Optical atomic magnetometry

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Abstract—This work presents new methods of optical magnetometry developed in the Center for Magneto-Optical Research at the Jagiellonian University. Using rubidium atoms contained in cm-long glass cells and amplitude-modulated laser light, we have recorded magneto-optical signals of extremely small widths. These signals allow measurements of magnetic fields with a sensitivity comparable to that achieved with magnetometers based on Superconducting Quantum Interference Devices (SQUIDs).

In 1846, M. Faraday discovered that the polarization plane of linearly polarized light undergoes rotation when the light beam propagates through a material sample placed in a longitudinal magnetic field [1]. The rotation angle φ is proportional to the magnetic field intensity B, and to the propagating distance d in active medium

$$\varphi = VdB. \tag{1}$$

where V is the Verdet constant. The dependence of the polarization rotation on the magnetic field enables the application of this phenomenon to magnetometry. For instance, it is used in contemporary magnetic-field sensors based on optical fibers [2].

A real breakthrough in studies of the Faraday effect came with the advent of lasers and their application to atomic spectroscopy. First measurements of that kind were performed by W. Gawlik *et al.* in 1974 [3], where it was shown that with intense light sources the dependence of the rotation angle on the magnetic field is more complex than in the case of weak light. In particular, very narrow new structures appeared close to B=0. It was found that the rotation angle associated with these narrow signals depended on the light intensity, hence they were related to the nonlinear Faraday effect (NFE) [4,5]. More accurate measurements allowed the discovery of a complex structure in these new signals; in most cases, it consisted of two contributions of different widths: the natural linewidth Γ of the atomic transition and the relaxation rate of the ground state γ ($\gamma << \Gamma$) [4,5].

The relaxation rate of the ground-state coherence is determined by the inverse relaxation time of the ground state. When using glass cells as containers for low-pressure gas, the effective lifetime of ground-state coherence is related to the atomic transit time across the laser beam which is of the order of some μs. Consequently, NFE signals of some μT widths and mrad amplitudes are observed (Fig. 1). More details on the physical principles of nonlinear magneto-optical effects can be found in recent reviews [4,5].

There are two principal methods which allow an extension of atomic coherence lifetimes. In the first method, noble gas under pressure of 1-100 mbar is added to the cell with the investigated atomic vapor. Since collisions with the noble gas atoms are highly elastic, they do not destroy atomic coherences, yet they reduce the mean free path and extend the time over which the atoms can interact with light before their coherences are destroyed by wall collisions. The second method employs coating of the inner cell walls with special anti-relaxation layers. This prohibits coherence loss in a wall-atom collision and extends its lifetime, thereby narrowing the width of the NFE signals. Both methods are capable of extending the coherence lifetimes up to some hundreds of ms, which enables observation of magneto-optical resonances of μG widths and mrad amplitudes (inset to Fig. 1).

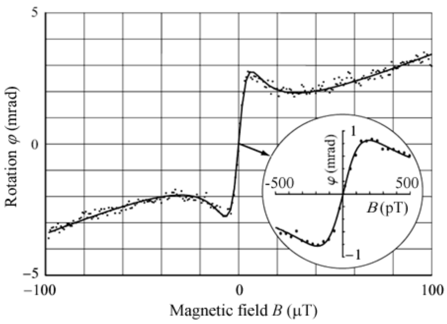

Fig. 1. Magneto-optical rotation as a function of the magnetic field measured with the cell with anti-relaxation-wall coating. From Ref. [6]

For weak magnetic fields, such that $\Omega_L<\gamma$, where $\Omega_L=g\mu_B B/\hbar$ is the Larmor frequency, g - the Landé factor, μ_B - the Bohr magneton, and $\hbar$ - the Planck constant over 2π, the rotation angle depends linearly on the magnetic field intensity. This allows the application of the nonlinear Faraday effect for precision magnetometry. The highest sensitivity that can be achieved with alkali

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atoms contained in an anti-relaxation-coated cell at room temperature is estimated to be at the level of 10^{-16} T/Hz$^{1/2}$ [7], which is comparable with the sensitivity of SQUIDs.

A significant advantage of this optical apparatus is its instrumental simplicity. The most essential elements of the methods are: the glass cell containing atom vapors either filled with buffer gas or equipped with an anti-relaxation layer, the laser emitting light of the frequency tuned to resonance with the atomic transition, high quality polarization optics including a linear polarizer and a balanced polarimeter.

The nonlinear Faraday rotation is a very sensitive method for measuring magnetic fields, yet it is limited to weak fields only and cannot be directly extended to fields higher than the widths of the typical resonance. An additional drawback of the method is its limitation to scalar measurements, which yields absolute intensity of the magnetic field but no information on its direction. Both limitations can be successfully overcome with the help of modulated light. The modulation can either be applied to the frequency (FM) or to the amplitude (AM) of a light beam.

A pulse of linearly polarized light interacting with the medium modifies the constituting particles' quantum states, in particular, it creates ground-state coherences, which results in the appearance of birefringence in the medium with an optical axis parallel to the light polarization. External magnetic field causes rotation of the birefringence around the magnetic field with frequency Ω_L (Larmor precession) [4,5]. If $\gamma << \Omega_L$, the birefringence axis rotates many times before it decays in atomic relaxation processes. If the light modulation is not synchronized with the Larmor precession, after many pulses the net birefringence averages to zero in the whole medium and no NFE signal is observed. However, if the pulse repetition and the Larmor frequencies are commensurate and synchronized, a macroscopic birefringence builds up in the medium and the optical anisotropy of the whole medium precesses with Ω_L. Consequently, the polarization plane of the transmitted light rotates in time and the amplitude reaches its maximum when the modulation and Larmor frequencies are synchronized.

Figure 2 depicts the layout of the system used in the Center for Magneto-Optical Research at the Jagiellonian University in Kraków for studying NFE with amplitude-modulated light. The magneto-optical sample is a glass cell (about 2 cm long) filled with rubidium atoms (isotope ^{87}Rb). The inner cell walls are coated with an anti-relaxation paraffin layer. A semiconductor diode laser is used as the light source. The laser wavelength (λ=795 nm) is precisely controlled by an external locking system [8] and its light is amplitude modulated by an acousto-optical modulator. The cell is placed within a magnetic shield made of three layers of mu-metal. The nonlinear Faraday rotation signals are recorded by a balanced polarimeter equipped with a high-quality crystal polarizer, two photodiodes and synchronous detector (lock-in).

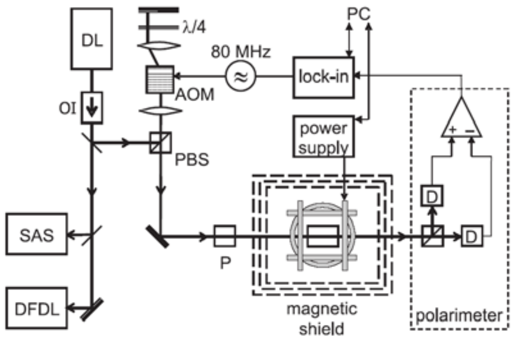

Fig. 2. Apparatus for measuring the rotation of a polarization plane in experiments with AM light. DL symbolizes the external-cavity diode laser, OI - the optical isolator, SAS denotes the laser frequency calibration system employing saturated absorption, DFDL is the laser frequency calibration system based on Doppler-free dichroism, AOM - the acousto-optical modulator, $\lambda/4$ denotes the quarter-lambda plate, PBS - the polarization beam splitter, P - the high-quality crystal polarizer, and D are photodiodes. From Ref. [9]

In addition to the zero-field resonance, the application of the above described technique results in the appearance of high-field resonances (Fig. 3). High-field resonances occur when the magnetic field and modulation frequency Ω_m fulfill the condition ($\Omega_L = n\Omega_m/2$ with $n=\pm1, \pm2,...$). The width of these resonances is the same, and the amplitude comparable to the zero-field resonance. This opens the possibility of applying these resonances for measuring magnetic field of higher intensities. High-field resonances can be created either by using amplitude modulation (AM) [9] or frequency modulation (FM) [10].

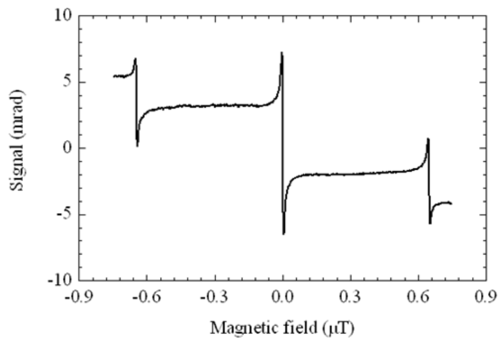

Fig. 3. Typical rotation signal in the experiment with amplitude modulation of light intensity. The two resonances at B≈±2 μT result from synchronous interaction of modulated light with rubidium atoms

The principle of the discussed magnetometric methods relies on determining the modulation frequency of the polarization plane rotation which is proportional to the magnetic field intensity. Such measurement can be automated if feedback is used to run the magnetometer in the so-called self-oscillating regime [11,12]. In a self-oscillating magnetometer the rotation signal which oscillates at twice the Larmor frequency is fed back to the laser intensity modulator. Consequently, the modulation frequency tracks the Larmor frequency and for each value of B the system is in resonance. Then it suffices to measure the oscillation frequency to determine the magnetic field intensity B. An alternative to self-oscillating mode is the passive-mode developed in Ref. [13]. In such a mode, the magnetic-field tracking is realized by keeping the maximum NFE signal with a computer realizing a special algorithm. With this mode, our group demonstrated the sensitivity of a magnetic field measurement of 4.3×10^{-13} T/Hz$^{1/2}$ with a dynamic range up to 10^{-5} T [13]. This is the current record in relative sensitivity, i.e. the ratio of absolute sensitivity to dynamic range, of the order of 10^{-9}.

One additional advantage of studying NFE with AM light is the possibility of generating the „comb" of magneto-optical resonances by the use of square-wave modulation of the light intensity. This comb may be useful in the situations where the value of some magnetic field needs to be adjusted to the exact multiplicity of a given, weaker field [9].

Until recently, magnetic field measurements based on NFE only allowed to determine the absolute value of magnetic field intensity. Recent development of the method now also allows the determination of its direction [14]. It has been discovered that nonparallelism of the field and light propagation directions leads to additional rotation resonances. The ratio of the amplitude of these new and regular resonances depends on the magnetic field direction relative to the light beam propagation, hence it allows its determination.

Optical magnetometers described in this paper open a range of new possibilities in measurements of that basic physical quantity. Very wide applications of such devices became possible because of an enormous increase in sensitivity, accuracy and range of measured fields, as well as reduction of the dimensions, production and exploitation costs. One obvious application of this kind is in scientific research, for example, in physics, astrophysics or geophysics. Other possible applications include the search of natural resources, nondestructive defectoscopy, military, and medical applications, such as noncontact magnetocardiography or brain activity studies. In Poland, research in this field is conducted by the Center for Magneto-Optical Research at the Jagiellonian University in close cooperation with the University of California at Berkeley.

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