International Conference on Space Optics—ICSO 2012

Ajaccio, Corse

9–12 October 2012

Edited by Bruno Cugny, Errico Armandillo, and Nikos Karafolas

Compact and frequency stabilized laser heads for Rubidium atomic clocks

Florian Gruet

Matthieu Pellaton

Christoph Affolderbach

Thejesh Bandi

et al.

esa icso proceedings cnes

International Conference on Space Optics — ICSO 2012, edited by Bruno Cugny, Errico Armandillo, Nikos Karafolas
Proc. of SPIE Vol. 10564, 105642Y · © 2012 ESA and CNES · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2309135

Compact and Frequency Stabilized Laser Heads for Rubidium Atomic Clocks

GRUET Florian; PELLATON Matthieu; AFFOLDERBACH Christoph; BANDI Thejesh; MATTHEY Renaud; MILETI Gaetano

Université de Neuchâtel, Laboratoire Temps-Fréquence, LTF,
2000 Neuchâtel, Switzerland
florian.gruet@unine.ch; gaetano.mileti@unine.ch

***Abstract*—We present the development and complete spectral characterization of our compact and frequency-stabilized laser heads, to be used for rubidium atomic clocks and basic spectroscopy. The light source is a Distributed Feed-Back (DFB) laser diode emitting at 780 nm or 795 nm. The laser frequency is stabilized on a sub-Doppler absorption peak of the ^{87}Rb atom, obtained from an evacuated rubidium cell. These laser heads, including the electronics for the light signals detection, have an overall volume of 0.63 liters. We also present a variant of the laser head into which is integrated an Acousto-Optical Modulator (AOM) that precisely detunes the laser frequency in order to minimize the AC Stark shift in Rb atomic clocks.**

I. Introduction

In atomic clocks, using laser diodes instead of plasma discharge lamp for optical pumping allows to enhance the clock frequency stability [1, 2], as well as reaching reduced mass and power consumption of the clock, which is important particularly for space atomic clocks. In order to achieve such improvement, the lasers have to satisfy stringent requirements on their spectral properties, together with good frequency stabilization. Due to their good spectral properties and mechanical robustness, DFB lasers are good candidates for this application. Here we report on the realization of two versions of compact and frequency-stabilized laser heads, intended for use in high-performance Rb atomic clocks for space.

II. Spectral Characterisation of the Ligth Sources

As a light source for our laser heads, we use commercially available DFB lasers, emitting at 780 nm or 795 nm (Rb D2 or D1 lines, respectively). These lasers are manufactured by the German company Eagleyard Photonics. They are mounted in TO-3 packages with an integrated Peltier thermo-electric cooler that ensures low sensitivity to external thermal variations, at low power consumption. A complete spectral characterization of the lasers' optical emission has been made using our laboratory electronics.

A. Basic properties

These DFBs, both 780 nm and 795 nm, have a threshold current of about 38 mA (when operated around ambient temperature) and reach an optical output power of about 65-70 mW at 120 mA, depending on the individual laser chip. The frequency vs. current and the temperature vs. current tuning coefficients are -1 GHz/mA and -25 GHz/K, respectively. The lasers reach the precise Rb D1 or D2 wavelengths at around 100 mA and 20°C, and show a large mode-hop free frequency tuning range of more than 80 GHz around the operating point, with a Side-Mode Suppression Ratio (SMSR) of > 40 dB.

B. Noise

Two different types of noise may be limiting for the clock performance, and therefore need to be measured. Optical power fluctuations of the laser are known as Relative Intensity Noise (RIN), which is the power noise normalized to the average power level, and frequency fluctuations are known as frequency noise.

RIN has been measured using a fast Fourier transform (FFT) spectrum analyzer, for different laser output power. Figure 1 shows the RIN of a 795 nm DFB operated at 5, 15 and 45 mW of output power. Typical RIN values, obtained for 795 nm and 780 nm DFBs operating at the precise Rb wavelengths, are between $2\text{x}10^{-14}$ and $5\text{x}10^{-14}$ Hz^{-1} at a Fourier frequency of 300 Hz.

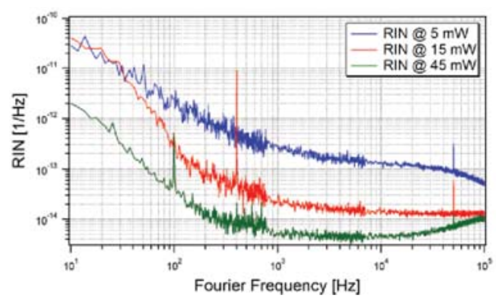

Figure 1. RIN of 795 nm DFB.

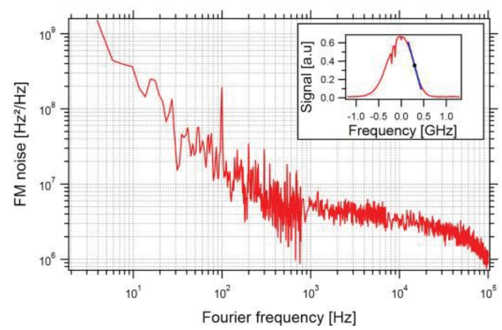

Figure 2. Frequency noise of a 780 nm DFB.

Work supported by the European Space Agency and the Swiss National Science Foundation

The frequency noise is also measured using a FFT spectrum analyzer. The slope of the Doppler-broadened absorption signal of atomic Rb is used as a frequency discriminator (at approximately half-maximum of the absorption signal, see inset in Figure 2). In this way, the laser's frequency fluctuations are converted into amplitude fluctuations and the power spectral density of the frequency noise can be measured. As shown in Figure 2, values of $1\text{x}10^7$ Hz^2/Hz at 300 Hz have been obtained.

C. *Laser linewidth*

Linewidth measurements have been performed by recording the beat note between two nominally identical lasers. The beat signal was detected using a fast photo-detector and monitored on a RF spectrum analyzer. Beat widths of 4.3 ± 0.2 MHz were obtained with 780 nm DFBs in free running operation at 120 mA. Assuming the two lasers to have the same linewidth, this corresponds to a linewidth of 2.15 MHz per laser.

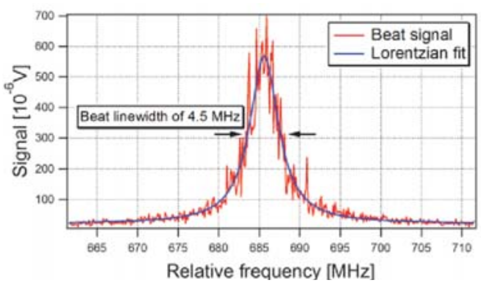

Figure 3. Beat-note signal between two 780 nm DFBs.

It has been reported in [3] that there is a correlation between the frequency noise and the linewidth. In our case, the linewidth can be obtained from the frequency noise spectrum (Figure 2) using the equation

$$\text{FWHM} = \sqrt{8\ln(2)\,A} \qquad (1)$$

where A is the integral of the frequency noise spectrum. In the case of the frequency noise spectrum shown in Figure 2, the laser linewidth is calculated to be 1.7 ± 0.3 MHz. This result is in reasonable agreement with the linewidth obtained from the beat-note measurements.

III. Laser Heads Design and Realization

The design of the laser heads is inspired by a previous design using Extended-Cavity Diode Lasers (ECDL), made in 2003 [4, 5]. All mechanical components as well as the rubidium cell were manufactured and mounted at LTF. Two designs were made, one for the "simple" laser heads, and another one for the laser head with integrated AOM.

A. *Laser Head*

Figure 4 shows the complete CAD design of the "simple" laser head, which is described below. All optical components are mounted on a thermally controlled baseplate. The laser module (1) is composed of the DFB laser that emits at 780 nm or 795 nm, a collimation lens and a miniature optical isolator designed for the right wavelength. This isolator has an aperture of 1.75 mm, a power transmission of > 48% and an optical isolation of > 36 dB. Because DFBs are quite sensitive to optical feedback this component is essential in order to avoid any retro-reflected beam that would perturb the laser emission. The part of the laser beam that passes straight through the first beamsplitter (2) is used to monitor dc optical power using a photo-detector (3) while the reflected part of the beam falls on another beamsplitter. Here the reflected part is used for sub-Doppler spectroscopy [6] on a reference rubidium cell (4) while the transmitted part goes out of the laser head. The sub-Doppler absorption signal is monitored by the second photo-detector (5) and is used to stabilize the laser frequency to the saturated-absorption lines, using lock-in detection. From the lock-in output a correction signal is produced that is fed to the laser current. The free space below the thermally controlled baseplate is used for the pre-amplification circuits of the two photo-detectors and is intended to accept miniaturized laser control electronics in future development phases. Three sub-D 9-pin connectors are used for connecting laboratory control electronics for the laser, the cell, and the photo-detectors' power supply. The total volume of the opto-mechanical part is 0.22 litres. The complete laser head has a volume of 0.63 litres.

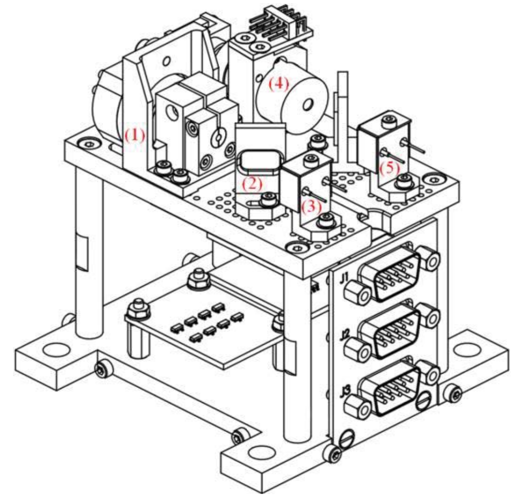

Figure 4. Laser head CAD design. (1) Laser module; (2) beamsplitter; (3, 5) photo-detectors; (4) rubidium cell.

B. *Reference Rubidium Cell*

Sub-Doppler spectroscopy of the rubidium atoms (see Figure 6) is only observable in a pure rubidium vapor. Any gas contamination of the cell would results in a broadening of the sub-Doppler lines, thus reducing the short-term frequency stability of the locked laser. Such pure rubidium vapor is confined in glass-blown cells carefully cleaned and filled in our in-house cell filling facility. Figure 5a shows such a cell, with a diameter of 10 mm and a length of 19 mm.

In order to increase the atomic density inside the cell – and thus the signal amplitude – the cell is heated to around 38°C and temperature-stabilized within a precision on the mK level. A coil around the cell allows applying a stabilized magnetic field. The overall cell assembly is mounted into two magnetic shields, in order to control the magnetic conditions on the cell. The complete cell setup has a volume of 30 mm^3 and a mass of 25 grams (Figure 5b).

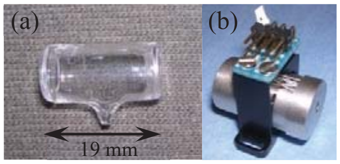

Figure 5. (a) Evacuated Rb cells; (b) cell setup with heater, magnetic field coil, and magnetic shields.

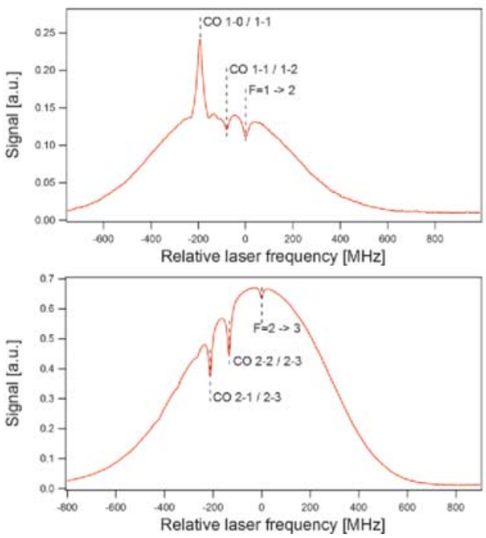

Figure 6. Sub-Doppler lines (indicated by dashed lines) observed on the Rb D2 line, super-imposed on the Doppler broadened absorption lines, as observed with the laser heads' reference cell.

C. AOM Laser Head

The AOM laser head was realized using a 780 nm DFB as light source. The design is similar to the others laser heads, using same laser module and cell assembly, with the difference that an AOM has been implemented. This AOM allows shifting the laser frequency by a well-controlled and stable frequency offset away from the fixed Rb sub-Doppler lines, in order to minimize AC-Stark shift effect in Rb atomic clocks [7]. Again, all components are mounted on a thermally controlled baseplate.

Figure 7 shows the design and the beam path of the AOM laser head. The laser module (1) is similar than the ones used in the others laser heads, with a collimation lens and an optical isolator. A first beamsplitter (2) allows part of the beam to go out of the laser head (OUT 1), and be used for clock operation. The polarizer (3) is used to reduce the optical power, if needed. A mirror sends the other part of the beam through a half waveplate (4) that allows selecting the beam polarization before the Polarizing Beamsplitter Cube (PBC) (5). Part of the beam makes a double-pass through the AOM (6) using a set of mirrors and a quarter waveplate (7). This single-shifted or double-shifted beam, depending on the order selected, will be used in the sub-Doppler absorption setup, and eventually enables laser frequency locking. Overall volume of the AOM laser head is 2.4 litres.

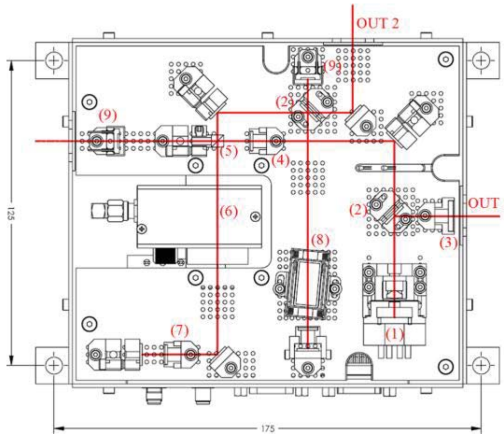

Figure 7. AOM laser head beam path. (1) Laser module; (2) beamsplitter; (3) polarizer; (4) half waveplate; (5) polarizing beamsplitter cube; (6) AOM; (7) quarter waveplate; (8) rubidium cell; (9) photo-detectors.

D. Fully Assembled Laser Heads

The two types of laser heads have been mounted and are fully operational. They are shown in Figure 8 and Figure 9.

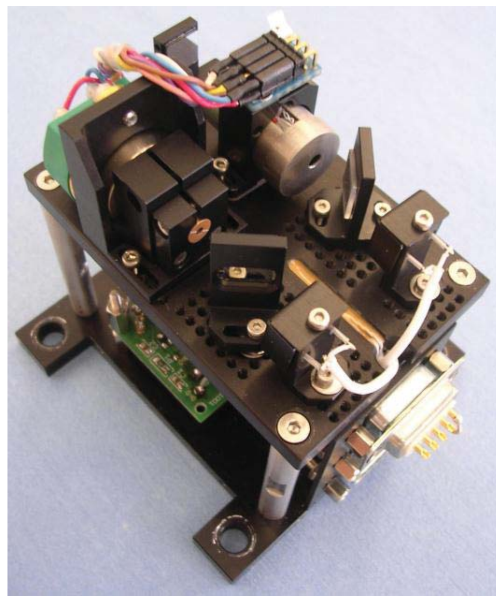

Figure 8. Photograph of a fully assembled laser head

Figure 9. Photograph of the fully assembled AOM laser head

IV. FREQUENCY STABILITY

The signal-to-noise limit for the short-term stability of the laser frequency can be estimated [5] using the equation

$$\sigma_f(\tau) = \frac{N_{PSD}}{\sqrt{2}Df_L}\tau^{-1/2} \quad (2)$$

where N_{PSD} is the power spectral density detection noise of the locked laser, f_L is the laser frequency and D is the discriminator slope of the error signal. In the case of the 780 nm laser head, the S/N limit has been calculated to be $4.8x10^{-12}\ \tau^{-1/2}$.

In order to measure the frequency stability, a beat note between two laser heads has been performed. Each laser is locked on a different atomic transition, distant of several MHz. The beat note is detected by a fast photo-detector and the beat note frequency is measured using a frequency counter referenced to a hydrogen maser. Figure 10 gives the measured fractional frequency stability in terms of Allan deviation [8] for each type of laser heads.

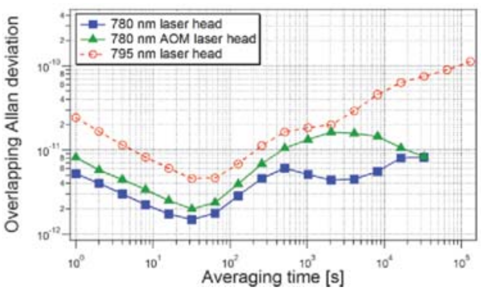

Figure 10. Frequency stability of the realized laser heads.

The best result is obtained for the 780 nm laser heads with a frequency stability at one second of $5.2x10^{-12}\ \tau^{-1/2}$, which agrees well with the predicted S/N limit. The AOM laser head shows slightly higher instability, due to some added frequency noise coming from the AOM. The bumps around 1000 seconds are due to temperature variations in the lab that mainly affect the electronics used to drive the laser heads and heaters. The stability of the 795 nm laser head is also slightly degraded, due to a lower contrast of the sub-Doppler absorption signals used to lock the laser (S/N limit of $2.1x10^{-11}\ \tau^{-1/2}$ in this case).

V. APPLICATIONS

The main applications for these laser heads are in the frame of high-performance rubidium atomic clocks, under development in our laboratory. Clock frequency stabilities of $4.2x10^{-13}\ \tau^{-1/2}$ for τ up to 10^4 s when operating on the Rb D1 line [9], and $4x10^{-13}\ \tau^{-1/2}$ for τ up to 10^4 s on the Rb D2 line [10] have been measured. The influence of intensity light-shift factor (α) on the clock stability can be reduced using the AOM laser head by fine-tuning of the laser frequency, which can significantly improve the clock's medium- to long-term stability [7]. An example of reduction in α using our AOM laser head is shown in Figure 11.

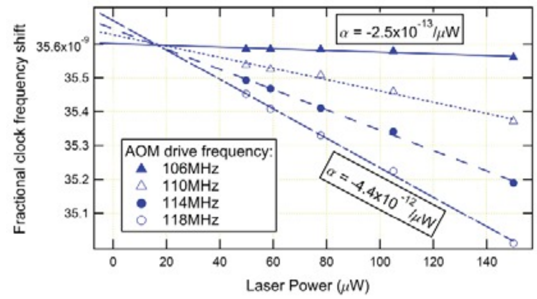

Figure 11. Reduction of α by fine-tuning of the laser frequency using the AOM laser head. The shifted frequency is stabilized to the F=2→2/F=2→3 cross-over resonance line.

Another application of great interest is the evaluation of frequency aging of DFBs. This parameter is to be understood as the change - with time - of the injection current required for the laser to keep a fixed wavelength when operated at constant temperature. For DFB lasers emitting at a wavelength of 780 nm corresponding to the Rb D2 transition, as used in Rb atomic clocks, the laser current at resonance has been found to decrease by 50 to 80 μA per month (-0.6 to -1 mA/year) [11]. Such aging has been measured with a frequency-stabilized laser head similar to the ones reported here, where the injection current is continuously adjusted by a feedback loop to maintain the laser frequency at the center of a sub-Doppler line, while the laser temperature is maintained constant.

VI. CONCLUSION

We have presented the realization and spectral characterization of compact and frequency-stabilized laser heads, emitting on the Rb D1 or D2 lines. In total, six compact and frequency stabilized laser heads, including one with AOM, have been designed, realized and are fully operational. Narrow-linewidth (≈2 MHz) and low-noise operation of the laser heads was demonstrated. The frequency stability obtained for 780 nm laser heads is below $1x10^{-11}$ at all timescale, and below $1x10^{-10}$ for 795 nm laser heads. The laser heads have been successfully used in our developments on high-performance Rb atomic clocks. The total power consumption for the laser supply and heaters (laser, cell, baseplate) does not exceed 1.5 W at ambient temperature. Due to their excellent frequency stability and low volume, mass, and power consumption, the laser heads are ideal candidates for high frequency-stability light sources for use in advanced instrumentation such as space atomic clocks.

ACKNOWLEDGMENT

We thank P. Scherler, M. Durrenberger, and J. Di Francesco for technical support.

REFERENCES

[1] J. Vanier, C. Mandache, "The passive optically pumped Rb frequency standard: the laser approach," Appl. Phys. B, vol. 87, pp. 565-593, 2007.

[2] C. Affolderbach, F. Droz, G. Mileti, "Experimental Demonstration of a Compact and High-Performance Laser-Pumped Rubidium Gas Cell

Atomic Frequency Standard," IEEE Trans. Instrum. Meas., vol. 55, No 2. April 2006.

[3] G. Di Domenico, S. Schilt, P. Thomann, "Simple approach to the relation between laser frequency noise and laser line shape," Applied Optics, vol. 49, No.25, September 2010.

[4] C. Affolderbach, G. Mileti, "Tunable, stabilised diode lasers for compact atomic frequency standards and precision wavelength references," Optics and Lasers in Engin., vol. 43, pp. 291-302, July 2004.

[5] C. Affolderbach, G. Mileti, "A comparct laser head with high frequency stability for Rb atomic clocks and optical instrumentation," Review of Scientific Instr., vol. 76, 073108, July 2005.

[6] D. W. Preston, "Doppler-free saturated absorption," Am. J. Phys., vol. 64, pp. 1432-1436, November 1996.

[7] T. Bandi, C. Affolderbach and G. Mileti, "Laser-pumped paraffin-coated cell frequency standard", J. Appl. Phys., vol. 111, 124906 (2012).

[8] W. J. Riley, "Handbook of FrequencyStability Analysis", NIST Special Publication 1065, (National Institute of Standards and Technology, Boulder, CO 80305, USA), July 2008.

[9] S. Micalizio, A. Godone, C. Calosso, F. Levi, C. Affolderbach, F. Gruet, "Pulsed Optically Pumped Rubidium Atomic Clock With High Frequency-Stability Performance," IEEE Trans. Ultrason., Ferroelectr., Freq. Control, vol. 59, No. 3, pp. 457-462, March 2012.

[10] T. Bandi, C. Affolderbach, C. Calosso, G. Mileti, „High-performance laser-pumped rubidium frequency standard for satellite navigation," Electronics Letters, vol. 47, No. 12, June 2011.

[11] R. Matthey, C. Affolderbach, G. Mileti, "Methods and evaluation of frequency aging in distributed-feedback laser diodes for rubidium atomic clock," Optics Letters, vol. 36, No. 17, pp. 3311-3313, September 2011.