Magnetometers and Atomic Clocks based on VCSEL-prepared dark resonances

R. Wynands, C. Affolderbach, L. Hollberg[1], W. Kemp, J. Kitching[1], S. Knappe, H. G. Robinson[1], and M. Stähler

Institute for Applied Physics, Bonn University, Wegelerstraße 8, D-53115 Bonn, Germany
Tel +49-228-733483, Fax +49-228-733474
E-mail: wynands@iap.uni-bonn.de, Website: http://www.uni-bonn.de/iap/darkreso.html
[1] *National Institute of Standards and Technology, 325 S. Broadway, Boulder, CO 80303, USA*

We have experimentally investigated the potential of narrow coherent population trapping resonances for precision applications like magnetometry [1, 2] or atomic frequency standards [3]. CPT [4] can be observed in Λ systems where two ground states are coupled to a common excited state by two near-resonant light fields. Effective formation of ground state coherences takes place when the frequency difference of the light fields precisely matches the ground state splitting. This process leads to reduced absorption in the medium ("electromagnetically induced transparency") and thus reduced fluorescence intensity ("dark resonance") at the optical resonance frequency. Extremely narrow dark resonances can be observed when the two light fields have fixed phase and frequency difference and time-of-flight broadening is suppressed by the use of a buffer gas [5], making this type of system a promising candidate for precision applications.

The work described here uses the D_2 line in thermal Cs vapor where the ground state hyperfine splitting is 9.2 GHz. In a magnetic field the CPT resonance splits into several Zeeman components. This allows to determine the strength of the magnetic field through a precise measurement of the Zeeman-shifted positions of the dark resonance components. The outermost resonance components correspond to coherences between ground states with the largest possible magnetic quantum numbers and show the largest shift rate due to the magnetic field. Accordingly, the highest sensitivity to magnetic fields is expected from measurements of the frequency position of these resonance components. In contrast, the Zeeman component corresponding to ground state coherences between the two $m = 0$ ground states is well suited for frequency standard applications because its position is shifted by magnetic fields only in second order.

In the experiments reported here the laser fields are derived from a vertical-cavity surface-emitting laser (VCSEL) with a high intrinsic modulation bandwidth [6]. Thus direct modulation of the injection current at the ground state hyperfine frequency allows to induce the ground state coherence by the carrier and one of the modulation sidebands [7]. In order to increase the signal-to-noise ratio the modulation frequency is itself frequency-modulated at a few kHz, and a lock-in amplifier demodulates the transmission signal of the vapor cell. This technique also provides a steep slope at the line center in the quadrature signal, which allows for the highly precise determination of the resonance frequency.

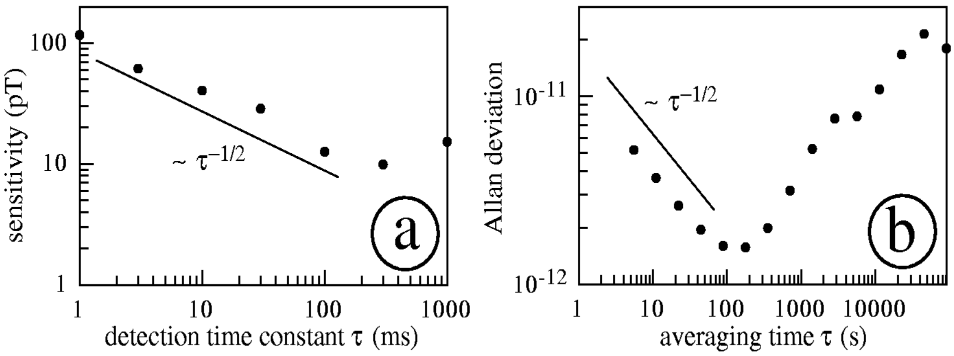

Figure 1: (a) Sensitivity of the experimental setup to magnetic fields for the Zeeman component corresponding to the coupling of $m = 3 \leftrightarrow m = 4$ ground states in Cs vapor. (b) Allan standard deviation of a cesium dark resonance atomic clock.

In lock-in spectra of the outermost Zeeman component the noise level outside the resonance line was compared to the steepest slope at the center of the resonance. From this data and the shift rate a sensitivity limit of 9.9 pT in 0.3 s integration time was derived (fig. 1a), which is already close to the noise levels of the best commercially available flux-gate magnetometers.

The potential of CPT resonances for frequency standards is demonstrated by modulating the laser current at 4.6 GHz, half the hyperfine frequency, so that the dark resonance is excited by the two first-order sidebands. This frequency is stabilized to the center component of the Zeeman split CPT resonance and monitored as a function of time [8]. The short-term stability of $9.3 \times 10^{-12}/\sqrt{\tau/\mathrm{s}}$ is comparable to the best commercial rubidium frequency standards (fig. 1b). At larger integration times the frequency stability is degraded by thermal drifts of the bufferd cesium cell. Further improvement is expected by a more suitable choice of buffer gas composition. The whole setup can be miniaturized into a physics package with a volume of only $20\,\mathrm{cm}^3$ and a total electrical power consumption of less than 100 mW.

[1] M. O. Scully, M. Fleischhauer, *Phys. Rev. Lett.* **69** 1360 (1992).

[2] A. Nagel, L. Graf, A. Naumov, E. Mariotti, V. Biancalana, D. Meschede, R. Wynands, *Europhys. Lett.* **44** 31 (1998).

[3] P. R. Hemmer, M. S. Shariar, H. Lamela-Rivera, S. P. Smith, B. E. Bernacki, S. Ezekiel, *J. Opt. Soc. Am. B* **8** 1326 (1993).

[4] E. Arimondo, *Progress in Optics* **35** 257 (1996).

[5] S. Brandt, A. Nagel, R. Wynands, D. Meschede, *Phys. Rev. A* **56** R1063 (1997).

[6] R. King, R. Michalzik, C. Jung, M. Grabherr, F. Eberhard, R. Jäger, P. Schnitzer, K. J. Ebeling, in *Vertical-cavity Surface-Emitting Lasers II*, R. A. Morgan and K. D. Choquette (eds.), Proc. SPIE 3286, p. 64 (1998).

[7] C. Affolderbach, A. Nagel, S. Knappe, C. Jung, D. Wiedenmann, R. Wynands, *Appl. Phys. B* **70** 407 (2000).

[8] J. Kitching, S. Knappe, N. Vukičević, L. Hollberg, R. Wynands, W. Weidemann, submitted for publication.