

# Microfabricated saturated absorption laser spectrometer

Svenja A. Knappe<sup>\*</sup>, Hugh G. Robinson, and Leo Hollberg

Time and Frequency Division, NIST, Boulder CO 80305<sup>†</sup>

<sup>\*</sup>Corresponding author: [knappe@boulder.nist.gov](mailto:knappe@boulder.nist.gov)

**Abstract:** We demonstrate a miniature microfabricated saturated absorption laser spectrometer. The system consists of miniature optics, a microfabricated Rb vapor cell, heaters, and a photodetector, all contained within a volume of 0.1 cm<sup>3</sup>. Saturated absorption spectra were measured with a diode laser at 795 nm. They are comparable to signals obtained with standard table-top setups, although the rubidium vapor cell has an interior volume of only 1 mm<sup>3</sup>. We discuss the performance and prospects for using such systems as a miniature optical wavelength reference, compatible with transportable instruments.

©2007 Optical Society of America

**OCIS codes:** (140.0140) Lasers and laser optics; (230.0230) Optical devices; (300.6460) Saturation spectroscopy

---

## References and links

1. W. Demtröder, in *Laser Spectroscopy* (Springer, Berlin, 1996).
2. T. W. Hänsch, M. D. Levenson, and A. L. Schawlow, "Complete hyperfine structure of a molecular iodine line," *Phys. Rev. Lett.* **26**, 946-949 (1971).
3. K. B. Macadam, A. Steinbach, and C. Wieman, "A narrow-band tunable diode-laser system with grating feedback and a saturated absorption spectrometer for Cs and Rb," *Am. J. Phys.* **60**, 1098-1111 (1992).
4. V. S. Letokhov, *High-Resolution Laser Spectroscopy*, K. Shimoda, ed., (Springer-Verlag, New York, 1976).
5. C. Wieman and T. W. Hänsch, "Doppler-free laser polarization spectroscopy," *Phys. Rev. Lett.* **36**, 1170-1173 (1976).
6. K. L. Corwin, Z. T. Lu, C. F. Hand, R. J. Epstein, and C. E. Wieman "Frequency-stabilized diode laser with the Zeeman shift in an atomic vapor," *Appl. Opt.* **37**, 3295-3298 (1998).
7. G. Wasik, W. Gawlik, J. Zachorowski, and W. Zawadzki, "Laser frequency stabilization by doppler-free magnetic dichroism," *Appl. Phys. B: Lasers and Optics* **75**, 613-619 (2004).
8. R. W. Wood, "The selective reflection of monochromatic light by mercury vapor," *Philos. Mag.* **18**, 187 (1909).
9. J. L. Cojan, "Study of the selective reflection of mercury resonance radiation by mercury vapor," *Ann. Phys. (France)* **9**, 385-440 (1954).
10. J. P. Woerdman and M. F. H. Schuurmans, "Spectral narrowing of selective reflection from sodium vapour," *Opt. Commun.* **14**, 248-251 (1975).
11. A. Badalyan, V. Chaltykyan, G. Grigoryan, A. Papoyan, S. Shmavonyan, and M. Movsessian, "Selective reflection by atomic vapor: experiments and self-consistent theory," *Euro. Phys. J. D* **37**, 157-162 (2006).
12. O. Schmidt, K. M. Knaak, R. Wynands, and D. Meschede, "Cesium saturation Spectroscopy revisited - how to reverse peaks and observe narrow resonances," *Appl. Phys. B* **59**, 167-178 (1994).
13. G. Meisel, K. C. Harvey, and A. L. Schawlow, "Saturation Spectroscopy of Na using optical-pumping," *Bull. Am. Phys. Soc.* **19**, 580 (1974).
14. H. Y. Jung, K. B. Im, C. H. Oh, S. H. Song, P. S. Kim, and H. S. Lee "Dependence of the saturated absorption signals of the Cs D2 line on the external magnetic field," *J. Korean Phys. Soc.* **33**, 277-280 (1998).
15. J. Kitching, S. Knappe, and L. Hollberg, "Miniature vapor-cell atomic-frequency references," *Appl. Phys. Lett.* **81**, 553-555 (2002).
16. S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, J. Kitching, L. A. Liew, and J. Moreland, "A microfabricated atomic clock," *Appl. Phys. Lett.* **85**, 1460-1462 (2004).
17. P. D. D. Schwindt, S. Knappe, V. Shah, L. Hollberg, J. Kitching, L. A. Liew, and J. Moreland, "Chip-scale atomic magnetometer," *Appl. Phys. Lett.* **85**, 6409-6411 (2004).
18. L. A. Liew, S. Knappe, J. Moreland, H. G. Robinson, H. Hollberg, and J. Kitching, "Microfabricated alkali atom vapor cells," *Appl. Phys. Lett.* **84**, 2694-2696 (2004).
19. S. Knappe, V. Velichansky, H. G. Robinson, L. Liew, J. Moreland, L. Hollberg, and J. Kitching, "Atomic vapor cells for miniature frequency references," in *Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum* (Tampa, 2003).

20. A. Onae, K. Okumura, J. Yoda, and K. Nakagawa, "Saturation spectroscopy of acetylene molecule towards frequency standard at 1550 nm region," in *CPEM Digest (Conference on Precision Electromagnetic Measurements, 1996)*.
  21. F. Nez, R. Felder, and Y. Millerioux, "Optical frequency determination of the hyperfine components of the 5S  $1/2$ -D $3/2$  two-photon transitions in rubidium," *Opt. Commun.* **102**, 432-438 (1993).
  22. S. Peil, S. Crane, and C. Ekstrom, "High-efficiency frequency doubling for the production of 780 nm light," in *Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum (Tampa, 2003)*.
  23. A. Sargsyan, D. Sarkisyan, and A. Papoyan, "Dark line atomic resonances in a sub-micron thin Rb vapor layer," *Phys. Rev. A* **73**, 033803 (2006).
  24. S. Knappe, V. Gerginov, P. D. D. Schwindt, V. Shah, H. G. Robinson, L. Hollberg, and J. Kitching, "Atomic vapor cells for chip-scale atomic clocks with improved long-term frequency stability," *Opt. Lett.* **30**, 2351-2353 (2005).
  25. G. Wallis and D. Pomerantz, "Field assisted glass-metal sealing," *J. Appl. Phys.* **40**, 3946-3949 (1969).
  26. S. Knappe, P. Schwindt, V. Shah, L. Hollberg, J. Kitching, L.A. Liew, and J. Moreland "A chip-scale atomic clock based on  $^{87}\text{Rb}$  with improved frequency stability," *Opt. Express* **14**, 1249-1253 (2005).
  27. W. E. Lamb, "Theory of an optical maser," *Phys. Rev. A* **134**, A1429-A1450 (1964).
  28. S. Kraft, A. Deninger, C. Truck, J. Fortagh, F. Lison, and C. Zimmermann, "Rubidium spectroscopy at 778-780 nm with a distributed feedback laser diode," *Las. Phys. Lett.* **2**, 71-76 (2005).
  29. R. Lutwak, P. Vlitaz, M. Varghese, M. Mescher, D. K. Serkland, and G. M. Peake, "The MAC - A Miniature Atomic Clock," in *Proceedings of the IEEE International Frequency Control Symposium and the Precise Time and Time Interval (PTTI) Systems and Applications Meeting (Vancouver, Canada, 2005)*.
  30. A. Brannon, M. Janković, J. Breitbarth, Z. Popović, V. Gerginov, V. Shah, S. Knappe, L. Hollberg, and J. Kitching, "A local Oscillator for Chip-Scale Atomic Clocks at NIST," in *Proceedings of the IEEE Frequency Control Symposium (Miami, FL, 2006)*.
- 

## 1. Introduction

Since the development of suitable single-mode diode lasers, sub-Doppler spectroscopy on alkali atoms such as rubidium and cesium has become an essential tool for a wide variety of atomic physics experiments [1]. In many of these experiments, it is essential to tightly stabilize the laser frequency to a specific atomic transition. Various spectroscopic techniques such as saturated absorption spectroscopy [2-4], polarization spectroscopy [5], dichroic-atomic-vapor laser lock (DAVLL) [6, 7], and selective reflection spectroscopy [8-11] have been used for sub-Doppler or Doppler spectroscopy in alkali vapor cells.

Saturation spectra have been characterized extensively for various transitions in terms of lineshape, linewidth, and amplitude as a function of parameters such as laser polarizations [12, 13], magnetic field [14], and laser intensity. Until now, most of these experiments used glass-blown vapor cells a few centimeters in size. They are used primarily in atomic physics experiments that typically fill large optical tables. Recently, MEMS (microelectromechanical systems) technology has enabled a new generation of miniaturized atomic devices such as chip-scale atomic clocks [15, 16] and atomic magnetometers [17]. These examples demonstrate the feasibility of shrinking laser spectroscopic table-top setups into chip-scale atomic devices for field applications.

In this paper, we introduce a miniaturized saturated absorption spectroscopy setup with a microfabricated vapor cell [18, 19] of 1 mm<sup>3</sup> interior volume. The system could be used directly to provide a stable optical frequency at 795 nm, 780 nm, 895 nm, or 852 nm by locking a single-mode diode laser to an atomic transition in rubidium or cesium atoms. Furthermore, this setup could easily be extended to other atoms and molecules such as potassium or iodine. Well-behaved distributed-feedback (DFB) lasers and distributed Bragg reflector (DBR) lasers are also available at wavelengths around 1.5  $\mu\text{m}$ , where they can be used for saturated absorption spectroscopy in acetylene [20] or in the two-photon transition in rubidium [21]. Finally, such a miniature spectroscopy setup could be used to frequency stabilize telecom lasers between 1540 nm and 1590 nm by adding a PPLN (periodically poled lithium niobate) waveguide in front of the Rb or K spectrometer. This idea has been demonstrated in relatively large systems with conversion efficiencies up to 70 % [22].

Saturated absorption spectra have been measured in extremely thin cells with thicknesses below the wavelength of the light but with transverse dimensions of several centimeters [23].

That method relies on the atoms flying perpendicularly to the laser beam. However those systems cannot easily be miniaturized or reduced to small devices.

## 2. Cell fabrication

The miniature atomic vapor cells were fabricated using procedures reported elsewhere [24], but described briefly here. A square hole was etched through a 1 mm thick silicon wafer by use of MEMS fabrication technologies such as potassium hydroxide etching (KOH) or deep-reactive ion etching (DRIE). Hole sizes ranged from 1 to 2 mm on a side. The silicon wafers were diced into 9 mm by 14 mm dies for easier handling and filling inside a vacuum chamber. Prior to insertion into the vacuum system a 300  $\mu\text{m}$  thick borosilicate glass window was anodically bonded [25] onto one side of each die. Each preform, made in this way, contains 1 to 4 pockets that can be filled with alkali atoms. A getter material was deposited onto the side walls of each pocket before the preforms were placed into a vacuum system. The preforms and the cover glass that will serve as the second window of the cell were baked at 300  $^{\circ}\text{C}$  for 2 to 12 hours. At the same time the getter was heat-activated. Care was taken to ensure that the getter was not active while the pressure was too high so that it was not saturated. The cell was then filled with alkali atoms by evaporating them through a glass nozzle of diameter 700  $\mu\text{m}$ , which was lowered into the cell preform [24]. The cell was then sealed with the second piece of borosilicate glass that was anodically bonded to the Si in the vacuum at 300  $^{\circ}\text{C}$ . The cells were subsequently diced into squares roughly 2 mm on a side. Cells filled with natural and isotopically enriched Rb as well as Cs have been made this way [26]. The cells were integrated with transparent heaters on both windows made from indium tin oxide (ITO) deposited onto 125  $\mu\text{m}$  thick glass slides. Gold bars deposited onto the ITO serve as electrical contacts. When current is passed through the ITO, the windows are heated, which keeps them at slightly higher temperature than that of the cell body, thus preventing alkali atoms from condensing on the windows. The window heaters raise the cell temperature to  $\sim 45$   $^{\circ}\text{C}$ .

## 3. Spectroscopy setup

The vapor cell and the heaters were then glued onto a PC board with solder pads and connectors for electrical contacts and were contacted with indium solder. The optical path through the vapor cell was created by micro-optical components, as diagrammed in Fig. 1. For convenience and ease of alignment, the system was constructed from commercially available cube polarizers and right-angle prisms that separate pump and probe beams.

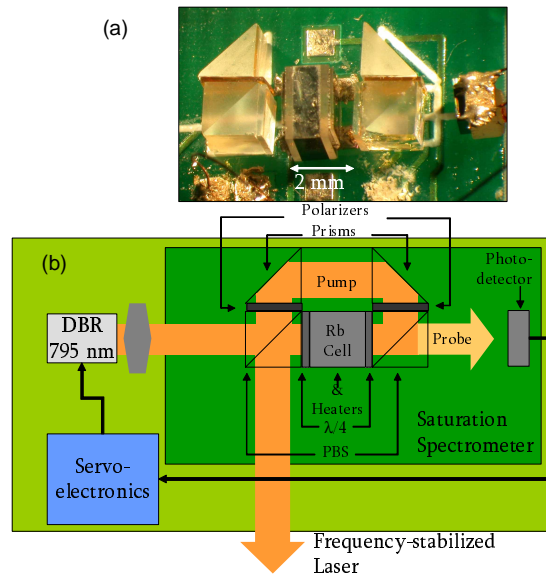


Fig. 1. (a). Photograph of the microfabricated saturated absorption spectrometer. (b) Schematic of the microfabricated setup, which consists of a vapor cell with two heaters, two polarizing beam splitters, two polarizers, two prisms, two quarter waveplates, and a photodetector. The laser and control electronics are not shown in the photo, but could be close to the tiny spectrometer or elsewhere.

Thin quartz plates serve as quarter wave plates and thin absorptive polarizers are used to further clean up the polarization in the reflected beams. A silicon photodiode was mounted onto an alumina substrate and used to detect the light from the probe beam. All of the components have planar surfaces and the beam paths are very short, so they can be easily glued together without complicated optical alignment. The spectrometer has a total volume of  $0.1 \text{ cm}^3$ , roughly the size of a green pea. Further size reduction could be achieved by implementing optical MEMS techniques, instead of using off-the shelf components.

#### 4. Results

Light from a DBR laser at 795 nm wavelength was used to measure a saturated absorption spectrum with the setup described above. With the vapor cell at  $45 \text{ }^\circ\text{C}$  the Doppler-broadened absorption is about 30 %. The spectrum shown in Fig. 2(a) is for the transitions  $5S_{1/2}, F = 2 \rightarrow 5P_{1/2}, F' = 1$  and 2 in an isotopically enriched  $^{87}\text{Rb}$  cell. The two Lamb dips [27] and the cross-over peak between them demonstrate the very good contrast achievable with this tiny spectrometer. The relevant energy level scheme of  $^{87}\text{Rb}$  is shown in Fig. 2(c). Figure 2(b) shows a similar spectrum for a cell with a natural mixture of Rb isotopes. The two center peaks correspond to the transitions  $5S_{1/2}, F = 2 \rightarrow 5P_{1/2}$  and  $5S_{1/2}, F = 3 \rightarrow 5P_{1/2}$  in  $^{85}\text{Rb}$ , where the excited-state hyperfine structure is not resolved in the Doppler-broadened case. An energy level diagram of  $^{85}\text{Rb}$  can be seen in Fig. 2(d).

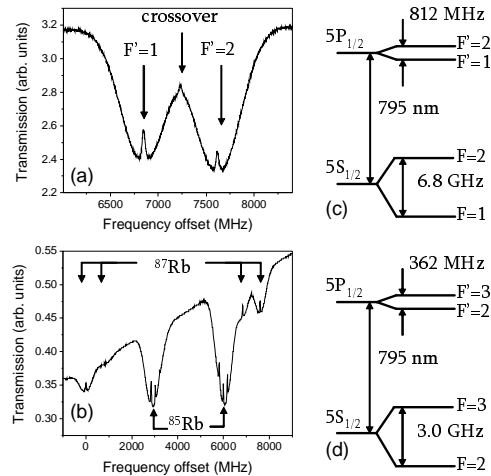


Fig. 2. (a). Spectrum of the transitions  $5S_{1/2}$ ,  $F = 2 \rightarrow 5P_{1/2}$ ,  $F' = 1$  and  $2$  isotopically enriched  $^{87}\text{Rb}$  measured with the microfabricated saturation spectrometer. (b) Saturated absorption spectrum of all  $D_1$ -line transitions in natural rubidium, measured in a microfabricated vapor cell. (c) Relevant energy level structure of  $^{87}\text{Rb}$ . (d) Relevant energy level structure of  $^{85}\text{Rb}$ .

When the size of the vapor cell in a saturated absorption spectrometer is decreased, the sensitivity of the device could be degraded for a variety of reasons: the resonance linewidth could increase, fluorescence could increase, the contrast of the resonance could be reduced, less light would be transmitted to the detector, etc. In the following sections we discuss some of these issues for this miniature spectrometer.

One problem that arises when miniaturizing the setup relates to the fluorescence from the alkali vapor that is detected by the photodetector. Since the atomic density inside the cell is much higher than that in conventional centimeter-sized cells, the fluorescence is more concentrated and the photodetector is located only a few millimeters from the cell, so the solid angle of detected fluorescence is relatively large. To reduce the effect of fluorescence, a polarizer was placed in front of the cell, transmitting the light of the probe beam only. Furthermore, a photodiode with a small active area of 1 mm diameter was used.

The linewidths of the saturation dips were measured as a function of pump beam intensity (see Fig. 3). When extrapolated to zero intensity, the linewidth approaches 31 MHz, while the natural linewidth of the rubidium transition is  $\sim 6$  MHz. The Doppler contribution resulting from the angle between the pump and probe beams was estimated to be below 20 MHz, and the linewidth of the DBR laser was estimated to be roughly 22 MHz. Furthermore, the linewidth of the Lamb dips depends on the period spent by the atoms in the laser beam, e.g., transit-time broadening. For a 1 mm diameter beam the time-of-flight width is roughly 500 kHz, which is much smaller than the natural linewidth of the alkali atoms (around 6 MHz). The size of the cell should therefore not limit the linewidth of the saturation dips and the use of a laser with a narrower spectral profile and more careful alignment of pump and probe beams should result in linewidths limited by the Rb natural width.

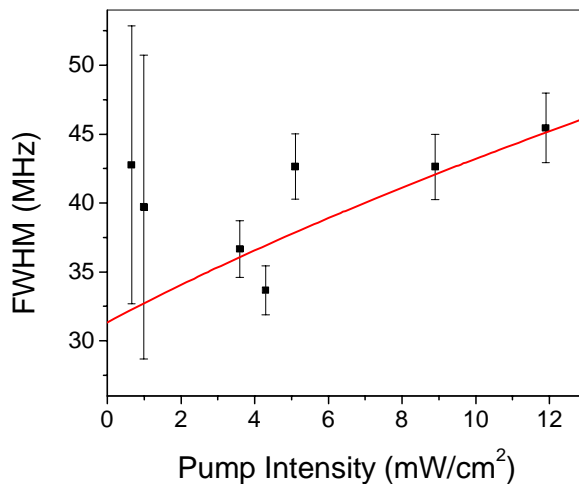


Fig. 3. Full width at half maximum (FWHM) of the saturation dips measured as a function of pump laser intensity (black squares). The probe laser intensity was held constant at 2.6 mW/cm<sup>2</sup>. The error bars were deduced from a Lorentzian fit to the resonance lineshape. The solid line is a fit to the measured data.

As expected, the contrast of the saturation dips depends on the laser polarizations as well as on the direction of the external magnetic field. Since the path length of the cell is only 1 mm, it must be heated to reach similar absorption depths as in centimeter-size vapor cells. In the configuration shown in Fig. 1, the pump and probe beam are oppositely circularly polarized. The external magnetic field was measured to be roughly perpendicular to the laser beams. The contrast in this setup (amplitude of saturation dips compared to Doppler background) was measured to be around 40 % for equal pump and probe intensities (implying some optical pumping in addition to saturation). In a field application, the setup will likely need a small magnetic shield to prevent frequency shifts due to altered optical pumping, but that is not a serious problem for most applications.

The linewidth and contrast of the resonances are comparable to those measured in larger table-top setups; however, the small size of the laser beam reduces the total power on the atoms probed and therefore will reduce the signal-to-noise ratio for constant intensity with reduced cell size. With saturation intensities around 1 mW/cm<sup>2</sup>, the power in a 1 mm diameter pump beam is around 10  $\mu$ W. For a silicon photodiode, the shot noise current from this power is around 1.5 pA/Hz<sup>1/2</sup>. So, even with a tiny cell, 10  $\mu$ W of optical power and 40 % resonance contrast, a shot-noise-limited signal-to-noise ratio of  $5 \times 10^5/\sqrt{\text{Hz}}$  can be expected. Thus, even a 40 MHz linewidth will provide sufficient signal-to-noise to support a frequency resolution of  $100 \text{ Hz} \times \sqrt{\text{Bandwidth}}$ , e.g., 10 kHz with a measured bandwidth of 10 kHz. This is a promising, but an admittedly optimistic, number, since systematic errors and uncertainties will likely be much larger. Nevertheless, we expect that a microfabricated sub-Doppler spectroscopy setup like the one described here could be used to stabilize a diode laser with a long-term frequency instability less than 100 kHz. In addition, a low-power laser system could be implemented with one of these setups directly as a compact optical wavelength standard. All components could be hermetically sealed into a commercially available transistor can, providing a small, stable wavelength reference about the size of a green pea.

Recently, new generations of DFB and DBR lasers and VCSELs have become available for spectroscopic applications using the D<sub>1</sub> and D<sub>2</sub> lines of cesium and rubidium [28]. In combination with the compact microfabricated saturation spectrometer described here, they could be a practical tool for small turnkey wavelength references. A possible setup for such a

wavelength reference is shown in Fig. 1(b). Very small electronics for a laser wavelength servo and a temperature servo have been previously demonstrated [29, 30] for application in chip-scale atomic clocks [15, 16] and magnetometers [17]. Finally, the range of wavelengths could be extended to 1.5  $\mu\text{m}$  by adding a frequency doubler such as a PPLN waveguide.

## 7. Conclusion

We present a miniature microfabricated laser sub-Doppler spectrometer that could be used as a miniature optical wavelength reference of volume 0.1  $\text{cm}^3$ . Signals in the vapor cell of volume 1  $\text{mm}^3$  are found to be comparable to those in table-top setups. Short path lengths of a few millimeters allow for easy alignment.

<sup>†</sup> Contribution of NIST an agency of the U.S. government; not subject to copyright.