

Compact and ultra-stable rubidium frequency-reference modules for space quantum sensors

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We present two compact frequency-reference modules based on novel spectroscopic and manufacturing approaches. The first module is fabricated using additive manufacturing and rapid-prototyping 3D design techniques. The error signal required for laser stabilization is generated by modulating the atomic reference rather than the laser itself, resulting in a more robust system with significantly reduced volume, weight, cost, and power consumption. The second device is constructed from space-qualified materials (Zerodur), and assembled using certified bonding techniques, making it a promising candidate for space based quantum technologies. We demonstrate a novel double-differential Zeeman-dither spectroscopy scheme that substantially decreases the sensitivity to magnetic field perturbations and laser power fluctuations. A direct comparison of this scheme with a single σ_+ one yields an improvement by about two orders of magnitude both for 10% laser intensity and 100 mG magnetic field fluctuations.

Keywords: frequency stabilization, saturated absorption spectroscopy, additive manufacturing, Zerodur

1. INTRODUCTION

Atom-based quantum sensors are a key future technology for high-sensitivity, high-accuracy measurements both on earth and in space, with applications covering earth's gravitational field, inertial navigation, electro-magnetic fields, and even gravitational waves or weather research.¹⁻⁶ Atomic gasses—both ultra-cold and thermal—All of these applications hinge on the laser sources as the main means of manipulation of the atoms and their internal and external states. Typically, these lasers need to be stabilized to within a few tens kilohertz with the absolute frequency of a desired atomic transition, which corresponds to an absolute long-term stability of 10^{-10} . The challenges include SWaP and the required stability against magnetic field, temperature, and laser-intensity fluctuations.

In this paper, we present our progress towards a space-qualified, compact, ultra-stable reference spectroscopy for the frequency stabilization of these lasers using Zeeman dithered saturated absorption spectroscopy.⁷ We take two complementary approaches, one based on 3D-additive manufacturing and one on ultra-low expansion materials, with the first one being more suitable for LEO missions and the second one aiming at ultra-high precision missions. We use the hyperfine lines in the D2 transition in Rubidium, as this is where most planned atom quantum sensors operate.^{5,8}

Zeeman dithering spectroscopy

Zeeman dithering spectroscopy uses magnetic fields to shift the frequency of an absorption line using the Zeeman effect. The sign of the frequency shift (Δf) depends on whether the light drives a σ_+ or σ_- transition, i.e. the projection of the handedness of the light onto the magnetic field. A modulation in the magnetic field modulates the frequency of a σ transition relative to the laser frequency and thus in turn the absorption by the atoms. By demodulating the measured absorption we can derive a Doppler-broadened error signal.⁹ By counter-propagating a strong pump beam, one can saturate the transition and a sub-Doppler Lamb-dip appears, which then serves as

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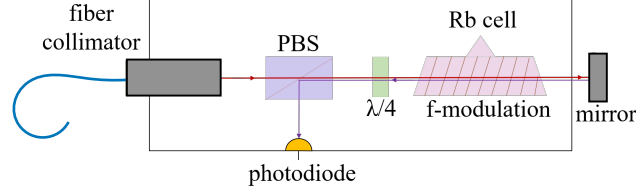


Figure 1. Optical setup of the Single-detection spectroscopy configuration

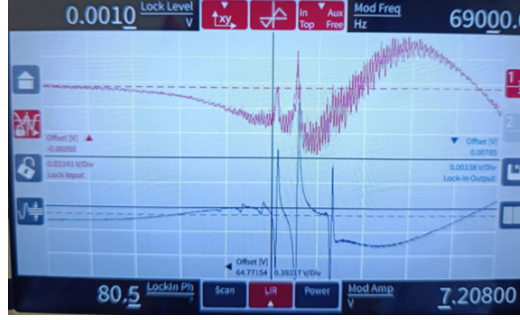


Figure 2. The signals from the 3D-printed mini spectroscopy (increasing frequency with arbitrary units). The upper (red) trace is the direct output of the photo-diode. The lower (blue) trace is the demodulated error signal. The signal has been optimized for 1/3 cross-over line of the D2 line in ^{87}Rb . The beam power was 800 μW into a beam diameter of 4 mm.

a narrow-linewidth frequency reference.¹⁰ A common method to realize the Zeeman dithering is to use circularly polarized light.¹¹

We aim at developing a highly stable, space-compatible Rb-spectroscopy with two goals in mind: a simple, compact spectroscopy, e.g. for nano-satellites and a more stable and accurate spectroscopy for precision atom-quantum sensors. A step towards the first goal has been realized in using a fiber-coupled 3D-printed optical assembly (see figure 3d). A demonstrator towards the second goal is based on ultra-low expansion coefficient glass ceramic (Zerodur), as described in section 3. Finally, we test the new double-subtraction method in a laboratory setup.

2. 3D-PRINTED FIBER-COUPLED SPECTROSCOPY

Additive manufacturing offer not only the potential of rapid development and iteration but also as a method of producing space-qualified components at a low cost and great flexibility. We have developed a toolkit for producing complex optical setups in a highly reliable and flexible way, which is based on constructing the optical setup in CAD program using 'negative optical elements' (see section 2.1)

The module was produced using LCD induced vat photopolymerization, which offers high-resolution details, fast curing speeds, and affordable prices.¹² The optical configuration is presented in Fig. 1 and the final spectroscopy module in Fig. 3, which is based on σ polarized light. The laser light from the optical fiber is collimated and sent through a polarizing beam splitter followed by a quarter wave plate producing circularly polarized light. This is followed by small Rubidium cell and a retro-reflecting mirror. Note that even though the mirror turns the left-handed polarized light into right-handed, it stays σ_+ polarized and thus interacts with the same optical transition in the Rubidium atoms. After passing through the waveplate, though, its linear polarization is orthogonal to the incoming one and thus is reflected to the photo diode for detection. The Rb cell has a magnetic coil directly wound on it, which due to its small size can be driven directly from a standard function generator. The signal from the photo-diode is amplified using a two stage 1 MHz bandwidth transimpedance amplifier and fed to an FPGA-based PID laser controller. The error signal of a lock to the $F=2 \rightarrow F'=1/3$ crossover peak¹³ is shown in Fig. 2.

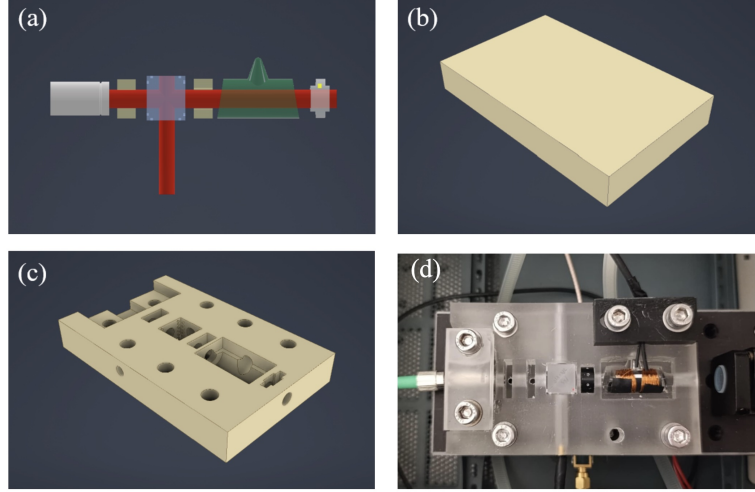


Figure 3. The Optical Negative Elements Technique. a) The optical element assembly, b) combined with a block base, c) the resulting in the final module design, and d) the printed and assembled module.

2.1 Optical Negative Elements Technique

The optical elements in the 3D-printed optical circuit (Fig. 3d) have been placed without any mechanical adjustment in their pre-defined positions.

We have developed a CAD technique for the design of arbitrary 3D printed optical circuits: The Optical Negative Elements Technique (see fig 3). First, individual CADs are created for each optical element, which contain rather than the actual element, the space required to mount it, including the mounting and space where the optical beam propagates. Using these elements, one can then construct an arbitrary optical circuit, as shown in Fig. 3a. This 'negative' optical circuit together with other mounting element is then simply subtracted in the CAD software from the solid optical bread-board (Fig. 3b) resulting in the final CAD design (Fig. 3c), which can then be directly printed.

Care had been taken to minimize the SWaP of the spectroscopy module. Volume reduction was achieved through to the elimination of external optical components and their mechanical adjustment through the pre-alignment afforded by precision 3D printing. Furthermore, the size of the Rb Cell was greatly reduced (to 20 mm length) by careful choice of beam parameters as well as by increasing the absorption by heating the entire 3D printed setup to up to 50°C (see figure 3d for a size comparison to standard Rb Cells). Finally, the magnetic field generating coil used for the frequency modulation of the signal is directly wound around the cell thus further reducing the size and complexity.

3. ULTRA-STABLE SPECTROSCOPY MODULE

Some applications require a higher degree of stability than can be achieved using 3D printing and single polarization detection. The 3D printed optical circuit will operate well under stable conditions near room temperature. However, it cannot withstand large temperature fluctuations and, due to using a single σ polarization, is sensitive to fluctuations in the DC magnetic field.

Here, we present a prototype ULE spectroscopy module. Its mechanical stability is guaranteed by cementing the optical elements directly onto a Zerodur base plate and by minimizing the degrees of freedom in adjustment.^{14,15}

The dependence of the frequency reference on magnetic fields is greatly reduced by driving both σ_+ and σ_- polarized transitions at the same time and subtracting their modulated signals. Once de-modulated using lock-in techniques, the error signals for the two add, but any DC-magnetic fields will shift the two transitions in opposite directions, thus changing the shape, but not the center of the signal.¹⁶

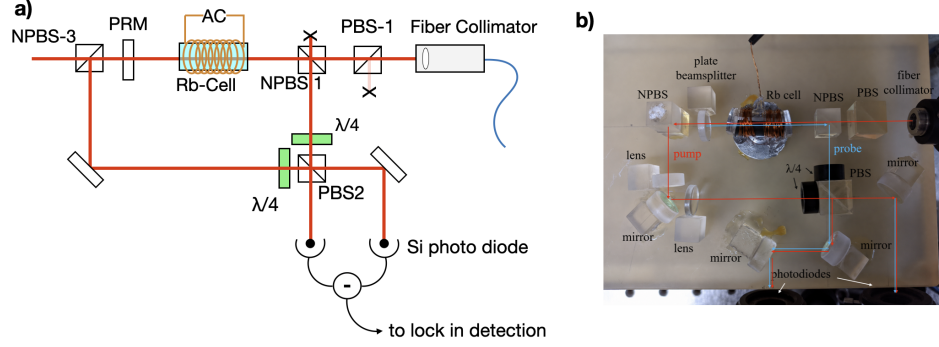


Figure 4. a) Layout of the spectroscopy. b) Zerodur prototype. The optical elements are fiber collimator (4 mm beam diameter), polarizing beam splitters (PBS), polarizing beam splitters (NPBS), $\lambda/4$ wave plates, mirrors, a 10% reflecting mirror (PRM), Rubidium Cell (Rb-Cell) with magnetic field-generating coil.

Of some concern is the fact that the detection of the sub-Doppler Lamb dip necessarily also detects the Doppler-broadened background, which results in a voltage offset of line center. This is usually removed by subtracting a fixed voltage from the signal. Unfortunately, any change in laser intensity or in the density of the Rubidium gas, e.g. due to temperature fluctuations, causes the offset to change and thus results in a shift of the locking frequency. Therefore, we eliminate the Doppler-broadened background in (Fig. 6a) by subtracting the signal from the strong pump-beam (Fig. 6b) from the probe beam (Fig. 6a) resulting in an offset-free spectroscopy signal (Fig. 6c. Normally,

3.1 optical setup

The Zerodur setup demonstrates a novel spectroscopic technique based on subtracting the signal of the pump beam from the one of the probe beam, which is achieved using a single balanced detection.

After entering the breadboard from a fiber collimator, the light passes a polarizing beam splitter to ensure a well-defined polarization state. It then passes a non polarizing beam splitter with 70% reflectivity and passes the Rubidium cell as the pump beam. A small fraction of the pump beam (10%) are reflected back and form the probe beam, which then passes the Rubidium cell. The non-polarizing beam splitter reflects 70% toward the detection unit, which measures the difference between intensity of the left and right hand polarized components of the probe beam. The remainder of the pump beam (90%) is attenuated by a non-polarizing beam splitter after which it reaches the balanced circular-polarization detection unit. The quarter waveplate is oriented such that the polarity of the signal is inverted with respect to the probe beam.

We can now understand the functioning of the spectroscopy by tracing back the light from the detector. The left photo diode (the $n^+ +$ side), detects the right-hand polarized probe beam and the left-hand polarized pump beam. The right photo diode (the $n^- -$ side), detects the left-hand polarized probe beam and the right-hand polarized pump beam. The ac-magnetic field shifts the σ_+ and σ_- transitions in opposite directions, but since the signals are subtracted the resulting signal currents have the same sign. The strong pump beam imprints large Doppler-free Lamb-dips on the weak probe beam. Inversely, the weak probe beam imprints only small Doppler-free Lamb-dips on the strong probe beam, which leaves the signal dominated by the Doppler background. Therefore, by choosing the appropriate attenuation of the pump beam and choosing the opposite parity on the detector (via the angle of the wave plate), we can subtract the Doppler-background from the signal containing the large Doppler-free Lamb dips.

This double differential is immune to DC magnetic field and laser intensity fluctuations. Any DC magnetic field shifts the σ_+ and σ_- transitions in opposite direction which both equally contribute to the signal resulting in zero shift of the line-center. A shift in laser intensity is doubly compensated: The background subtraction ensures that the line center is located at zero signal (i.e. that there is no contribution from the Doppler background at the center of the line that one wants to lock to.). Furthermore, due to the intensity subtraction the zero σ_+ minus σ_- detection is independent of the laser intensity.

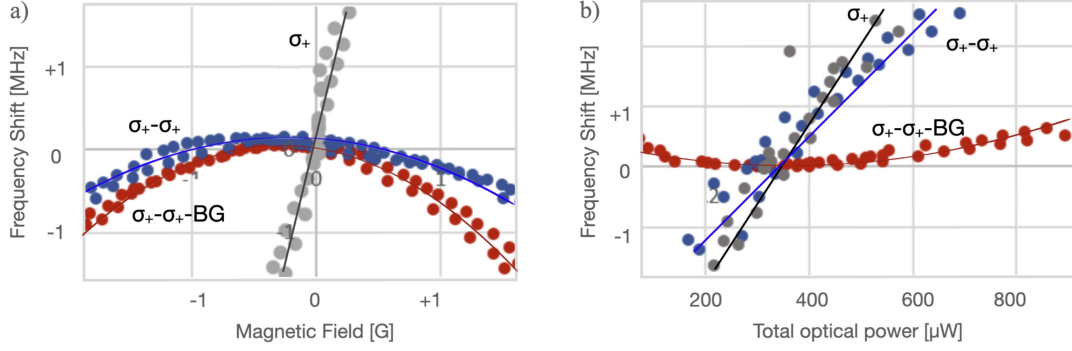


Figure 5. Stability of the spectroscopy against a) DC magnetic field drifts and b) laser intensity, both measured by comparison to an independent reference laser. The gray dots correspond to a σ_+ polarized spectroscopy similar to the 3D printed version mentioned above. The blue dots are from a spectroscopy where in the lock is derived from subtracting the σ_+ and σ_- signal. The red dot additionally subtract the Doppler broadened background. The solid lines are a guide to the eye indicating the approximate dependence of the signals.

As a proof-of-concept and as a first iteration towards a space-compatible setup, we have constructed a compact spectroscopy module from Zerodur.^{14,15} The setup can be seen in Fig. 4. All elements are glued directly onto a Zerodur breadboard using Crystalbond 509-3 and 590, with a non-cubic elements being supported additionally by Zerodur cubes. The adhesive melts at 70°C and 120°C respectively, thus allowing re-alignment of the optical components by heating the mount. The two different temperatures allow realign the base without detaching the optical element mounted on it.

Fig.6a shows the error signal produced by the module from the subtracted circularly polarized components of the probe beam only. In Fig.6b we see the background signal, where two Lamb dips are observed, due to optical pumping effects. Lastly, in Fig. 6c we see the final double-compensated signal, where the background signal is subtracted by the initial signal in Fig. 6a. Figure ?? and ?? show the dependence of the line center on DC magnetic field and the laser power respectively.

We have measured the magnetic field and laser intensity dependence of this novel spectroscopy in a more traditional laboratory setup, which allowed us by blocking the appropriate beams to implement a pure σ_+ setup (similar to^{7,11}), a $\sigma_+ - \sigma_-$ setup (similar to^{16,17}) and the double-differential setup of the Zerodur spectroscopy. We find a linear magnetic field dependence of about $\delta^2 f / \delta B^2 = 4 \text{ MHz/G}$ for the σ_+ spectroscopy and a quadratic dependence of $\delta f / \delta B^2 = -0.3 \text{ MHz/G}^2$ and -0.5 MHz/G^2 for the single and double-differential spectroscopies respectively, for 100 mG this results in a shift of 400 kHz, -1.54 kHz and 5 kHz, respectively. For the laser intensity fluctuations, we find a dependency of $\delta f / [\delta(P/P_0)]$ of 5 MHz and 3 MHz for the pure σ_+ - and single-differential ($\sigma_+ - \sigma_-$) setups respectively. The double-differential spectroscopy does not show any linear dependence but a quadratic one with $\delta^2 f / [\delta(P/P_0)]^2 = 37 \text{ kHz}$. This translates for a 10% power fluctuation for to a frequency shift of 110 kHz, 90 kHz and 0.2 kHz respectively — a reduction in the sensitivity to laser power fluctuations by $\times 400$

This represents an improvement by about two orders of magnitude both for 10% laser intensity and 100 mG magnetic field fluctuations. Clearly, the dependence of the laser frequency stabilization on both magnetic field perturbations and power fluctuations has been much reduced.

4. CONCLUSIONS

In conclusion, we have demonstrated a novel ultra-stable spectroscopy using double-differential detection. We have shown our progress towards space-compatible ultra-stable spectroscopes for laser stabilization for space-based atom quantum devices with two distinct directions: one aimed at low-cost compact and one at ultra-stable laser frequency stabilization. The first one is based on 3D printing whereas the second one constructed using adhesives on a Zerodur base plate. The double-differential detection spectroscopy has been shown to be very stable against magnetic field drifts and more than $400\times$ more stable against laser intensity fluctuations.



Figure 6. Error signal - double subtraction (example). Polarization subtraction (a), background signal (b), double-compensated signal (c).

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