WATER VAPOUR DIAL OPTICAL FREQUENCY LASER REFERENCE SYSTEM

(1) **Renaud Matthey**, (1) **Christoph Affolderbach**, (1) **Gaetano Mileti**
(2) **Stéphane Schilt**, (2) **Daniela Werner**, (2) **Sang-Hoon Chin**, (2) **Laura Abrardi**, (2) **Luc Thévenaz**

(1) Observatoire cantonal de Neuchâtel, rue de l'Observatoire 58, 2000 Neuchâtel, Switzerland
E-mail: renaud.matthey@ne.ch

(2) Ecole polytechnique fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland
E-mail: Luc.Thevenaz@epfl.ch

ABSTRACT

A four-wavelength low-power continuous-wave frequency laser reference system has been realised in the 935.4-nm range for water vapour DIAL application. The system is built around laboratory extended-cavity and DFB diode lasers. Three lasers are directly locked to three water vapour absorption lines of different strength, whereas the forth laser wavelength lies out of any absorption line (off-line). On-line stabilisation is performed by wavelength modulation spectroscopy technique, while precise off-line stabilisation is realised by an offset locking at 18.8 GHz. Offset frequency larger than 320 GHz has also been demonstrated at 1.55 μm, based on an all-fibre optical frequency comb. First steps towards the use of a photonic crystal fibre as ultra compact reference cell with long optical pathlength were made.

1. INTRODUCTION

High-quality and reliable water vapour DIAL measurements require spectral purity > 99.5 % as well as excellent accuracy, short- and long-term stabilities of the lidar operating wavelengths [1]. A way to achieve these requirements is to make use of the injection-seeding technique: a single-mode low-power cw laser that fulfils these conditions seeds a pulsed power oscillator [2-4]. Master-oscillator power-amplifier (MOPA) is another configuration, where the seed laser is pulsed amplified by optical fibre amplifiers [5] or by a single-pass tapered amplifier [6]. For enhanced humidity measurements, like airborne or satellite DIAL, synchronous operation at two or three on-line wavelengths corresponding to absorption lines of different strength may be advantageous. Here, we report on the development and evaluation of a four-wavelength frequency-stabilised laser reference system for water vapour, further referred to as frequency detection unit (FDU). The aim is relative frequency stabilities $\Delta\nu/\nu \leq 2\cdot10^{-7}$. For off-line wavelength, one usually relies on a wide frequency interval of low absorption for approximate laser wavelength control, like an injection current kick of the laser diode. In our system, the off-line wavelength is precisely controlled and stabilised.

2. SYSTEM DESCRIPTION

The 935-nm wavelength region offers absorption lines with appropriate strength and lower ground-state energy for high quality DIAL water vapour measurement in the troposphere, but also in the upper troposphere and lower stratosphere [7]. Fig. 1 depicts the water spectrum around 935.4 nm in terms of absorption coefficient. The centres of the lines referred to as strong (S), medium (M) and weak (W) line with respect to their relative strength, are, together with the off-line wavelength (O), the frequency references considered in the FDU.

The frequency stabilisation scheme we used for direct locking is based on wavelength modulation spectroscopy (WMS). For pure laser wavelength modulation (WM) the zero crossing of the odd derivatives, which occurs at the absorption line centre, and the linear region around this point, make them convenient for use as error signal in a regulation loop. Actually, WM is often accompanied by an undesired residual intensity modulation (IM). The critical consequence, especially for small absorbance, results in an inaccurate laser locking frequency. Demodulation at the third harmonic is a possible solution to this problem, but at the cost of the 3*f* signal amplitude which is much smaller than the first harmonic. We preferred another approach to insure that the laser locking point coincides with the centre of the absorption line. This approach is based on the adjustment of the detection phase of the lock-in demodulation in order to remove the IM offset background in the 1*f* signal [8]. Error signal modelling demonstrated that implementation of a bal-

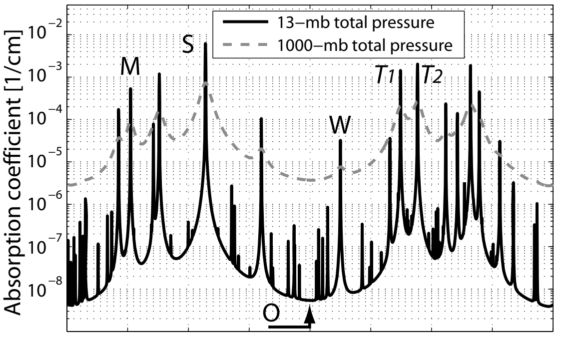

Fig. 1. Water vapour absorption coefficient spectrum in the 935.4-nm region for 13-mbar of pure water vapour (straight line) and for 13-mbar water vapour partial pressure and 1000-mbar total pressure environment (dashed line). In addition to the S, M, W and O-lines, T_1 and T_2 are lines used for tests.

anced detection used in conjunction with WM strongly reduces the influence of the residual IM in case of small absorbance. Another effect of the WM is to broaden the laser line spectrum, so that the modulation must be kept low enough for adequate subsequent injection seeding.

Stabilisation of a laser at a frequency located out of any absorption feature is accomplished by stabilising it relatively to another stable frequency reference, at a precise frequency difference. The frequency reference may be another direct-stabilised laser, or an intermediate optical frequency generated from a stabilised laser. For our purposes, the laser locked to the W-line serves as reference (master) to the off-line laser (slave). The frequency difference is 18.791 GHz, well within the commercially available detector bandwidth.

Our offset locking is sketched in Fig. 2. The beat note signal between the two lasers is detected by a fast photodetector and converted to low frequency using a mixer and an appropriate reference oscillator. In combination with a narrow low-pass (LP) filter, this arrangement can be seen as creating an artificial reference line for the beat frequency, centred at the reference oscillator frequency. After amplification, the power of the radio frequency signal is measured using an envelope detector. Derivatives of the filter transfer function are obtained at the harmonics of the modulation frequency with a lock-in amplifier. The first harmonic signal is used as an error signal (as the 1*f* signal in WMS technique) to control the slave laser frequency.

The seed laser system is depicted in Fig. 3. Four independent injection seed lasers (ISLs) operate in cw at wavelengths λ_1 to λ_4, corresponding to the S, M, W absorption lines and off-line wavelength, respectively. The output of each ISL is directed to its corresponding frequency reference unit (FRU), while a beamsplitter splits off part of the laser power, which constitutes the FDU output to further injection seeding. For S and M absorption lines, the FRU consists in an absorption cell (AC1 and AC2, respectively) and a photodetector. For the W-line, the laser beam is split into two parts before the absorption cell AC3, in order to implement a balanced detection to remove the large optical offset in the 1*f* signal. A fraction of ISL3 beam is picked and combined with ISL4 into a beat note fed into the offset locking unit (OL) to stabilise ISL4. A laboratory electronics module (E) is dedicated to each laser; it contains the laser temperature and current control as well as the frequency stabilisation servo electronics (modulation and lock-in amplifier). The cells are filled with water vapour under reduced pressure, in order to decrease the pressure-broadened linewidth down to the Doppler-limit (~ 1.2 GHz FWHM) to improve the stabilisation of the lasers and to increase the peak absorption. Their optical path-length is comprised between 75 cm and 4 m.

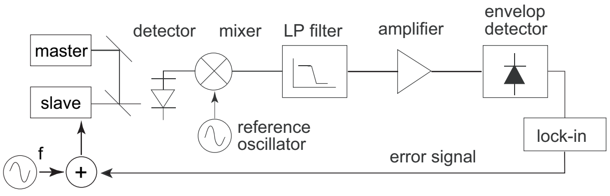

Fig. 2. Offset-locking scheme based on the stabilisation of the beat signal using a low-pass filter (230 MHz cut-off frequency) and a wavelength modulation of the slave laser.

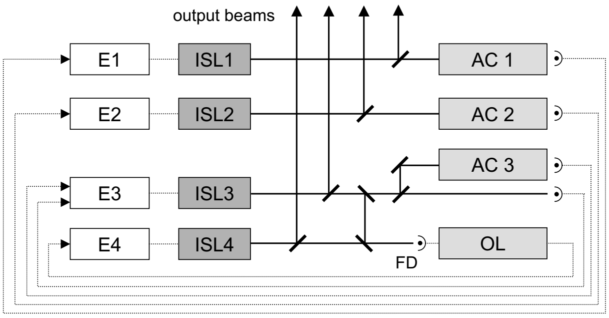

Fig. 3. Schematic diagram of the FDU instrument. ISL: injection seed laser, AC: absorption cell, OL: offset-locking subsystem, FD: fast photodetector, E: electronics module with laser control and lock-in amplifier. The dimensions of the realised instrument are 75 x 53 x 15 cm^3.

Implementation of three independent FRUs allows the optimisation of each FRU separately with respect to the different absorption strengths of the reference lines. It avoids frequency multiplexing complexity or multiple beam superposition problem in case a single multipass cell is used. Finally, it improves the redundancy of the FDU with respect to the possible failure of one FRU.

The ISLs are based on a compact laboratory extended-cavity diode laser (ECDL) in Littrow configuration [9]. The diffraction grating position is controlled by two PZTs. They allow fine cavity adjustment and possible extension of the mode-hop-free tuning range. The dimensions of an ISL are 85 x 82 x 45 mm (0.35 litre) including an electronic circuit for protection of the laser diode, for a total mass of 330 g.

We also evaluated and implemented prototype distributed feedback (DFB) laser diodes emitting around 935-nm. With their intrinsic single-mode operation without mode-hop over larger wavelength intervals, DFB lasers are easier to handle. They are more compact and less sensitive to vibrations and other environmental perturbations. Table 1 lists the ISL main characteristics.

3. STABILITY RESULTS

The frequency stability of all ISLs, respectively in free-running regime and locked to their corresponding FRUs, was measured using frequency discriminators or a high-precision wavemeter (10 MHz accuracy), respectively.

Parameter	Required	ECDL	DFB
wavelength [nm]	935.4	935.4	935.4
optical power [mW]	20-30	30-40	10
current (operational) [mA]	-	75-100	30-35
linewidth (1 ms) [MHz]	< 10	0.3	2.7
FRF stability (14 s) [MHz]	< 50	0.3	1
FRF drift (24 h) [MHz]	< 500	200	100
ROP stability (14 s) [%]	--	$< 4\cdot10^{-3}$	$< 2\cdot10^{-3}$
ROP stability (3 h) [%]	--	0.12	0.04

Table 1. Overview of the ISL performances. FRF: free-running frequency (measured over 50 hours using H_2O frequency discriminators); ROP: relative optical power (measured over 24 hours). Requirements refer to values retained as objectives for space applications (airborne and ground-based applications are less demanding). Stabilities and drifts are expressed as Allan deviation. Linewidths were determined by heterodyne beat note measurement technique.

The wavemeter was calibrated at 780 nm with a reference laser stabilised to a Rb Doppler-free saturated absorption resonance [9]. The results in free-running regime are given in table 1.

For locked lasers, the stability amounts to 1-5 MHz at 1 to 10 seconds and less than 10 MHz at 1000 s for all lasers (Fig. 4). Extrapolated stabilities over one day lie between 15 MHz and 100 MHz, depending on the absorption strength of the reference line and alignment optimisation. The measured frequency stability of ISL1 is clearly limited by the stability of the wavemeter over all averaging times, but below 10 MHz. The real longtem stability of ISL2 is represented by the plateau around 8 MHz for times between 500 s and 4000 s. For longer averaging time, this behaviour is masked by the increasing drift of the wavemeter. The "bump" between 10 and 600 s is due to instabilities arising from optical interference fringes in the multipass reference cell (etalon effect).

The stability of ISL3 shows the largest frequency drift over several hours due to the relatively larger influence of the etalon effect on the weak absorption line signal. This drift critically depends on the collimation of the laser beam and on the alignment of the FRU3 multipass cell. The stability is reported for two cases. In the first case, the beam quality and the multipass cell alignment were not optimised. When extrapolated on 24-hour the stability reaches 800 MHz. In the second case, when the optical set-up was better controlled, this value drops down to 50 MHz. The stability of ISL4 when offset-locked to ISL3 (< 100 MHz on an extrapolated daily basis) is an additional evidence of the susceptibility of ISL3 to optical adjustment.

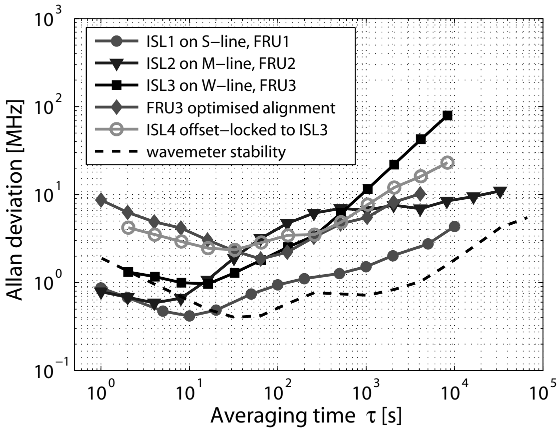

Fig. 4. Stability of the ISLs when locked to their corresponding absorption line. An additional stability curve is shown for the W-line, when ISL3 and FRU3 were better aligned. Stabilities and drifts are expressed in term of Allan deviation.

To demonstrate the correct operation of the offset locking set-up and to measure its frequency stability, two close strong absorption lines separated by 9.5 GHz were considered around 935.75 nm (in air) These lines are marked T1 and T2 in Fig. 1. The master laser (ISL3) was locked to line T1 using the 4-m absorption cell, while the other line, T2, served as frequency discriminator for the slave laser (ISL4) when offset-locked by 10 GHz away from ISL3 (an additional shift of 0.5 GHz was added to set ISL4 on the absorption line slope). An external frequency generator replaced the 18.791-GHz reference oscillator. The wavelength of ISL3 was monitored by the wavemeter. The stability of the frequency difference between ISL3 and ISL4 is shown in Fig. 5. It is compared to the stability of the ISL1 locked on the strong line and shown in Fig.5. At short-term, the difference in the stabilities can be explained by the difference in the modulated laser linewidths. Starting from averaging time above 60 s, the stabilities are identical. This demonstrates that the offset-locked laser follows the master laser and that possible instabilities provoked by the offset locking are below the wavemeter drift.

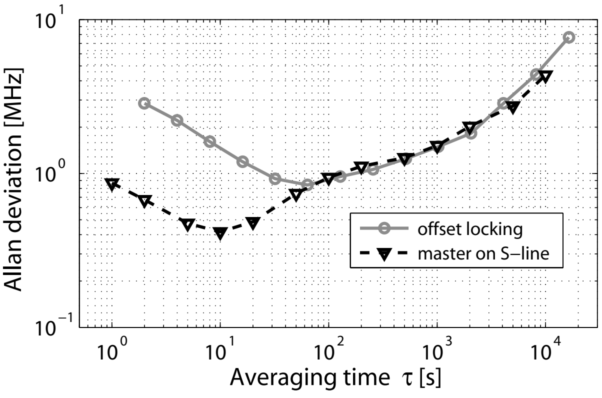

Fig. 5. Offset-locking stability evaluation of the frequency difference between the master (ISL3) and the slave (ISL4) lasers. It is a measure of the slave laser stability (offset-locked) relative to the master laser. The master laser was locked to line T1, of line strength equivalent to the S-line.

4. OPTICAL FIBRE CONFIGURATIONS

The offset-locking scheme reveals quite robust and simple. The major limitation of this technique lies in the maximum achievable offset frequency, which is given by the bandwidth of the fast photodetector (25 GHz in the present configuration). Much larger offset frequencies can be obtained by combining the proposed technique with an optical frequency comb (OFC). OFC made of tens to hundreds of equally spaced optical frequencies with several gigahertz frequency spacing can be generated from a singlemode laser. By locking one line of the comb to a molecular absorption line, all the OFC sidebands have a determined and stable frequency. One of these lines may then be used as a master laser to offset-lock a slave laser some gigahertz away.

We implemented an all-fibre OFC generator around 1550 nm with line frequency spacing of 2.3 GHz. When combining the OFC with the electrical filter technique offset locking larger than 150 GHz were reached, with a detector of 1-GHz bandwidth only. Performances were improved by achieving offset-locking using direct optical injection locking of a slave DFB laser. In this way, feedback electronics is no longer needed. As illustrated in Fig. 6, frequency offset up to 326 GHz (2.6 nm) was reached, being limited only by the spectral tuning range of the slave laser.

A possible solution to improve the stability of the laser when locked to a weak line is to increase the optical path length of the cell. A convenient solution consists in using a hollow-core photonic crystal fibre (HC-PCF) filled with water vapour at reduced pressure as a reference cell. Additional advantages offered by a HC-PCF-based cell are in terms of volume, mass and mechanical stability. Such a cell could also be used to measure the laser spectral purity. The preliminary tests with a HC-PCF filled with carbon dioxide at 1.57 μm are quite promising (cf. Fig. 7). Main issues are the HC-PCF filling with low-pressure gas and efficient splicing of the fibre to prevent leakage.

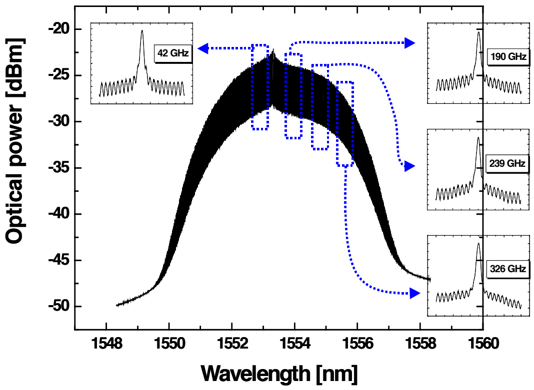

Fig. 6. OFC spectrum generated from a 1553-nm reference laser. Comb lines are spaced by 2.3 GHz. The insets display the slave laser when injection-locked to different comb lines.

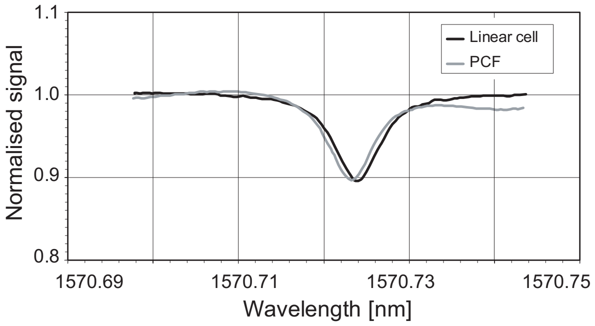

Fig. 7. Normalized transmission through a 1-m linear cell and a 1-m HC-PCF, both filled with CO_2 at reduced pressure (100 mbar). The wavelength was scanned by current tuning a DFB laser. Amplitude and width of the absorption lines are identical. The slight wavelength shift between the two measurements is due to the precision and operation repeatability of the laser temperature control.

5. CONCLUSIONS

A four-wavelength optical reference system for water vapour applications in the 935 nm range has been developed. Three lasers are locked to water vapour absorption lines while the last laser is locked off-line. For lasers locked to water vapour lines with large or medium strength – lines S and M in this work -, frequency stabilities below 15 MHz were observed on a daily basis. The observations were limited by the precision of the measurement instrument. The frequency stability degrades to 50 MHz or more (over 24 hours) for a weak absorption line. Promising results of large frequency offset-locking have been obtained at 1.55 μm when using an optical frequency comb. Such a scheme could serve to lock several lasers on a master laser (itself locked to a strong line), for instance off-line, weak line or even medium line lasers. First tests with a HC-PCF filled with CO_2 showed that this new type of fibres can perfectly play the role of a spectroscopic reference cell.

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