Nonlinear magneto-optical rotation with amplitude modulated light

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The technique of nonlinear magneto-optical rotation with amplitude modulated light is developed. The technique is an alternative to its counterpart with frequency modulated light and can be applied to sensitive measurements of magnetic fields ranging from microgauss to the Earth-field level. The rotation signals exhibit nontrivial features such as narrowed non-Lorentzian line shapes and multicomponent resonances. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2190457]

We report on the development of the technique of resonant nonlinear magneto-optical rotation in rubidium vapor with amplitude modulated light. The amplitude modulated magneto-optical rotation (AMOR) has been measured by lock-in detection in modulated transmitted light as a function of magnetic field, light intensity, size of the absorption cells, their isotopic content, and modulation wave forms.

First applications of the amplitude modulation (AM) of light intensity to atomic and molecular spectroscopy go back to the synchronous optical pumping studies of Bell and Bloom[1] and Corney and Series.[2] Since then the method has been applied in many situations, see Ref. 3 for a review.

In the present work we concentrated on using AM light and optical pumping synchronous with Larmor precession for studies of the nonlinear magneto-optical rotation[4] and on establishing an alternative to the frequency modulated light nonlinear magneto-optical rotation (FM NMOR).[5] In both methods ultranarrow resonances at zero magnetic field are replicated at higher fields. Thus they are suitable as magnetometry techniques for the fields ranging from the microgauss level to the Earth field with sensitivity reaching $\sim 10^{-11}$ G/$\sqrt{\text{Hz}}$. While the FM NMOR method is straightforward to implement and sensitive to highly nonlinear magneto-optical effects,[6] it is prone to distortions by a possible spurious AM of laser light[7] and the ac Stark-effect shifts. These shifts caused by intense light occur in FM NMOR where the light frequency is tuned to the side of a resonance line, but can be minimized in AMOR which uses resonant excitation. AMOR technique can be used when it is impossible or difficult to change the light-source frequency; AM also offers additional freedom in optimizing the modulation wave form for better control of the atomic dynamics and observed signals. Recently, AM was employed also by Matsko *et al.* in a self-oscillating magnetometer that reached 2×10^{-7} G/$\sqrt{\text{Hz}}$ sensitivity and 1 G dynamic range.[8] It should be noted that in Ref. 8 the modulation frequency is in the microwave range, while in our work it is below 100 kHz.

The layout of the experimental setup is presented in Fig. 1. Experiments were performed with rubidium atoms in two different glass cells: one of 5 cm length and 2.5 cm diameter containing natural isotopic mixture of ^{85}Rb and ^{87}Rb, and the second of 1.5 cm length and 1.8 cm diameter containing ^{87}Rb. Both cells contained 3 torr of Ne as a buffer gas and were kept at 20 °C. The cells were placed within a three-layer μ-metal magnetic shield and were surrounded by several coils used to produce magnetic field B along the laser beam and to compensate transverse fields.

As the light source we used an external-cavity diode laser locked to the center of the $F=2\rightarrow F'=2$ hyperfine component of the D_1 transition $5\,^2S_{1/2}\rightarrow 5\,^2P_{1/2}$ (795 nm). The main part of the beam was transmitted in a double pass through an acousto-optical modulator (AOM) driven by an 80 MHz radio-frequency signal whose amplitude was modulated with various wave forms of frequency Ω_m. In this way the laser light was frequency shifted by 160 MHz and its intensity I was modulated at $\Omega_m/2\pi$ ranging from 20 to 100 kHz and with different modulation depths m

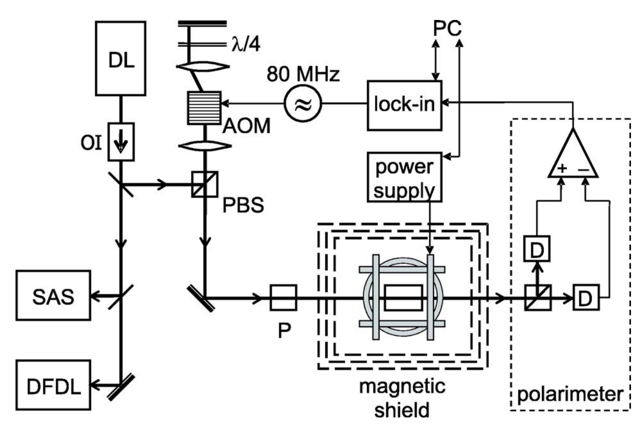

FIG. 1. Experimental setup. DL stands for external-cavity diode laser, OI—optical isolator, SAS—saturated absorption frequency reference, DFDL—Doppler-free dichroic lock, D—photodiodes, P—crystal polarizer, PBS—polarizing beam splitter, λ/4—quarter-wave plate, and PC is a computer controlling the experiment.

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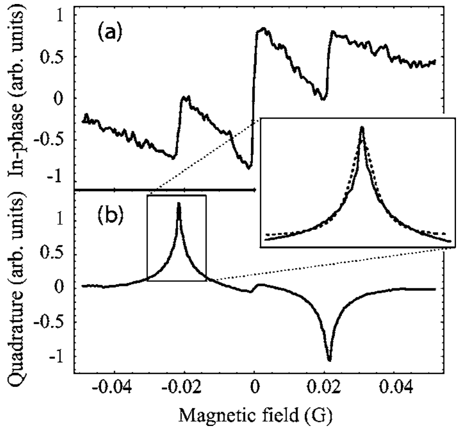

FIG. 2. Short-cell ^{87}Rb signals taken with 1.5 cm long cell and sine-wave modulation with $m=25\%$ and light power of 10 μW. In-phase component (a) and quadrature component (b). The maximum rotation angle is about 0.25 mrad. Note that both components are shown on the same scale but have different signal-to-noise ratios. The inset shows the Lorentzian fit to the sideband resonance as a dashed line.

$=(I_{\max}-I_{\min})/I_{\max}$. The results presented below were obtained at $\Omega_m/2\pi=30$ kHz. The linearly polarized beam of 2 mm diameter traversed the cell and was analyzed by a balanced polarimeter consisting of a Glan prism and two photodiodes detecting two orthogonally polarized components of the transmitted light. The difference signal was analyzed by a lock-in detector whose in-phase and quadrature outputs at the first harmonic of Ω_m were stored on a personal computer (PC) as functions of the magnetic field.

The AMOR signals recorded with a sine-wave AM as a function of B (Fig. 2) have a characteristic form consisting of a central resonance at $B=0$ and two side resonances (sidebands) appearing when $\Omega_L=\Omega_m/2$, where $\Omega_L=g\mu_B B/\hbar$ is the Larmor frequency, μ_B being the Bohr magneton, and g the Landé factor. The signal form is essentially identical with that seen with FM NMOR.[5] New features appear with square-wave modulation and are described in detail below.

The widths of the resonances depend on several factors: the light power, Rb diffusion in buffer gas, and the magnetic field inhomogeneity. The narrowest widths (full width at half maximum) obtained with the present nonoptimized setup are about 2.1 mG for the short cell and about 2.6 mG for the long cell. The resonances seen with both cells differ not only in their widths but also in the line shapes. The short-cell resonances have non-Lorentzian shapes (see the inset in Fig. 2), similar to those found recently in electromagnetically induced transparency and attributed to diffusion-induced Ramsey narrowing.[9] Indeed, the resonance widths determined by diffusion time of Rb atoms in Ne gas of 3 torr pressure through a 2 mm wide beam should be about five times larger than what we measure. On the other hand, the long-cell resonances exhibit closer to Lorentzian line shapes which we explain by stronger effects of the magnetic field inhomogeneities that accumulate over the longer-cell length and overwhelm the diffusion-induced Ramsey narrowing.

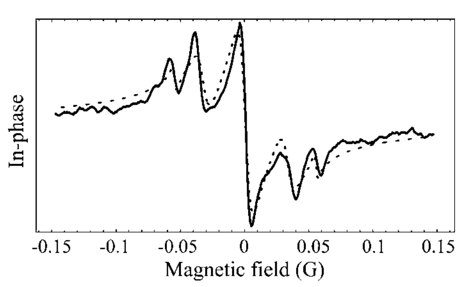

FIG. 3. AMOR resonances with the 5 cm cell containing natural rubidium obtained with a light power of 15 μW. The sidebands occurring at higher magnetic fields are associated with ^{85}Rb while the ones that are closer to $B=0$ are due to ^{87}Rb. Dashed line depicts a fit with a set of dispersive Lorentzians.

Using the 5 cm cell with natural rubidium we recorded resolved sideband resonances associated with the two Rb isotopes. Since the Landé factors and Larmor frequencies for the two isotopes are different $[g(^{85}\mathrm{Rb})\approx 1/3, g(^{87}\mathrm{Rb})\approx 1/2]$, the resonances occur at different magnetic fields which gives rise to double sidebands, as shown in Fig. 3. The sideband positions yield the ratios which deviate by about 10% from the 2/3 ratio of the Landé factors of the two isotopes and weakly depend on the light power. The origin of this discrepancy is currently under investigation.

The square-wave modulation leads to occurrence of additional "harmonic" resonances at magnetic fields corresponding to $\Omega_L=n\Omega_m/2$, with n being an integer larger than 1. These resonances arise due to the presence in the modulation wave form of Fourier components at multiples of Ω_m. While single sidebands are visible for modulation with a duty cycle of 0.5 within our range of the magnetic field scan [Fig. 4(a)], for a duty cycle of 0.35 the first and second harmonics are clearly seen with comparable amplitudes [Fig. 4(b)]. When the duty cycle of the square-wave modulation decreases, i.e., the light pulses are shorter, the number of harmonics increases. Figure 4(c) shows this effect for a duty cycle of 0.2 when up to five harmonics are well visible under conditions similar to those of Figs. 4(a) and 4(b). The experimental recordings are compared to a theory based on the model of Ref. 10. Time-dependent solutions of the model are multiplied by the sine and cosine reference signals and integrated to simulate the lock-in signals. The calculated signals (broken line) reproduce most salient features of the experimental ones except for a residual resonance seen at $B=0$ in the quadrature component. The amplitude of this residual resonance increases with light intensity, thus we attribute it to the alignment-to-orientation conversion.[11,12] It is noteworthy that, unlike in FM NMOR, the in-phase component is noisier than the quadrature one.

Our study demonstrates the applicability of the AMOR technique to studies of magneto-optical phenomena which are highly sensitive to ground-state level shifts, for example, due to a magnetic field. The AMOR method has the same possible applications as the FM NMOR. In particular, it should be useful in Earth field and space magnetometry and in NMR/MRI.[13] For these applications the method can be used with miniature cells[12–14] which, together with low-current semiconductor lasers, should allow substantial miniaturization and reduced power consumption. The use of low duty-cycle square-wave modulation (train of short pulses) allows studies of the dynamics of the induced atomic observables and results in appearance of many equally spaced sideband resonances. These resonances, occurring at harmonics of Larmor frequency, reach high magnetic fields even with low frequency of light amplitude modulation which significantly reduces experimental requirements. The resonances have maximum amplitudes at resonant frequency of laser light which reduces possible distortions caused by ac Stark effect. These features make the AMOR technique a useful

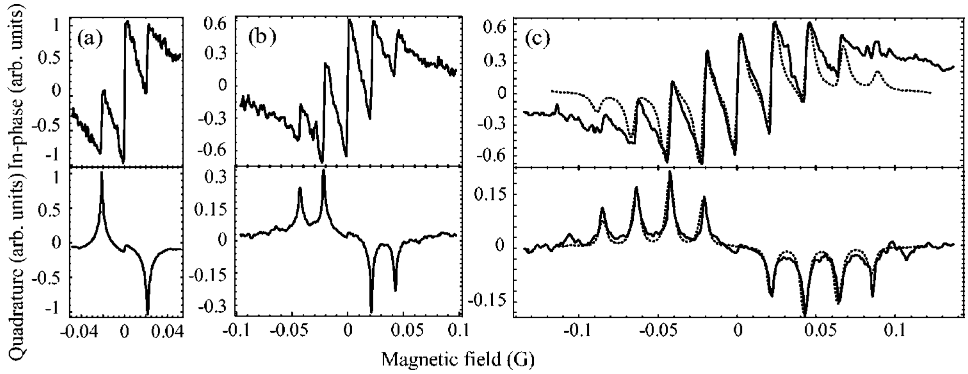

FIG. 4. AMOR resonances recorded with the 1.5 cm ^{87}Rb cell, square-wave 100% modulation of 0.5 duty cycle, and 10 μW average power (a), 0.35 duty cycle and 6 μW average light power (b), and 0.2 duty cycle and 5 μW average light power (c). Upper row shows in-phase signals, lower row shows quadrature signals. The broken lines show theoretical fits.

method of nonlinear magneto-optics and an attractive possible alternative to FM NMOR.

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