A novel approach to quantitative spectroscopy of atoms in a magnetic field and applications based on an atomic vapor cell with \( L = \lambda \)

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We describe the so-called \( \lambda \)-Zeeman method to investigate individual hyperfine transitions between Zeeman sublevels of atoms in an external magnetic field of 0.1 mT–0.25 T. Atoms are confined in a nanocell with thickness \( L = \lambda \), where \( \lambda \) is the resonant wavelength (794 or 780 nm for \( D_1 \) or \( D_2 \) line, respectively, of Rb). Narrow resonances in the transmission spectrum of the nanocell are split into several components in a magnetic field; their frequency positions and transition probabilities depend on the \( B \) field. Possible applications are described, such as magnetometers with nanometric spatial resolution and tunable atomic frequency references. © 2008 American Institute of Physics. [DOI: 10.1063/1.2960346]

It is well known that energy levels of atoms placed in an external magnetic field undergo frequency shifts and changes in their transition probabilities. These effects were studied for hyperfine (hf) components of atomic optical transitions (hereafter “hf transitions”) in the transmission spectra obtained with an ordinary centimeter-size cell containing Rb and Cs vapor in Ref. 1. However, because of Doppler broadening (hundreds of megahertz), it was possible to partially separate different hf transitions only for \( B > 0.15 \) T. Note that even for these large \( B \) values, the lines of \( ^{87}\text{Rb} \) and \( ^{85}\text{Rb} \) are strongly overlapped, and pure isotope have to be used to avoid complicated spectra. In order to eliminate the Doppler broadening, the well-known saturation absorption (SA) technique was implemented to study the Rb hf transitions.2 However, in this case the complexity of the Zeeman spectra in a magnetic field arises primarily from the presence of strong crossover (CO) resonances, which are also split into many components. That is why, as is mentioned in Ref. 2, the SA technique is applicable only for \( B < 5 \) mT. The CO resonances can be eliminated with selective reflection spectroscopy,3 but to correctly determine the hf transition position, the spectra must undergo further nontrivial processing. Another method based on the fluorescence spectrum emitted from a nanocell at thickness \( L = \lambda / 2 \) was presented in Ref. 4. However, in this case the sub-Doppler spectral linewidth is relatively large (\( \sim 100 \) MHz); also the laser power may be too low to detect a weak fluorescence signal. Coherent population trapping (CPT) allows one to study the behavior of hf transitions in a magnetic field with very high accuracy (several kilohertz),5 however the experimental realization is complicated. Moreover, measuring hf level shifts of several gigahertz for \( B \sim 0.1 \) T using CPT is not realistic.

We present a method based on narrow (close to natural linewidth) velocity selective optical pumping/saturation (VSOP) resonance peaks of reduced absorption located at the atomic transitions. As was recently shown in Ref. 6, the ratio \( L / \lambda \) is a significant parameter for VSOP resonance formation. The VSOP peaks appear at laser intensity \( \sim 1 \) mW/cm² in the transmission spectrum of the nanocell with atomic vapor column of thickness \( L = \lambda \), where \( \lambda \) is the resonant wavelength of the laser radiation (794 or 780 nm for \( D_1 \) or \( D_2 \) line, respectively). At \( B > 0 \), the VSOP resonance is split into several Zeeman components, the number of which depends on the quantum numbers \( F \) of the lower and upper levels. The amplitudes of these peaks and their frequency positions depend unambiguously on the \( B \) value. This so-called \( \lambda \)-Zeeman method (LZM) allows one to study not only the frequency shift of any individual hf optical transition, but also the modification in transition probability in the region of 0.1 mT–0.25 T (LZM is expected to be valid up to several tesla). Possible applications of a nanocell for diagnostics and mapping of large magnetic gradients and for making widely tunable compact frequency references are addressed too.

Experimental realization of LZM is simple enough (see Fig. 1). The circularly polarized beam of an extended cavity diode laser (\( \lambda = 794 \) nm, \( P_L \sim 5 \) mW, \( \gamma_L < 1 \) MHz) resonant with the \( ^{87}\text{Rb} D_1 \) transition frequency, after passing through a Faraday isolator, was focused (\( \Phi = 0.5 \) mm) onto a Rb nanocell with a vapor column of thickness \( L = \lambda \) at an angle close to normal. The design of a nanocell is presented in Ref. 6. The source temperature of the atoms of the nanocell was 110 °C, corresponding to a vapor density \( N \sim 10^{13} \) cm⁻³, but the windows were maintained at a temperature that was 20 °C higher. Part of the laser radiation was diverted to a centimeter-size Rb cell to obtain a \( B = 0 \) SA spectrum, which served as frequency reference. The nanocell transmission and SA spectra were detected by photodetectors and recorded by

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FIG. 3. Transmission spectra for B=(a) 0.24 T, (b) 0.23 T, (c) 0.154 T, and (d) 0.117 T; lower curve is SA spectrum.

FIG. 4. (a) (1) ratio A(1)/A(3) and (2) ratio A(1)/A(2) vs B. (b) (1) Δ(1,3) and (2) Δ(1,2) vs B.
possible Zeeman transitions for $\sigma^+$ polarized excitation are depicted in Fig. 5(a). Particularly, it was revealed that for $B>10\,\text{mT}$, also the $^{87}\text{Rb}$ $D_2$, $F_e=1\rightarrow F_e=3$ “forbidden” transitions (labeled 7–9) appear in the spectrum, for which new selection rules with respect to the quantum number $F$ apply. Moreover, for $20\,\text{mT}<B<0.2\,\text{T}$ the probability of transition 7 exceeds that of transition 6, the strongest transition at $B=0$. Figure 5(b) gives the $B$-field dependence of amplitude (transition probability) ratio $A(7)/A(6)$, $A(8)/A(6)$, and $A(9)/A(6)$ (curves 1, 2, and 3, respectively). Both in Figs. 4(a) and 5(b), there is good agreement between experiment and theory. The nanocell transmission spectrum for these transitions at $B=0.21\,\text{T}$ is presented in Fig. 6. The two arrows show the positions of the $^{85}\text{Rb}$ $F_e=2\rightarrow F_e=4$ Zeeman transitions (theory$^4$ well predicts that their probabilities have to be small). The upper insets show the $B$-field dependence of $\Delta(7,6)$ and $\Delta(8,7)$. We note that transition 7 is strongly shifted (by $5.6\,\text{GHz}$) from the $B=0$ position of the $F_e=1\rightarrow F_e=2$ transition. The latter allows development of a frequency reference based on a nanocell and PRMs, widely tunable over a range of several gigahertz by simple displacement of the magnet. LZM can be successfully implemented also for studies of the $D_1$ and $D_2$ lines of Na, K, Cs, and other atoms.

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