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***Methods and setup for spectral characterization of laser diodes
for atomic clocks***

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METHODS AND SETUP FOR SPECTRAL CHARACTERIZATION OF LASER DIODES FOR ATOMIC CLOCKS

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I. INTRODUCTION

Today laser diodes are extensively used in numerous research fields and applications, due to their simplicity of handling and control, frequency agility, single-mode frequency ability, reliability, low power consumption and compactness. Here we present methods to characterize advanced laser diodes emitting at 780 nm or 795 nm [1] as well as at 852 nm or 894 nm [2], in view of their implementation in Rb and Cs atomic clocks [3,4] and other optical high-precision applications. The characterization consists of the usual parameters (threshold current, slope efficiency, frequency tuning, polarization, and beam geometry) with additional emphasis on spectral parameters that are of highest importance in atomic clock applications, such as amplitude and frequency noises, linewidth and sensitivity to optical feedback.

II. SETUP DESCRIPTION

Our group has been involved in the development of stabilized laser diodes and their spectral characterization for more than 25 years. This work has resulted in the realization of several benches operating at different wavelengths and the establishment of characterization procedures that are continuously improved and adapted to the different requirements of each specific project [5,6] and target application. The setup described in this communication has been initially designed in the frame of a European project aiming for the characterization of a large number of laser diodes emitting at 852 nm and 894 nm and is presently being upgraded in the frame of a project funded by the European Space Agency. Therefore, the setup description and optical components given here are in accordance with these wavelengths; they can easily be adjusted in case of characterization of 780 nm or 795 nm emitting laser diodes that could be used for Rb applications [7,8].

In order to be able to characterize a large number of lasers, the initial alignment procedure for each sample should be as quick and simple as possible. To do so, the implemented solution is to keep every optical element fixed after the alignment of the beam path with the first laser sample and then mounting the next successive samples on a precision XYZ table. By positioning precisely the sample, the collimation, alignment and fiber coupling are all realized at once, requiring only minimal fine-tuning of the overall test bench.

The device under test (DUT) is placed on a holder adapted to the laser package. Currently, TO9, TO3, or C-mount can be accepted and the system can be adapted to accept other laser packages by modifying the DUT holder only. A lens with anti-reflection coating positioned immediately after the DUT collimates the laser beam. The overall bench setup is shown in Figure 1 and its main three sections are described in the following.

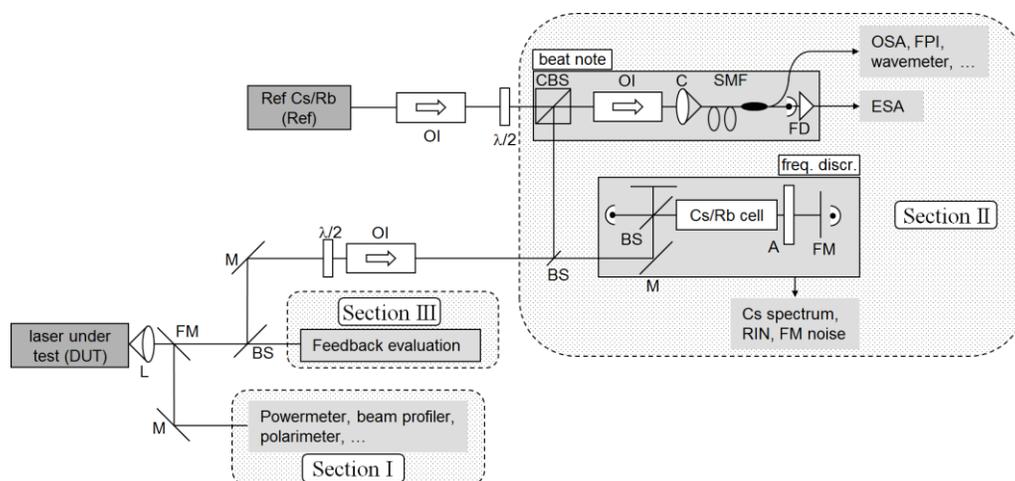


Figure 1. Scheme of the characterization bench. L: lens; FM: flip mirror; M: mirror; BS: beamsplitter; $\lambda/2$: half-wave plate; OI: optical isolator; A: attenuator; CBS: beamsplitter cube; C: coupler; SMF: single-mode fiber; FD: fast detector.

A. Section I: Usual parameters

The first part of the setup is dedicated to the measurement of standard parameters, such as threshold current, optical power versus current and temperature, laser polarization and beam geometry.

By means of a flip mirror placed immediately after the DUT collimation lens, the laser light is directed to various measurement instruments operating in free space. A power meter is used to measure the threshold current, the slope efficiency (optical power versus injection current) and the optical power versus temperature coefficient. The beam polarization and profile are measured with a polarimeter and a beam profiler, respectively.

When the flip mirror is removed from the optical path, the laser beam is separated into two parts by a beamsplitter with a ratio of 80% in reflection (directed to section II) and 20% in transmission (directed to section III).

B. Section II: Spectral parameters

The quality of the spectrum of a laser diode implemented in an atomic clock is of outmost importance for the performances of the clock. For that reason a complete part of the characterization bench is devoted to spectral measurements such as side-mode suppression ratio (SMSR), linewidth and laser noises. Two different types of laser noise are relevant for clock application. One is known as relative intensity noise (RIN, [9]) and corresponds to the optical power fluctuations with respect to the mean power level. The second is the frequency noise and relates to the frequency fluctuations of the laser.

The laser beam is directed to two sub-systems (named “freq. discr.” for frequency discriminator and “beat note” in Figure 1) for spectral and noise measurements. An optical isolator is implemented before the sub-systems to avoid undesired perturbation of the laser spectrum by retro-reflection into the DUT. The half-wave plate in front of the optical isolator allows the alignment of the polarization axis of the laser beam to the input polarizer of the optical isolator and to the other downstream polarization sensitive components, so they do not need to be realigned for each DUT.

The frequency discriminator sub-system is composed of an evacuated Cs cell, a photo-detector, an attenuator and a retro-reflecting flip mirror and allows retrieving the Cs sub-Doppler absorption spectrum and the mode hop-free tuning range when the laser emission frequency is tuned to the atomic resonance. The frequency noise of the laser is measured by means of a Fast Fourier Transform (FFT) spectrum analyzer. The relative intensity noise (RIN) measurement is also performed at atomic resonance wavelength and with the same sub-system when the Cs cell is removed from the light path, using the same FFT spectrum analyzer.

In the beat-note sub-system, the beam of the DUT is coupled into a single-mode optical fiber. By picking up the light at the exit of this fiber, the laser linewidth can be evaluated using a fiber-coupled Fabry-Perot interferometer (FPI) or by beat-note measurement with a reference laser if the resolution of the FPI (5 MHz) is not sufficient. The beat note is detected by a fast photo-detector and measured with an electrical spectrum analyzer (ESA). A single-mode narrow linewidth laser (e.g., an external-cavity laser diode; ECDL) or a laser previously tested is used as reference laser.

The output of the single-mode can also be injected into fiber-coupled measurement instruments. The wavelength (or frequency) tuning coefficients are established from measurements with a fiber-coupled wavemeter, while the SMSR is evaluated with an optical spectrum analyzer (OSA). In these cases, obviously, no light from any other laser source than the DUT must be injected into the optical fiber.

C. Section III: Optical feedback

The signal-to-noise limit of a high-performance laser-pumped atomic clock is often determined by the laser frequency and amplitude noises. Optical feedback onto the laser diode always occurs and, depending on its intensity, may degrade the laser’s spectral properties [10,11] and thus degrade the clock’s frequency stability [12,13]. The setup to appraise the optical feedback sensitivity of a laser diode is shown in Figure 2 and consists in a direct re-injection of attenuated laser light into the laser chip. It is composed of the assembly of neutral density (ND) filters for coarse attenuation, and of a linear polarizer and a quarter-wave plate for fine tuning of the feedback strength.

The calibration of the feedback optical power has been performed as follow: The optical power at the laser output is first measured using a power meter. The linear polarizer is then aligned with the main polarization axis of the laser. The reflected beam is slightly misaligned so that its power can be measured as a function of the coarse (ND filters) and fine (orientation of the quarter-wave plate) attenuation settings, without blocking, even partially, the laser output beam. Under the approximation that the reflected power doesn’t vary due to this small misalignment ($\sim 2^\circ$), the complete attenuation setup is calibrated with respect to the coarse and fine attenuation settings. This calibration does not need to be repeated for each laser diode under test; a single calibration is sufficient – however, it shall be realized at each wavelength range.

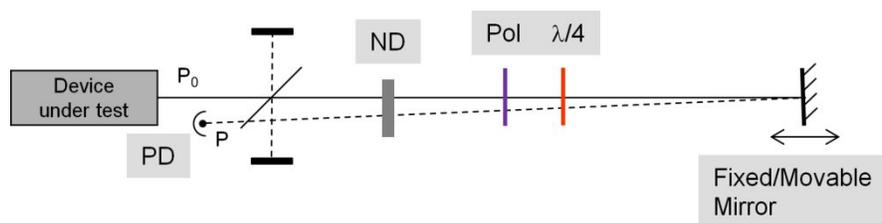


Figure 2. Optical feedback calibration setup. PD: photo-detector; ND: neutral density filter; Pol: polarizer; $\lambda/4$ quarter-wave plate; P_0 : laser output power; P : feedback optical power.

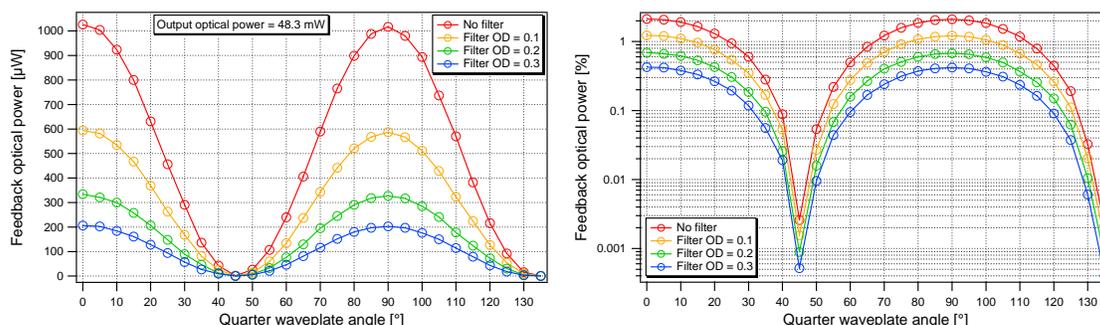


Figure 3. Optical feedback power in function of the quarter-wave plate angle for different attenuation filter optical densities.

The attenuation factor of the feedback control re-injection scheme is referred to as *feedback power ratio* (FPR) and is defined as the ratio between the optical power re-injected into the laser and the power emitted by the laser. Figure 3 displays the feedback optical power in μW , as a function of quarter-waveplate angle α . The cosine-wave behavior of the feedback optical power P in function of α (with respect to the linear polarizer axis), of the laser output power P_0 and of the feedback power ratio FPR_0 at angle $\alpha = 0$, expressed as,

$$P = P_0 \cdot FPR_0 \cos^2(2\alpha) \quad (1)$$

is respected within $\pm 1.5\%$ for all angles α except for angles 45° and 135° where the feedback optical power is close to zero and its measurement limited by the power meter sensitivity. Accordingly, the feedback power ratio FPR, expressed in [dB], is

$$FPR[\text{dB}] = FPR_0[\text{dB}] + 10 \cdot \log_{10}(\cos^2(2\alpha)) \quad (2)$$

To measure the sensitivity to optical feedback for a given laser diode DUT, the return beam is aligned such as to obtain maximum coupling and feedback into the diode. This guarantees well-defined test conditions and good reproducibility of the measurement.

D. Laser diode controller

A home-built digital controller for the laser diode is dedicated to the characterization bench. The free-running passive frequency stability of a laser diode mounted on a Peltier element in a TO3 package was measured as < 2 MHz. Considering a temperature tuning coefficient of 25 GHz/K, such value would correspond to a temperature stability as low as 100 μK . The noise of the laser current source is below 1 nA/ $\sqrt{\text{Hz}}$.

III. MEASUREMENT PROCEDURE

The first parameter to be measured is the emission wavelength as it is mandatory for the laser to reach the atomic resonance frequency in view of its application in an atomic clock. The procedure shown in Figure 4 is then employed (it follows the setup description order described in Chapter II).

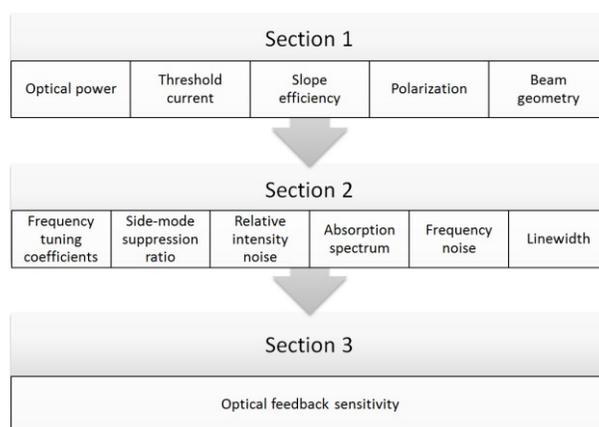


Figure 4. Measurement procedure.

A. Power and Wavelength

The optical power, threshold current and slope efficiency are measured at different temperatures (e.g., from 20°C to 30°C) around the atomic (in the present case Cs) resonance wavelength. The laser injection current is varied while the optical power is measured at the same time with an optical power meter.

The frequency sensitivities to current and temperature are determined for different temperatures of the laser diode and at a wavelength around the atomic transition wavelength by means of a precise (10 MHz resolution) wavemeter.

B. Side-mode suppression ratio

The side-mode suppression ratio is measured at different laser injection currents, using an optical spectrum analyzer (OSA). This measurement allows also verifying the single mode operation of the laser diode and can highlight potential modehops. An example of such measurements is shown in Figure 5.

C. Noises

The RIN is measured using a Fast Fourier Transform (FFT) spectrum analyzer, covering frequencies ranging from few mHz to 100 kHz. The FFT spectrum analyzer measures the power spectral density (PSD) in V/√Hz from the signal of the photo-detector once shone by the laser beam; the RIN is then calculated from the PSD and the DC voltage of the detector signal.

The frequency noise is also measured by means of a FFT spectrum analyzer. For this purpose, the laser frequency is set in the middle of one of the slopes of the atomic Doppler absorption signal. The slope of this signal is then used as a frequency discriminator (see inset in Figure 6, right) to convert the laser's frequency fluctuations into amplitude fluctuations. The PSD of the frequency noise is measured using a photo-detector, provided the laser's intensity noise is sufficiently low.

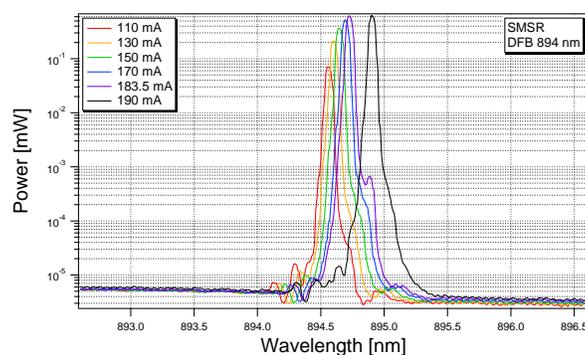


Figure 5. Example of SMSR measured for different injection currents in the case of an 894 nm DFB laser.

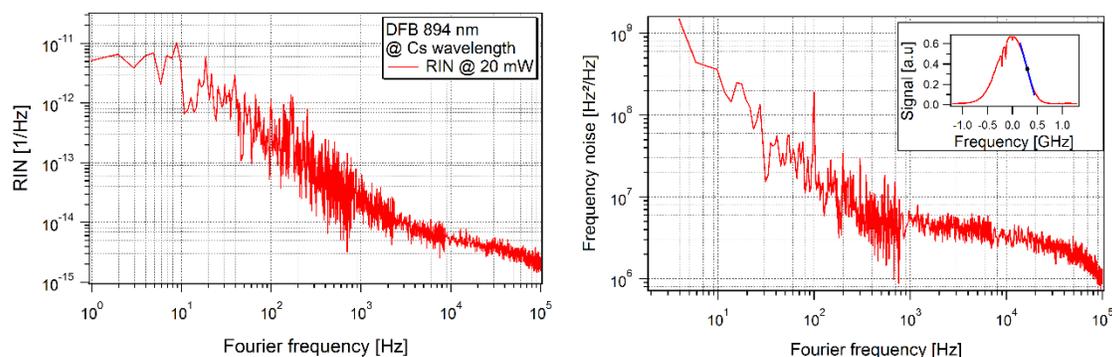


Figure 6. Examples of noise measurement. Left: RIN of an 894 nm DFB laser; right: frequency noise of a 780 nm DFB laser.

D. Linewidth

The laser linewidth is determined using two different techniques. In the first approach, the linewidth is obtained from heterodyning the DUT emission with a narrower reference laser (ECDL) of known linewidth (typically 150 kHz) and using a fast photo-detector and a RF spectrum analyzer. The beat-note width will then correspond to the sum of the two lasers' individual linewidths (in the case of the convolution of two Lorentzian profiles). The other technique is based on the β -separation line method [14] that consists in extracting the linewidth (full width at half-maximum, FWHM) from the PSD frequency noise spectrum.

E. Beam geometry and polarization

The beam geometry (divergence and diameter) is measured using a beam profiler after collimation of the laser beam with a lens of 2.75 mm focal length. The polarization is measured using a polarimeter.

IV. OPTICAL FEEDBACK EVALUATION

To determine the effect of optical feedback on the laser frequency spectrum, two techniques are used. The first technique consists in measuring the beat-note signal between the DUT and the reference laser, the latter being frequency stabilized to an atomic reference. Figure 8 on the left shows the behavior of such a beat signal without any optical feedback on the DUT, while the DUT's injection current is varied by regular steps of 0.1 mA. One can note that the beat frequency is increasing linearly by steps of about 90 MHz, corresponding to the frequency tuning coefficient of the DUT with respect to its current. By applying a FPR of about -40 dB to the DUT and repeating the same procedure the beat frequency is not increasing linearly anymore and the beat signal is not appearing in some areas of the beat frequency spectrum, due to modehops caused by the external cavity formed by the laser facet and the re-injection mirror. We observed that these areas widen by increasing the FPR, even leading to a multimode operation of the DUT above -25 dB FPR level (not shown here). Even if this technique allows seeing the effect of optical feedback at quite low FPR, it however lacks sensitivity to establish a FPR value below which the laser behavior is not degraded.

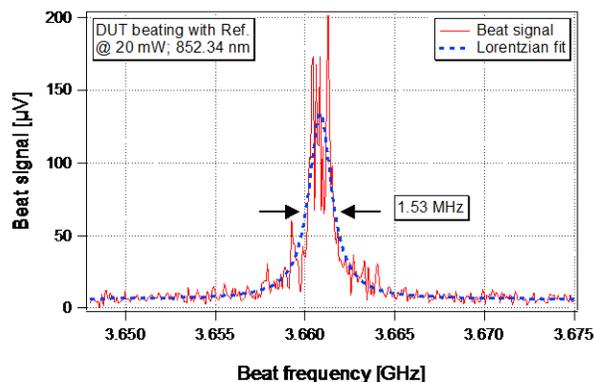


Figure 7. Beat-note signal between a laser diode (DUT) and a reference laser of 150 kHz linewidth.

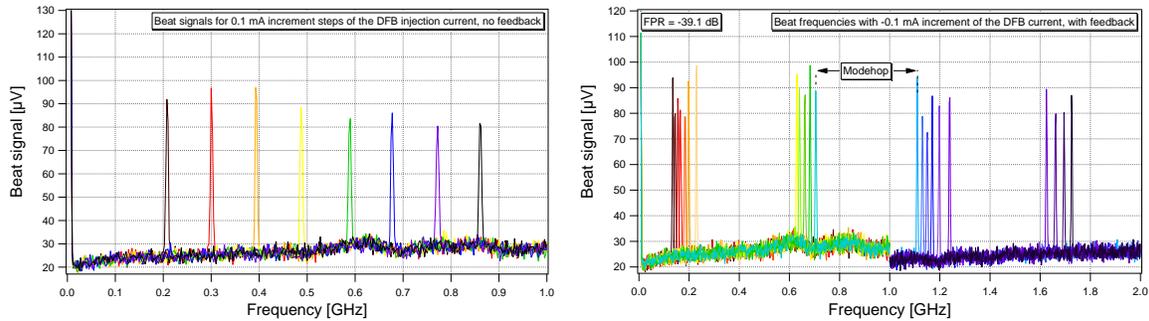


Figure 8. Variation of the beat note when the injection current of the DUT is increased by 0.1 mA steps. Left: no optical feedback; right: with optical feedback (FPR = -39.1 dB).

The second technique shows a higher sensitivity and allows to determine quantitatively a FPR threshold value, corresponding to the maximum of FPR a laser diode can sustain without degradation of its spectral behavior. The method is indirect and consists in the observation of the sub-Doppler absorption spectrum of an atomic vapor in presence of optical feedback. If the laser spectrum is affected by optical feedback, the resulting atomic spectrum signal will be deformed. The FPR “threshold” is defined as the value above which a deformation of the atomic spectrum signal starts to appear. The case is displayed in Figure 9. In the case of the Figure 9 on the left, the FPR threshold is measured at -69.9 dB. Figure 9 on the right shows the evolution of the spectrum deformation when increasing the FPR (up to -48.2 dB in this case). Because in this method the laser frequency is swept rapidly across the atomic absorption line, much more laser operating points are sampled within a shorter time than in the first method described, and thus modehops are more easily detected.

V. TYPICAL RESULTS AND UNCERTAINTIES

As illustration of the characterization process, Table 1 gathers the complete set of results for a DFB laser emitting at the Cs D2 line wavelength (852 nm). An uncertainty budget was performed for some parameters such as the threshold current, the power and frequency tuning coefficients, the linewidth, the feedback power ratio, and is included in the table.

For the threshold current and the power tuning coefficients, the precision depends mainly on the uncertainty on the measured power, estimated at a level of $\pm 5\%$. The precision on the injection current and on the temperature are systematic uncertainties of less than 2% and 1%, respectively, and are neglected in the final evaluation of the power tuning coefficient.

Concerning the frequency tuning coefficients, the main uncertainty on the wavelength arises from the temperature settling of the laser diode when varying the laser current. This uncertainty is evaluated at the level of ± 2 pm. The uncertainty due to the wavemeter instrument is 10 MHz (24 fm at 852 nm) and can thus be neglected.

The linewidth value as retrieved from the beat-note measurement corresponds to the average width obtained from the individual fits of several beat spectra (approx. 20). The associated uncertainty on the beat width corresponds to the standard deviation for this ensemble of widths. The uncertainty on the linewidth retrieved from the frequency noise spectrum is set at 10%, as described in [14].

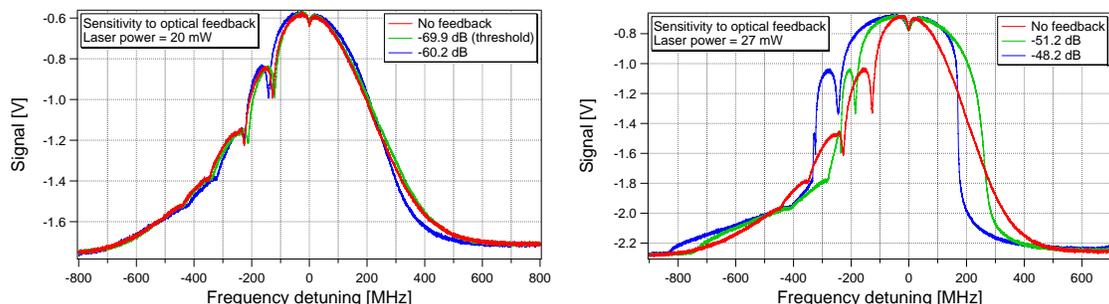


Figure 9. Cs absorption spectrum at 852 nm for different FPR levels applied to a laser diode sample emitting 20 mW of optical power (left) and 27 mW (right).

Table 1. Typical example of a complete set of characterization results for a laser diode sample.

Parameter	Value	Unit	Test conditions & remarks
Wavelength	852.34	nm	Cs @ 40 mW; @ T _{Cs} and I _{Cs}
Operating temperature	T _{Cs} = 48	°C	Cs @ 40 mW
Operating current	I _{Cs} = 140	mA	Cs @ 40 mW
Optical power	44.6	mW	@ T = 48°C; I = 150 mA
Threshold current	45.3 ± 3.6	mA	@ 25°C
Slope efficiency	0.47 ± 0.013	mW/mA	@ 25°C
Optical power vs. temperature sensitivity	-0.17 ± 0.45	mW/K	@ I _{Cs}
Frequency vs current sensitivity	-1.37 ± 0.03	GHz/mA	@ T _{Cs}
Frequency vs temperature sensitivity	-21.8 ± 0.18	GHz/K	@ I _{Cs}
Mode	Single-mode	-	@ λ _{Cs}
Side mode suppression ratio	> 52	dB	@ T _{Cs} and I _{Cs}
Relative intensity noise	$6 \cdot 10^{-11} \cdot f^{-1} < 10 \text{ kHz} \leq 5 \cdot 10^{-15}$	Hz ⁻¹	@ λ _{Cs} ; 40 mW
Frequency noise	$2 \cdot 10^{11} \cdot f^{1.13}$	Hz ² /Hz	@ λ _{Cs} ; 40 mW
Linewidth	1.53 ± 0.15	MHz	Calculated from FM noise (freq. ≥ 250 Hz), 40 mW
	1.7 ± 0.16		Width of the beat with Ref.
Polarization	Linear TE; ellipticity 0.4; azimuth 5.6	°	-
Divergence	24.2 / 40.6	°	Calculated from collimated beam diameter and lens data
Beam diameter	2.04 x 1.18	mm ²	f = 2.75 mm
Feedback power ratio (FPR) threshold	-69.4 ± 2.5	dB	Threshold to Cs spectrum deformation

Multiple measurements of the FPR threshold realized after misalignment and re-alignment of the laser beam have shown a good repeatability, below the level arising from the reading uncertainty for the waveplate angle. However, the uncertainty on the reading of the angle of the rotating quarter-wave plate is estimated at ±2°, a value which is taken into account when calculating the FPR threshold uncertainty from equation (2).

VI. CONCLUSION

We have presented methods and a setup for in-depth characterization of laser diodes for atomic clocks. The setup is initially designed for devices emitting at Rb and Cs D1 and D2 lines, at 795 nm / 780 nm and 894 nm / 852 nm respectively. In addition to usual parameters, spectral parameters such as intensity and frequency noises as well as linewidth are evaluated. An evaluation on the uncertainty and reproducibility of these methods has also been described. Techniques to determine quantitatively the sensitivity to optical feedback with high degree of precision have been demonstrated. A comparable, very low level of feedback sensitivity (FPR ≈ -70 dB) for the same DFB lasers (provided by III-V Lab) has also been reported in [15] when characterizing the frequency shift of the laser diode due to feedback, by using the out-of-feedback bandwidth error signal of the laser diode frequency lock.

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