VCSEL Absorption Spectroscopy of Chip-scale Rubidium Atomic Vapor

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ABSTRACT

Researchers from the Indian Space Research Organization in Bengaluru, India have developed and demonstrated the absorption spectroscopic capabilities of a chip-scale Rubidium (Rb) atomic vapor cell using a thermoelectric cooler integrated VCSEL light source in a magneto-optic package. The custom three-dimensionally printed design provides real time analysis of spectral data by laser interrogation of the D1 hyperfine transition states of the Rb vapor in the chip-scale cell. With over 600 hours of data, absorption resonance lines were recorded and analyzed for transitions ^{85}Rb and ^{87}Rb with absorption amplitude and FWHM data agreeing with known literature values. This magneto-optic Rb atomic cell package proves potential for atomic sensors, particularly in space borne applications or payloads.

HOT ATOMIC VAPORS

Recent developments of quantum sensors rely on sensing hot atomic vapors in a specific type of vapor cell.[1] By optically interrogating the atoms and their states, an absorption spectra can be obtained that can lead to changes or monitoring of the sensor's object of interest. The miniaturization of these quantum sensors also requires increasingly smaller-sized hot vapor cells. Fabrication on a single wafer with hundreds of vapor cells or chip-scale vapor cells enable quantum sensors to be utilized in a wide range of applications. Quantum sensing applications include: atomic clocks, gyroscopes, magnetometers, frequency-stabilized lasers, frequency standards, gas sensors, as well as GHz and THz imaging and detectors.[1]

There are multiple parameters that are changed and manipulated for different experiments. First, the vapor cell is filled with the appropriate metallic alkali vapor. Common vapors are Rubidium (Rb) or Cesium (Cs). Secondly, some applications require the addition of inert buffer gases and spin polarizable atomic species such as Xenon (Xe).[1] Lastly, and most importantly, the configuration of the chip-scale cells determine how the atomic vapors are spectrally observed. Vapor cells can be constructed with planar, spherical, and cubical shapes using MEMS fabrication technology.

Typically, the alkali vapor cell is the first priority of the system, as a miniature chip-scale cell and absorption spectroscopy based on that vapor cell can be a tedious task to setup and calibrate. The other component that is crucial for this type of sensor is the light source for optical interrogation of the atoms inside the vapor cell. A laser diode, Light Emitting Diode (LED), or a Vertical Cavity Surface Emitting Laser (VCSEL) are common choices for absorption spectroscopy in a small package.

PROBLEMS AND GOALS

The packaging containing the light source, vapor cell, heating element, and optics requires precise alignment to allow absorption spectra measurements to become repeatable and accurate. Compactness and error-free alignment can expand the range of applications for quantum sensors, especially in space applications.

Vibrations in handling and testing also can affect the alignment of components inside the packaging containing the vapor cell and optics. Careful consideration of the packaging materials and design must be taken to ensure longevity and repeatability. Because the cell needs to be heated, ex. 70ºC, thermal isolation and control is required for the light source. The element used in the vapor cell needs to have a boiling point that is reasonable to achieve and maintain for a constant vapor phase to observe atomic absorption resonances. Higher temperatures can also create stronger absorption resonances for observation. The cell heating design and method can effect temperature stability, power consumption, and number density of vapor required for absorption spectroscopy experiments. In this study, two approaches are developed for integrated thin film heaters.

When the packaging, optics, and alignment have shown to be reliable for absorption studies, obtaining spectra is one of the final steps for developing an atomic sensor using chip-scale vapor cells. Achieving stable and repeatable absorption spectra is critical for demonstrating a viable atomic sensor that can be implemented into a wide range of applications in space borne sensors and payloads.[1]

METHOD

Researchers from the Laboratory for Electro-Optics Systems in Bengaluru, India, have developed and performed absorption spectroscopic studies of a compact, three-dimensional (3D) printed, magneto-optic (MO) package containing a chip-scale Rubidium atomic vapor cell. The printed MO package allows the integration of key components including the vapor cell, the VCSEL used as the light source, magnets for affecting how the light passes through the polarizing elements, quarter wave plates, the filters, and photodiode for sensing the light. These elements and cross-section of the MO package are shown in **Figure 1**.

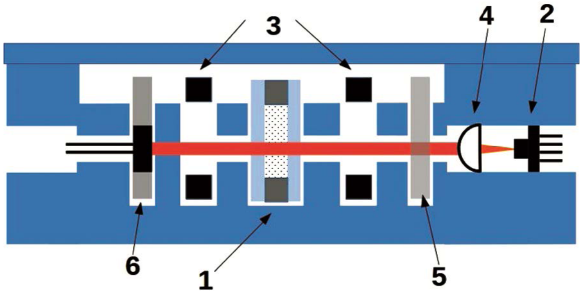


Figure 1. The schematic cross-section of the MO package. 1 – chip-scale vapor cell, 2 – VCSEL laser, 3 – annular magnets, 4 – collimating lens, 5 – ND filter, 6 – photodiode.[1]

The ability to 3D print the package eliminates high costs, allows custom design, and ensures accuracy and precision of up to 0.1 mm with a compact setup. The cross section in **Figure 1** shows precisely machined slots for the variety of optical elements and vapor cell. The package is split into two sections: a slotted housing and the outer housing. Both of these sections can be seen in **Figure 2**. The slotted housing is comprised of the holder section that contains the optical elements and vapor cell as well as the cap section that is press-fitted on the holder section and sealed with epoxy to create a vibration-immune package for handling and testing purposes. The outer housing contains the electronic components of the setup: VCSEL laser, collimating lens, and a miniature electrical connector. Other components, like the current source and temperature controller are outside the MO package and connected to the appropriate elements.

The MO package is made from a polylactic acid material creating a relatively low thermal conductivity design. This ensures good thermal isolation for the chip-scale vapor cell. Not only does this reduce how the temperature of the vapor cell affects the package and specifically the VCSEL temperature and output, but it reduces the steady state power consumption of the overall package.[1]

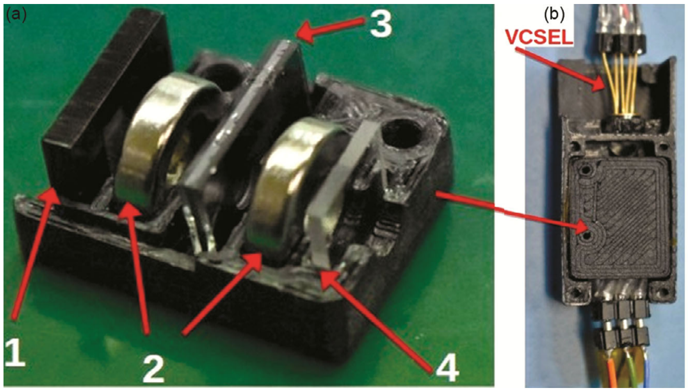


Figure 2. (a) showing the various components of the slotted MO housing 1 – photodetector on an acrylic holder, 2 – annular magnets, 3 – heater integrated Rb vapor chip, 4 – ND filter. (b) the closed slotted housing placed inside the outer housing.[1]

The chip-scale vapor cell's dimensions are 12 mm x 8 mm x 1.5 mm with an optical cavity 3 mm in diameter and an optical path length of 0.5 mm. The cell is designed with a glass-silicon-glass stack, and a Rb dispenser pill is used in the development stage and inserted into the cavity to be thermally activated and released. The boiling point of Rb is 39.48ºC. So, at room temperature, the Rb metal is in liquid phase and is found in condensed droplets on the windows of the cell. Therefore, the cell needs to be heated to transition the Rb metal into a vapor phase to observe atomic absorption resonances.[1]

To heat the Rb vapor cell to a temperature well above the boiling point, two approaches are taken and demonstrated: Nichrome (NiCr) and Indium Tin Oxide (ITO). **Figure 3** shows both methods of heating the vapor cell as well as a thermal image under test.

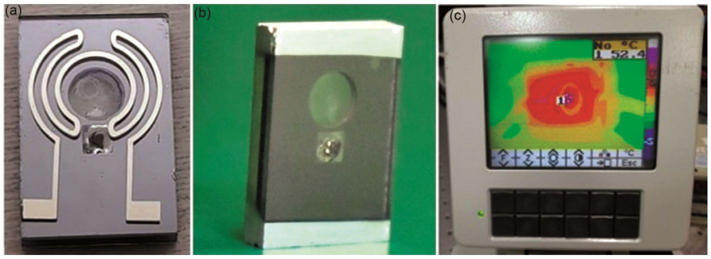


Figure 3. Heater integrated chip-scale Rb vapor cells (a) patterned NiCr heating element. (b) ITO coated vapor cell with aluminum contact pads. (c) thermal image of the integrated chip-scale heater under test.[1]

As seen in **Figure 3**, the two methods use vastly different techniques. The NiCr uses a patterned heating element with 2500 Å deposited on the vapor cell. This particular heater displayed a resistance of ~600 Ω and maintained a steady state temperature of 60ºC. The ITO uses a sputter coating on the cell in a blanket deposition process. This method used 2000 Å of ITO with both sides of the cell sputter coated. Although this technique covers the entirety of the clear glass surfaces, the transmission of the ITO films is greater than 88% at 795 nm. Aluminum is added to the sides of the film for electrical contact pads. The ITO heater displayed a resistance of ~20 Ω and reached a steady state temperature of 56ºC. With these conditions, and the heaters discussed, the vapor cell temperature reached around 70ºC providing a sufficient environment for the Rb for hot atomic vapor absorption spectroscopy studies.[1]

For the absorption spectroscopy, a VCSEL is chosen for the light source due to its single mode output and narrow spectral linewidth. Built into the VCSEL source are a thermoelectric heater and thermistor for better control of the laser output. Because change in temperature of the VCSEL directly correlates to a shift in center frequency of the laser output, the temperature of the VCSEL needs to be maintained with a precision of 100 mK to stabilize the laser output. Researchers used the VCSEL in a TO-46 package with a set temperature range of 50 - 55ºC and a current ramp from 1.45 mA to 1.55 mA in steps of 70 nA at 1 ms dwell times. Researchers utilized the WTC3243 Temperature Controller from Wavelength Electronics, mounted on its Evaluation Board, WTC3293, for high precision control and stability of the VCSEL. The temperature controller, as well as all major electronic components can be seen in **Figure 4** showing the experimental setup of the absorption spectroscopy design.

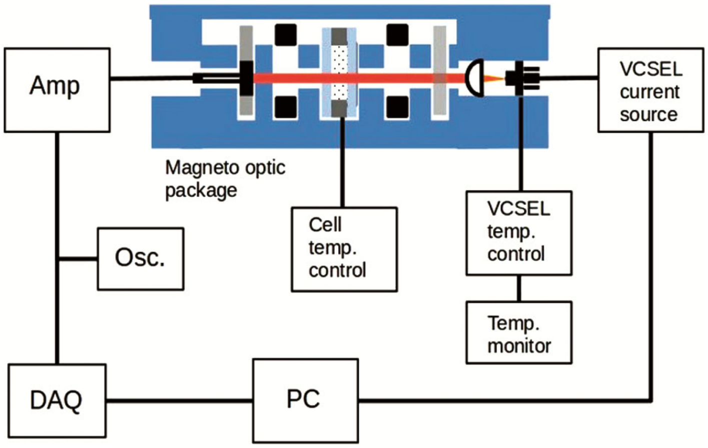


Figure 4. Layout of the experimental set up of the absorption spectroscopy of chip-scale Rb vapor cell.[1]

For testing preparations, the MO package was placed on a vibration isolated bench. The VCSEL temperature was set to 54ºC using the WTC3243 controller connected to a Raspberry Pi board for plotting the set and process values of the temperature from digitized voltages every second. The vapor cell was heated to around 75ºC. The ITO film integrated heater dissipated about 750 mW of power and was left for 10 minutes to achieve thermal equilibrium before any tests were performed. The VCSEL temperature was adjusted to obtain a complete spectrum in the center of the oscilloscope data acquisition scan.[1]

For the Rb vapor absorption spectroscopy, the VCSEL current is scanned using a sawtooth shaped current ramp across the D1 absorption lines of the Rb atoms inside the vapor cell. Because Rb absorption spectrum is known, two peaks are selected from recorded data as the reference and correspond to the Doppler broadened lines ^{85}Rb F=2 → F' = 2,3 (794.985 nm) and ^{87}Rb F=1 → F' = 1,2 (794.980 nm).[1] Using these parameters and reference peaks for calibration and Gaussian fittings, absorption spectroscopy studies of the chip-scale Rb atomic vapor cell were carried out in the MO package using the D1 absorption line of both ^{85}Rb and ^{87}Rb. Using the scanned injection current of the VCSEL, the absorption spectrum is obtained from the hot atomic Rb vapor.

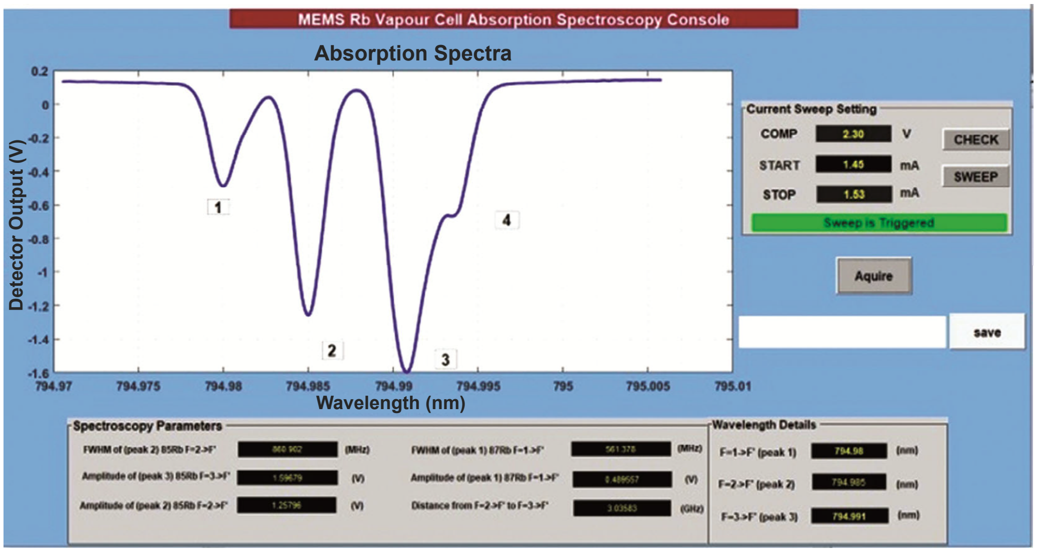
RESULTS

With 3.5 µL volume of hot atomic vapor, the absorption spectrum was recorded and analyzed. More than 600 hours of operation in lab conditions were used for obtaining steady and repeatable spectra from the MO package. Real-time data was acquired with identified peaks with Full-Width at Half-Maximum (FWHM) based on Gaussian fittings. The identified peaks are labeled in **Table 1**, correlating to a typical screenshot of the user interface after the absorption spectrum is acquired in **Figure 5**.

Table 1. Labeling of absorption resonance peaks[1]

PEAK	TRANSITION
1	^{87}Rb($^{2}S_{1/2}$ F=1 → $^{2}P_{1/2}$ F' = 1, 2)
2	^{85}Rb($^{2}S_{1/2}$ F=2 → $^{2}P_{1/2}$ F' = 2, 3)
3	^{85}Rb($^{2}S_{1/2}$ F=3 → $^{2}P_{1/2}$ F' = 2, 3)
4	^{87}Rb($^{2}S_{1/2}$ F=2 → $^{2}P_{1/2}$ F' = 1, 2)

With over 500 ON / OFF cycles, the design and operation of the MO package shows excellent repeatability along with high mechanical and thermal stability over long periods of time.



Current Sweep Setting
COMP 2.30 V
START 1.45 mA
STOP 1.53 mA
Sweep is Triggered

Spectroscopy Parameters
FWHM of (peak 2) 85Rb F=2->F' 860.902 (MHz)
Amplitude of (peak 3) 85Rb F=3->F' 1.59679 (V)
Amplitude of (peak 2) 85Rb F=2->F' 1.25796 (V)
FWHM of (peak 1) 87Rb F=1->F' 561.378 (MHz)
Amplitude of (peak 1) 87Rb F=1->F' 0.489557 (V)
Distance from F=2->F' to F=3->F' 3.03583 (GHz)

Wavelength Details
F=1->F' (peak 1) 794.98 (nm)
F=2->F' (peak 2) 794.985 (nm)
F=3->F' (peak 3) 794.991 (nm)

Figure 5. Screen shot of the GUI developed for acquiring and analyzing the absorption resonance spectrum of the chip-scale vapor cell in the MO package.[1]

Table 2 shows the spectral parameters for two selected atomic resonance transitions. The absorption amplitude is the value of the minimum detector output for the relevant transition, and the ratio of the detector output to the off resonance background is expressed as a percentage below the amplitude values. These show the strength of the absorption in the atomic vapor medium.[1]

Table 2. Spectral characteristics of selected absorption resonances chip-scale vapor cell obtained from the compact package at cell temperature of 70ºC[1]

PEAK	WAVELENGTH (nm)	FWHM (MHz)	ABSORPTION AMPLITUDE (V)	ABSORPTION COEFFICIENT (m^{-1})
1	794.980	567±16	0.477±0.014 (19.08%)	433.42
2	794.985	850±15	1.24±0.017 (49.6%)	1370.36
Separation between Peak 2 and Peak 3			3.03583 GHz	

Characteristics for only two typical absorption resonances are shown and analyzed in the above table due to the line merging of Doppler broadening. This contributes broadening of around 500 MHz to the linewidth. Because certain excited hyperfine states of Rb are only narrowly separated (less than the Doppler broadening), they cannot be distinguished from one another and are merged together using this particular method. However, the peaks selected in Table 2 are separated by more than 3 GHz, allowing resolvable spectrum for analysis. The determined separation or frequency interval between peaks 2 and 3 agrees well with known literature values for the ^{85}Rb ground state hyperfine levels, validating the effectiveness of the presented MO package for hot atomic vapor absorption spectroscopy.[1]

One of the primary concerns and requirements for developing atomic sensors using chip-scale vapor cells is the ability to obtain stable absorption spectrum.[1] Here, researchers have developed and demonstrated a thermally stabilized, tunable VCSEL MO package for absorption spectroscopy on a heater integrated chip-scale Rb vapor cell. The constructed design was tested and used to obtain absorption spectrum for over 600 hours, proving the stability and reliability of the system. This design, with future additions and upgrades, can be used for a wide range of applications in space borne sensors and payloads and wherever atomic sensors are needed.

WAVELENGTH'S ROLE

With design concerns of compactness and wavelength stability, both the size and stability of the temperature controller are critical in the success of the absorption spectroscopy study. The VCSEL diode required high temperature stability due to the center frequency shifting with change in temperature. To match the small size of the 3D printed magneto-optic package, housing the VCSEL and optics, researchers used Wavelength Electronics' WTC3243 Temperature Controller with a compact design of 1.3 x 1.28 x 0.313 inches. This ensured efficient space management as well as allowing operation in other handheld or portable equipment similar to the 3D printed magneto-optic package for absorption spectroscopy in atomic sensors.

The WTC3243 can drive up to ±2.2 A of current to a thermoelectric with both heating and cooling current limits. The PI control loop offers maximum stability while maintaining efficiency. The WTC3243 can deliver as low as 0.0009ºC temperature stability over one hour with 0.002ºC stability across ambient. For this experiment, researchers maintained the VCSEL temperature in the range of 50ºC to 55ºC with a precision of 100 mK from the temperature controller.

Researchers also took advantage of the WTC3293 Evaluation Board to rapidly prototype their temperature control system. Onboard switches, connectors, and trimpots make configuration and operation simple. Temperature setpoint, proportional and integrator time constants can be adjusted via onboard trimpots. This evaluation board enabled researchers to quickly integrate the WTC3243 temperature controller with their 3D printed magneto-optic package for absorption spectroscopy of chip-scale Rb atomic vapor cell.

PRODUCTS USED
WTC3243, WTC3293 Evaluation Board

KEYWORDS
Chip-scale vapor cell, absorption spectroscopy, VCSEL, 3D printing, tunable diode laser spectroscopy, magneto-optic, temperature controller, WTC3243, WTC3293, Rubidium, Rb, atomic sensor

REFERENCES

1. Giridhar, M. S.; Karanth, S. P.; Akshaya; Elumalai, S.; Sriram, K. V. Absorption Spectroscopic Studies of Chip-scale Rubidium Atomic Vapour Cells in a Compact 3D Printed Magneto-Optic Package. *IJPAP* **2023**, 61, 301-308. https://doi.org/10.56042/ijpap.v61i5.71432

USEFUL LINKS

- WTC3243 Product Page
- WTC3293 Product Page

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A	August 2023	Initial Release