

# Microfabricated saturated absorption laser spectrometer

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**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.

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

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## 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.

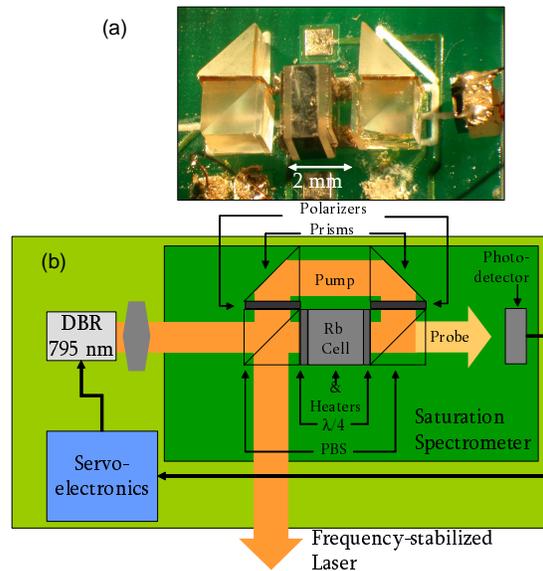


Fig. 1. (a). Photograph of the microfabricated saturated absorption spectrometer. (b) Schematic of the microfabricated setup, which consists of a vapor cell with two heaters, two polarizing beam splitters, two polarizers, two prisms, two quarter waveplates, and a photodetector. The laser and control 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  $45^\circ \text{C}$  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).

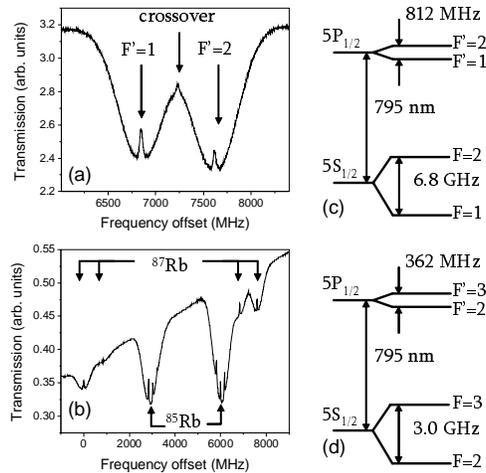


Fig. 2. (a). Spectrum of the transitions  $5S_{1/2}$ ,  $F = 2 \rightarrow 5P_{1/2}$ ,  $F' = 1$  and  $2$  isotopically enriched  $^{87}\text{Rb}$  measured with the microfabricated saturation spectrometer. (b) Saturated absorption spectrum of all  $D_1$ -line transitions in natural rubidium, measured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

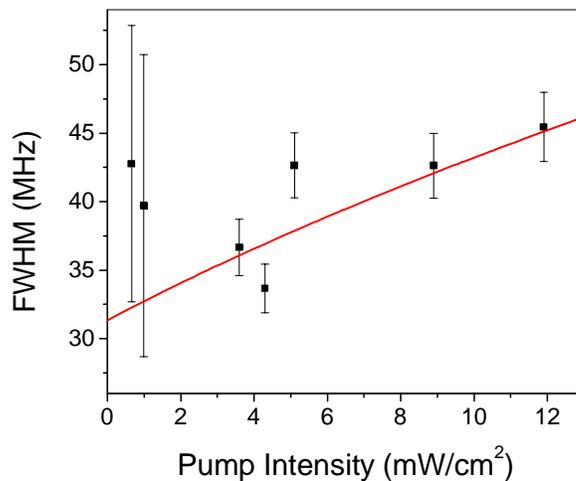


Fig. 3. Full width at half maximum (FWHM) of the saturation dips measured as a function of pump laser intensity (black squares). The probe laser intensity was held constant at 2.6 mW/cm<sup>2</sup>. The error bars were deduced from a Lorentzian fit to the resonance lineshape. The solid line is a fit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

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