key point. It is defined as the ratio between the deviation of the optical frequency Δf determined by the amplitude of the 3.4 GHz oscillation and the modulation frequency $f_{\rm m}$ itself: $I_{\rm m} = \Delta f / f_{\rm m}$. Very small value of $I_{\rm m}$ compromises the resonance amplitude and contrast. However, the $I_{\rm m}$ increasing can cause an additional resonance broadening. The optimization of the modulation index is also related to the kind of Rb cell used. Evacuated and coated cells, as well as the presence of buffer gas and its pressure modify the Rb fluorescence profile differently and need particular optimization of $I_{\rm m}$.

The dynamic region of the magnetometer is estimated to be $(10^{-7}-10^{-3})$ T. The minimal and maximal MFs are determined by the resonance width and the nonlinear Zeeman effect, respectively. The sensitivity in our measurements is estimated to be 50 nT.

The developed methodology can be used for MF measurement in many fields including MF mapping of plasma objects with high accuracy and spatial resolution as well as in particular applications where both all-optical passive sensor and remote measurement are important.

Acknowledgments

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