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Compiled January 31, 2012

A simple and efficient scheme based on one-dimensional nanometric thin cell filled with Rb and strong permanent ring magnets allowed direct observation of hyperfine Paschen-Back regime on $D_1$ line in $0.5 - 0.7$ T magnetic field. Experimental results are perfectly consistent with the theory. In particular, with $\sigma^+$ laser excitation, the slopes of $B$-field dependence of frequency shift for all the 10 individual transitions of $^{85,87}$Rb are the same and equal to 18.6 MHz/mT. Possible applications for magnetometry with submicron spatial resolution and tunable atomic frequency references are discussed. © 2012 Optical Society of America

*OCIS codes:* 020.1335, 010.3640

Rubidium atoms are widely used in atomic cooling, information storage, spectroscopy, magnetometry etc [1,2]. Miniaturization of alkali vapor cells is important for many applications [3–6]. Atom located in magnetic field undergoes shift of the energy levels and change in transition probabilities, therefore precise knowledge of the behavior of atomic transitions is very important [7]. In case of alkali atomic vapor use a sub-Doppler resolution is needed to study separately each individual atomic transition between hyperfine (hf) Zeeman sub-levels of the ground and excited states (in case of a natural mixture of $^{85}$Rb and $^{87}$Rb the number of closely spaced atomic transitions can reach several tens). Recently it was shown that a one-dimensional nanometric-thin cell (NTC) with the thickness of Rb atomic vapor column $L = \lambda$, where $\lambda = 794$ nm is the wavelength of laser radiation resonant with $D_1$ line of Rb, is a good tool to obtain sub-Doppler spectral resolution. Spectrally narrow velocity-selective optical pumping (VSOP) resonances located exactly at the position of atomic transitions appear in the transmission spectrum of NTC at laser intensities $\cong 10$ mW/cm$^2$ [4,6,8]. When NTC is placed in a weak magnetic field, the VSOPs are split into several components depending on total angular momentum quantum numbers $F = I + J$, with amplitudes and frequency positions depending on $B$-field, which makes it convenient to study separately each individual atomic transition.

In this Letter we describe a simple and robust system based on NTC and permanent magnets, which allows of achieving magnetic field up to 0.7 T sufficient to observe a hyperfine Paschen-Back regime [9]. The magnetic field required to decouple the nuclear and electronic spins is given by $B \gg A_{hfs}/\mu_B \cong 0.2$ T for $^{87}$Rb, and $\cong 0.07$ T for $^{85}$Rb, where $A_{hfs}$ is the ground-state hyperfine coupling coefficient for $^{87}$Rb and $^{85}$Rb and $\mu_B$ is the Bohr magneton [10]. For such a large magnetic field the eigenstates of the Hamiltonian are described in uncoupled basis of $J$ and $I$ projections $(m_J, m_I)$. In Fig. 1 six transitions of $^{85}$Rb labeled *4 - 9*, and four transitions

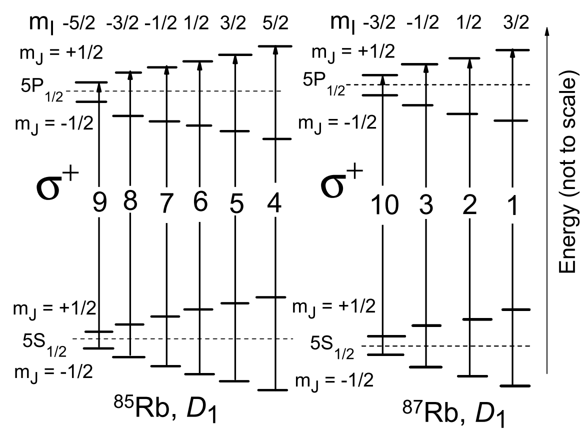


Fig. 1. Diagram of $^{85}$Rb ($I = 5/2$) and $^{87}$Rb ($I = 3/2$) transitions for $\sigma^+$ laser excitation in HPB regime. The selection rules: $m_J = +1$; $m_I = 0$.

of $^{87}$Rb labeled *1 - 3* and *10* are shown in the case of $\sigma^+$ polarized laser excitation for the HPB regime.

The sketch of the experimental setup is shown in Fig. 2. The circularly ($\sigma^+$) polarized beam of extended cavity diode laser (ECDL, $\lambda = 794$ nm, $P_L = 30$ mW, $\gamma_L < 1$ MHz) resonant with Rb $D_1$ line, was directed at normal incidence onto the Rb NTC *(2)* with the vapor column thickness $L = \lambda = 794$ nm (a typical example of a recent version of the NTC is described in [6]). The NTC was placed in a special oven with two openings. The transmission signal was detected by a photodiode *(4)* and was recorded by a four-channel digital storage oscilloscope. A polarizing beam splitter (PBS) was used to purify initial linear radiation polarization of the laser radiation followed by a $\lambda/4$ plate *(1)* to produce a circular polarization. The magnetic field was directed along the laser radiation propagation direction **k**. About 30% of the pump power was branched to the reference unit with

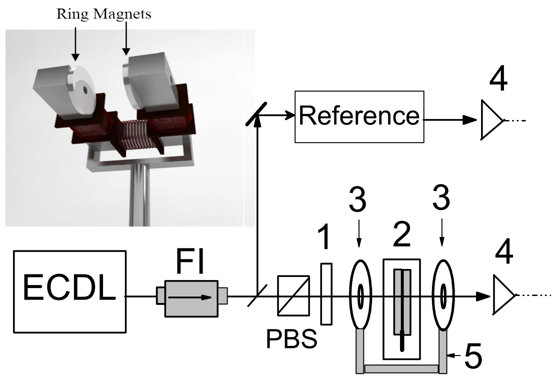


Fig. 2. Sketch of the experimental setup. ECDL - diode laser, FI - Faraday isolator, *1* - $\lambda/4$ plate, *2* - NTC in the oven, PBS - polarizing beam splitter, *3* - permanent ring magnets, *4* - photodetectors, *5* - stainless steel Π-shape holder (shown in the inset).

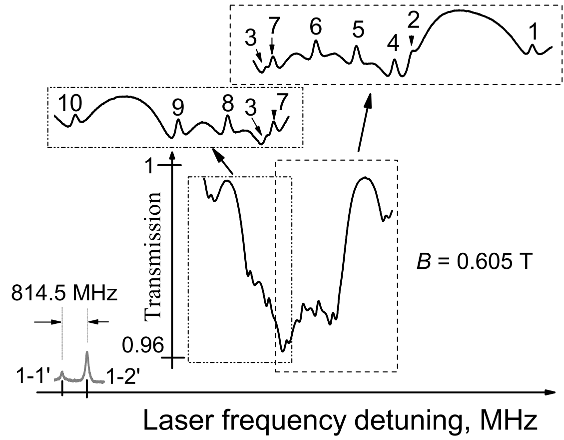


Fig. 3. Transmission spectrum of Rb NTC with $L = \lambda$ for $B = 0.605$ T and $\sigma^+$ laser excitation. Well resolved VSOP resonances located at atomic transitions are labeled *1 - 10* (six transitions, *4 - 9* belonging to $^{85}$Rb, and four transitions, *1,2,3* and *10* belonging to $^{87}$Rb). Change in probe transmission is $\Delta T = 4\%$. The lower gray curve is the fluorescence spectrum of the reference NTC with $L = \lambda/2$, showing the positions of $^{87}$Rb, $F_g = 1 \rightarrow F_e = 1, 2$ transitions for $B = 0$, labeled as $1 - 1'$ and $1 - 2'$ (all frequency shifts are measured from $F_g = 1 \rightarrow F_e = 2$).

an auxiliary Rb NTC. The fluorescence spectrum of the latter at $L = \lambda/2$ was used as a frequency reference for $B = 0$. The magnetic field was measured by a calibrated Hall gauge. Extremely small thickness of NTC is advantageous for application of very strong magnetic fields by permanent ring magnets (PRM) otherwise unusable because of strong inhomogeneity of magnetic field: in NTC, the variation of $B$-field inside atomic vapor column is less by several orders than the applied $B$ value. The ring magnets are mounted on a $50 \times 50$ mm$^2$ cross section Π-shaped holder made from soft stainless steel (see inset in Fig. 2). Additional form-wounded Cu coils allow of applying extra $B$-field (up to $\pm 0.1$ T). NTC is placed between PRMs. The linearity of the scanned frequency was tested by simultaneously recorded transmission spectra of a Fabry-Pérot etalon (not shown). The nonlinearity has been evaluated to be about 1% throughout the spectral range. The imprecision in the measurement of the absolute $B$-field value is $\pm 5$ mT. The recorded transmission spectrum of the Rb NTC with $L = \lambda$ for $\sigma^+$ laser excitation and $B = 0.605$ T is shown in Fig. 3. The VSOP resonances labeled *1 - 10* demonstrate increased transmission at the positions of the individual Zeeman transitions. In the case of HPB the energy of the ground $5S_{1/2}$ and upper $5P_{1/2}$ levels for Rb $D_1$ line is given by a simple formula [9]:

$$E_{|J,m_J,I,m_I\rangle} = A_{hfs} m_J m_I + \mu_B (g_J m_J + g_I m_I) B. \quad (1)$$

The values for nuclear ($g_I$) and fine structure ($g_J$) Landé factors, and hyperfine constants $A_{hfs}$ are given in [11]. The magnetic field dependence of frequency shift for components *4 - 9* ($^{85}$Rb) is shown in Fig. 4 (solid lines: HPB theory; symbols: experiment, inaccuracy does not exceed 2%). The similar dependence for $^{87}$Rb (components *1 - 3* and *10*) are shown in the inset of Fig. 4. The HPB regime condition is fulfilled better for $B > 0.6$ T. As it is seen from Eq. (1), and also confirmed experimentally, the dependence slope is the same for all the transition components of both $^{85}$Rb and $^{87}$Rb: $[g_J(5S_{1/2})m_J + g_J(5P_{1/2})m_J]\ \mu_B B = 18.6$ MHz/mT (as $g_I \ll g_J$ we ignore its contribution). Onset of this value is indicative of Rb $D_1$ line HPB regime. Note that in our previous study for $B \sim 20$mT [12] and under the same conditions we observed 32 transitions, as opposed to 10 remaining in HPB regime.

Rb NTC could be implemented for mapping strongly inhomogeneous magnetic fields by local submicron spatial resolution. Particularly, for 0.1 T/mm gradient, the displacement of NTC by 5 $\mu$m results in 10 MHz frequency shift of VSOP resonance, which is easy to detect. Also development of a frequency reference based on NTC and PRM, which is $B$-field-tunable in over 10 GHz range, is of high interest. The above studies and techniques can be successfully implemented also for HPB studies of $D$ lines of Na, K, Cs, and other atoms.

The research leading to these results has received funding from the FP7/2007-2013 under *grant agreement* n° 205025 - IPERA. Research conducted in the scope of the International Associated Laboratory IRMAS (CNRS-France & SCS-Armenia).

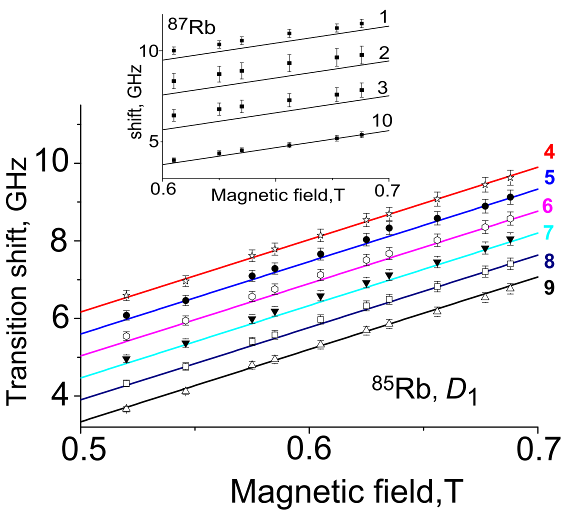


Fig. 4. Magnetic field dependence of frequency shift for transition components labeled *4 - 9* ($^{85}$Rb) and *1 - 3, 10* ($^{87}$Rb, in the inset). Solid lines: theory; symbols: experiment. The inaccuracy is $\leq 2\%$ for components *4 - 9, 1* and *10*, and $\leq 5\%$ for components *2* and *3*. Larger error for *3* and *2* is caused by closely located strong transition *7* and location on the transmission spectrum wing, respectively.

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