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Optics and Lasers in Engineering 44 (2006) 677–686
OPTICS and LASERS in ENGINEERING

Frequency-stabilized seed laser system for dial applications around 0.94 μm

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Available online 15 September 2005

Abstract

Absolute frequency stabilization of an extended-cavity diode laser at 0.94 μm is reported. The diode laser was frequency locked against rovibrational absorption lines of water vapour by using the frequency modulation spectroscopy technique. The stabilized oscillator shows a short-term frequency stability level of ~40 kHz for integration times of 1 s and a long-term frequency drift lower than 10 MHz for observation times longer than 10^3 s. The frequency-stabilized oscillator system is mounted on a compact breadboard (75 cm × 50 cm) and constitutes the seed laser system for the injection of a high-energy DIAL laser transmitter operating in the 0.94-μm spectral region.

Keywords: Frequency-stabilized laser; Extended cavity diode laser; FM spectroscopy; IR water vapour absorption; Dial instrument

1. Introduction

A variety of near infrared solid-state lasers are currently under development to realize efficient LIDAR (Light Detection And Ranging) and DIAL (Differential Absorption Lidar) instruments devoted to remote sensing of the atmosphere. In

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0143-8166/$ - see front matter
doi:10.1016/j.optlaseng.2005.04.017

particular, a dial instrument basically measures the backscatter of laser pulses emitted into the atmosphere at two adjacent wavelengths, one of which centred on an appropriate absorption line of the species under investigation (on-line wavelength) and the second one outside of the absorption band (off-line wavelength) [1]. Because the water vapour plays a fundamental role in many atmospheric processes and is a highly variable constituent of the atmosphere, different dial systems for the measurement of water vapour in the upper troposphere and lower stratosphere have already been developed or are currently under development [2–5]. In order to achieve high-measurement sensitivity at troposphere height, particularly in case of very dry air from the lower stratosphere, dial operation in the 935–940 nm wavelength spectral region is recommended [5,6]. In this spectral region the strong $3v$ overtone vibrational bands of H_2O is accessible, which is more intense (one order of magnitude) than the overtone vibrational bands ($4v$ and $5v$ around 830 and 720 nm, respectively) previously adopted [7]. Moreover, to perform high-resolution and high-accuracy measurements the dial instrument has to be based on high-energy pulsed oscillators (dial transmitters) with good frequency stability and accuracy (tens of megahertz), narrow emission linewidth (<100 MHz), and high spectral purity ($>99\%$). Indeed, the knowledge of the absolute wavelength in combination with that spectral shape of the launched pulse determines the achievable systematic measurement errors [6]. When the dial transmitter has to meet at the same time all these requirements it is necessary to implement a frequency control apparatus to achieve the single-mode and line narrowing of the pulsed transmitter as well as the long-term frequency stabilization [8–10].

In this work, absolute frequency stabilization of a CW extended-cavity diode laser (ECDL) around 0.94 μm is reported. The frequency-stabilized laser system is assembled onto a compact breadboard (75 cm × 50 cm), is fully transportable, and constitutes the seed laser system for the injection of a high-energy (up to 100 mJ) dial laser transmitter at 0.94 μm based on gain-switched titanium sapphire laser. The whole experimental characterization of the realized seed laser system is here presented with particular attention to both the short-term and long-term laser frequency stability.

2. Frequency stabilization of the seed laser system

A seed laser system in a wavelength range from 935 to 943 nm can be realized using different oscillators, operating in CW or pulsed regimes, such as $Ti:Al_2O_3$ and Cr:LiSAF diode pumped solid-state lasers, and semiconductor lasers (InGaAs and GaAs) [11]. Solid-state lasers usually show better functional performance with respect to semiconductor lasers, but have a much lower efficiency and are more complex than laser diodes. As far as the injection of high-energy dial transmitters is concerned, CW oscillators make it possible high-efficiency seeding of the slave laser without the need of any synchronization technique, as in case of pulsed seed laser systems [9,10]. For these reasons, the implemented seed laser system was based on a CW semiconductor laser. In particular, extended-cavity diode laser configuration was selected for its excellent performance in terms of wide wavelength tunability range, narrow emission linewidth, and fine control of the laser frequency [12]. Distributed feedback and distributed Bragg reflector lasers were discarded, although they may represent a more compact solution in view of space applications, these being components not yet commercially available at the selected wavelengths.

Fig. 1 shows the frequency-stabilized seed laser system which has been realized. An ECDL in Littrow configuration (Toptica, model DL-100) was used [13]. Coarse tuning of the laser wavelength from 934 to 944 nm is achieved by a micrometric screw acting on the tilting angle of the diffraction grating, whereas a piezoelectric (PZT) transducer allows for a fine and electrically controlled frequency tuning (~0.3 GHz/V) within the extended-cavity free spectral range (±4 GHz). The maximum output power of the ECDL is 70 mW (at the pump current of 150 mA) with an emission linewidth <2 MHz for observation times of 1 ms (measured by means of the beat note with a similar laser diode). An optical isolator with ~42 dB of isolation at 935 nm (OFR, model IO-5-l-HP) prevents from undesired reflection of the laser beam which may be detrimental for the diode laser operation. Using a 125-mm focal lens (L_1) the full transmission of the optical isolator was 92%. A small fraction (~1 mW) of the available power has leaked out for the stabilization loop, whereas the largest part (~45 mW) is used as the CW injection beam for the pulsed dial transmitter through a variable beam splitter based on the combination of a half-wavelength retardation plate and a polarising beam splitter.

To lock the frequency of the ECDL laser to the water vapour absorption lines, an optoelectronics frequency servo loop based on the FM spectroscopy method was implemented [14]. In this technique the laser field is phase modulated and the detection of the absorption feature is realized by means of synchronous detection of

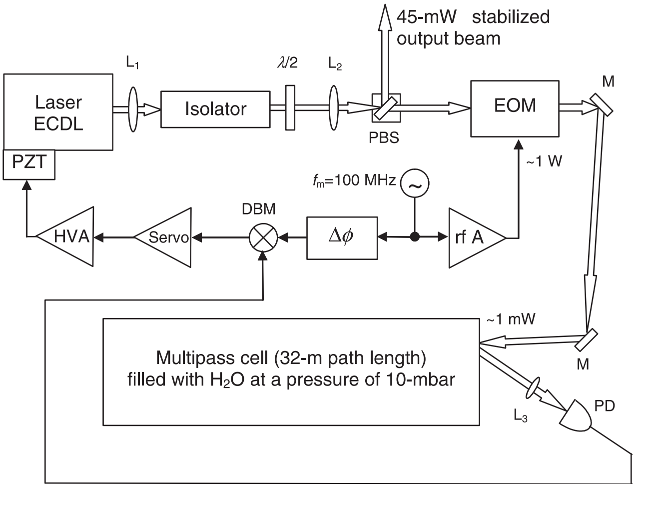

Fig. 1. Seed laser system at 935 nm. L: lens; PBS: polarizing beam splitter; EOM: electro-optic modulator; M: mirror; PD: fast photodiode; PZT: piezoelectric transducer; DBM: doubled balanced mixer; HVA: high-voltage amplifier; rf A: radio-frequency power amplifier.

the photocurrent generated in the photoreceiver placed at the output of the absorbing sample. The absorption and dispersion profiles due to the molecular resonance unbalance the pure FM modulation and convert the original modulation into an amplitude modulation that is detected by the photodiode. The synchronous demodulation of the photocurrent retrieves both the in-phase and in-quadrature components of the amplitude modulation related to the dispersion and absorption profiles, respectively. These signals depend on the modulation parameters (modulation frequency and index) and on the absorption contrast and linewidth of the molecular feature. They are odd functions of the detuning between the laser frequency and the resonance frequency, and therefore can be used as error signals to lock the laser frequency to the resonance centre (the choice between the in-phase and in-quadrature components comes from the adopted experimental parameters [14,15]).

Due to the quite low intensity of the water vapour absorption at 0.94 μm, to obtain a good absorption contrast it was necessary to place the H_2O vapour inside a suitable multipass cell to increase the optical interaction length. To this purpose, a Herriott-type multipass cell (SIT, CMP-30 model), filled with H_2O at a pressure of ~1 kPa (10 mbar), showing an interaction length of ~32 m, was used. The laser beam was modulated (100 MHz modulation frequency, ~2 rad phase modulation index) by means of an external electro-optic device (New Focus, model 4001) and then coupled to the multipass cell using a 75-mm lens (L_2) and two plane dielectric mirrors. After 78 bounces between the gold-coated spherical mirrors of the multipass cell, the laser beam was coupled out from the same input cell mirror (reflection configuration) and focused through a 25-mm focal length lens (L_3) on the active area of a 125-MHz bandwidth photodetector (New Focus, model 1811-FS-M).

The synchronous detection of the photodiode output voltage was performed by a doubled-balanced mixer (Minicircuits, model RPD-1) driven by the 100 MHz signal. The intermediate frequency signal at the output of the mixer was low-pass filtered (10 kHz bandwidth) and amplified with a precision low-noise amplifier. To lock the laser frequency against the water vapour lines the demodulated signal was fed back to the high-voltage PZT amplifier through integral and proportional servo electronics. A typical control loop bandwidth of ~2 kHz was achieved, strongly limited by the mechanical resonances of the PZT mounting. This control bandwidth was fast enough to efficiently reduce the frequency laser instability for integration time longer than 1 ms (typical round-trip time for a satellite DIAL instrument) and to suppress the long-term laser frequency drifts. Faster control of the laser frequency, achievable for example by means of the diode laser injection current, was not necessary for this specific application.

3. Experimental characterization

The experimental characterization of the seed laser system started with the high-resolution spectroscopy of the water vapour absorptions within the 10 nm tunability range of the ECDL. After the spectroscopic measurements, the laser frequency was then locked to the centre of different water vapour absorption lines and measurements of the frequency stability, thus achieved, were performed.

3.1. Water vapour spectroscopy around 0.94 μm

High-resolution spectroscopy of water vapour absorption features within the 10 nm tunability range of the ECDL was first performed to assess the intensities and the widths of the selected lines. The molecule of water may vibrate in a number of different ways due to the combination of symmetric stretch (v_1, which corresponds to $\sim 3657\,cm^{-1}$), asymmetric stretch (v_3 which corresponds to $\sim 3756\,cm^{-1}$), and bending (v_2 which corresponds to $\sim 1595\,cm^{-1}$) of the covalent bonds between the hydrogen and oxygen atoms [16]. Within the ECDL tunability range from 934 to 944 nm the water vapour shows 271 rovibrational transitions belonging to the $3v$ overtone vibrational bands ($3v_1$, $2v_1\ v_3$, $v_1\ 2v_3$, and $3v_3$), with line intensities ranging from 10^{-26} to 6×10^{-22} cm/molecule [17]. Assuming a water vapour pressure of 1 kPa, an absolute temperature of 300 K, and an interaction length of 32 m, the peak absoprtion values corresponding to the above reported line intensities range from 0.03 to 100%. The absorption profile is well described by the Voigt function which is the convolution between a Gaussian (due to the inhomogeneous Doppler effect) and a Lorentzian (due to the homogeneous effect of the molecular collisions) broadening profiles. For a temperature of 300 K and a wavelength of 935 nm the full width half maximum (FWHM) value of the Doppler broadening is ~0.93 GHz and the pressure broadening linewidths for the $3v$ bands of the water vapour are in the range from 0.3 to 0.7 GHz. These broadening values set the FWHM of the Voigt profile in the order of gigahertz.

To perform high-resolution spectroscopy of H_2O absorption lines, the ECLD wavelength was coarse tuned using the micrometric screw acting on the laser grating. Then a linear scan voltage was applied to the PZT transducer in order to finely sweep the laser frequency across the selected water absorption line. Fig. 2 shows the transmission spectra corresponding to the three absorption lines, located at 935.684 nm (201 vibrational band, $J' = 4\ K'_a = 0\ K'_c = 4 \rightarrow J'' = 3\ K''_a = 0\ K''_c = 3$

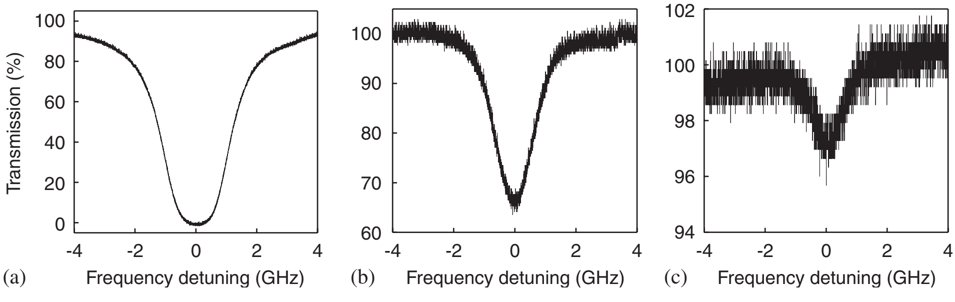

Fig. 2. Transmission spectra corresponding to three different water vapour lines at 935.684 (a), 935.299 (b), and 939.710 nm (c).

transition where J, K_a, and K_c are the quantum numbers denoting the water rotational levels), 935.299 nm (201, $J' = 6$ $K_{(a)'} = 5$ $K'_c = 1 \rightarrow J'' = 5$ $K''_a = 5$ $K''_c = 0$), and 939.710 nm (102, $J' = 3$ $K'_a = 3$ $K'_c = 1 \rightarrow J'' = 4$ $K''_a = 4$ $K''_c = 0$), obtained using a direct measurement method (recording of the output voltage of the photodiode). The FWHM of the recorded profiles were, respectively, 2.54, 1.44, and 1.14 GHz, and the corresponding absorption contrasts were 100%, 35%, and 3%, respectively. The use of absorption lines with such different contrasts is motivated by the need of investigating a wide range of water vapour concentrations in atmospheric layers located at different altitudes. The signal to noise ratio (SNR) limited the resolution of the above spectroscopic measurements to a peak absorption contrast of ~1%.

To achieve higher sensitivity and therefore to resolve all the line contrasts shown by the $3v$ bands of the water vapour, the FM method was then adopted. Fig. 3 shows the FM lineshapes corresponding to the absorption lines previously reported in Fig. 2, recorded at the output of the doubled-balanced mixer (DBM), when the laser beam was phase modulated at 100 MHz with a modulation index ~2 rad.

3.2. Characterization of the laser frequency stability

To lock the ECDL frequency against the selected water absorption lines, the FM lineshape signals were used as error signals for the optoelectronic servo loop, which acts through the PZT on the instantaneous frequency of the ECDL. The measured frequency to voltage conversion coefficients (frequency discriminator gains) corresponding to the slopes at the resonance centre of the FM lineshapes, ranged from ~20 to ~0.02 V/GHz. In particular, the frequency discrimination coefficients (and SNR values in 10 kHz bandwidth) related to the lineshapes reported in Fig. 3 were 3.0 V/GHz (36 dB), 16.5 V/GHz (38 dB), and 1.4 V/GHz (27 dB). By the use of this technique a peak absorption sensitivity up to $5 \times 10^{-8}\,\text{cm}^{-1}$ in an observation bandwidth of 100 Hz was obtained, corresponding to line strength of 7×10^{-27} cm/molecule. Assuming a white noise spectral density, the sensitivity of the spectrometer was $5 \times 10^{-9}\,\text{cm}^{-1}/\text{Hz}^{1/2}$, which compares well with the sensitivities of similar spectrometers based on the FM method.

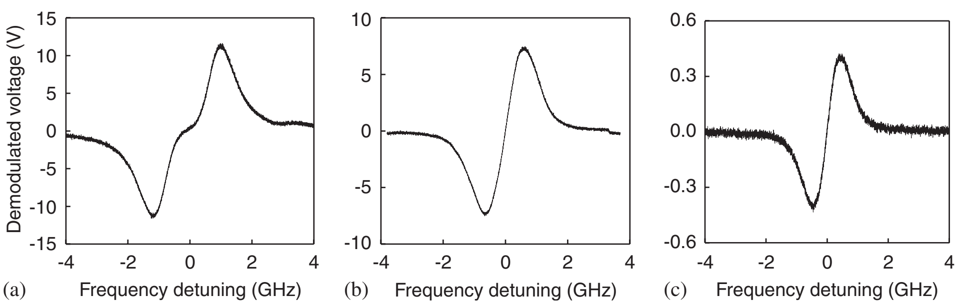

Fig. 3. FM lineshape signals corresponding to the lines shown in Fig. 3. The measurement bandwidth is 10 kHz.

The characterization of the laser frequency stability was performed by means of the error signal analysis, for integration times shorter than 1 s (short-term stability) [18,19], and using a high-resolution wavemeter (High Finesse, WS/7 model) for integration times up to few hours (long-term stability).

Fig. 4 shows the residual laser frequency fluctuations, obtained as the ratio between the voltage at the output of the DBM and the frequency discrimination coefficient, for an observation time of 100 s (sampling period of 10 ms), when the seed laser was locked against the water line at 935.299 nm (Fig. 3b), corresponding to the best SNR. The control loop bandwidth was ~2 kHz, limited by the mechanical resonances of the PZT mounting. In the locking condition the root mean square (rms) value of the seed frequency was 0.4 MHz for an integration time of 10 ms. Assuming a white frequency noise, the 1 s frequency stability of the locked seed laser was ~40 kHz. When other absorption lines were used to stabilize the ECDL frequency, the stabilities were reduced due to the reduction in the SNR of the FM-spectroscopy error signal. For example, when the ECDL was frequency locked against the water lines at 935.684 and 939.710 nm (Fig. 3a and c, respectively) the 1 s short-term frequency stabilities were ~0.2 and ~1 MHz, respectively.

The long-term laser frequency stability was measured both in free-running and locked conditions using the 10-MHz resolution wavemeter. Fig. 5 shows the absolute frequency of the ECDL as a function of the observation time. When the ECDL was operated in free-running regime, over a time interval of 1 h, a maximum value of peak-to-peak frequency fluctuations of ~230 MHz and a rms value of ~53 MHz were measured (see Fig. 5). When the laser was locked against the water line at 939.710 nm (Fig. 3c), over an observation time of 2 h, the maximum peak-to-peak frequency excursion and the rms value were reduced to 24 and 3.5 MHz, respectively. Similar results were obtained when the ECDL was locked to others absorption lines.

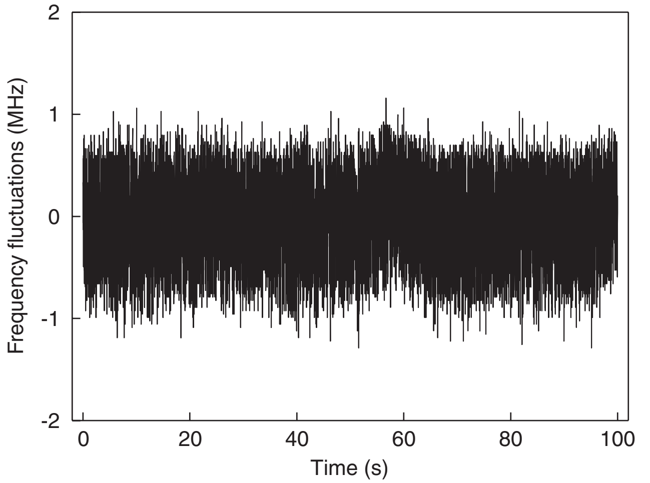

Fig. 4. Short-term frequency fluctuations as a function of the observation time when the seed laser is locked to the water line at 935.299 nm. The sampling period was 10 ms.

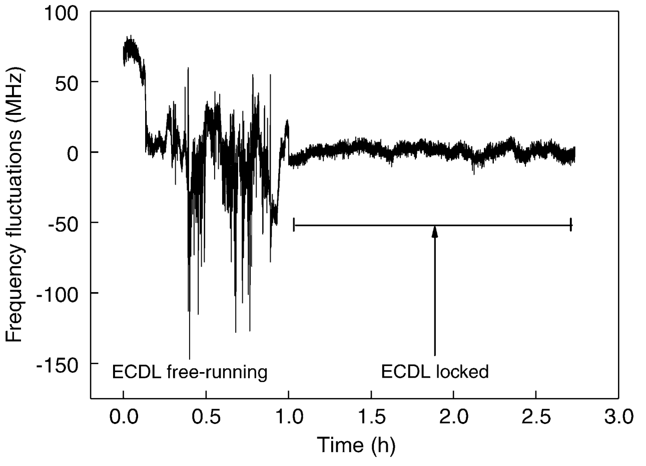

Fig. 5. Long-term frequency fluctuations as a function of the observation time when the seed laser is unlocked ($t < 1$ h) and locked ($t > 1$ h) to the water line at 939.710 nm.

Table 1
Seed laser system performance

Parameter	Measurement result
Emission wavelength	From 934 to 944 nm
Maximum output power	45 mW
Power stability	0.6% @ 100 s
Fine tuning range	±4 GHz (PZT)
Emission linewidth ($\Delta\nu$)	<2 MHz @ 1 ms
1-s frequency stability	
100% line contrast	0.2 MHz
35% line contrast	0.04 MHz
1% line contrast	1 MHz
10^3-s frequency stability for line contrasts > 1%	< 10 MHz

Table 1 summarizes the final performance of the frequency stabilized seed laser system.

4. Conclusions

The absolute frequency stabilization of an extended cavity laser diode against water vapour lines, in the wavelength range from 934 to 944 nm, was performed by means of a frequency modulation spectroscopy method. The stabilized diode laser achieved a minimum relative frequency instability level $\Delta\nu/\nu_0 \approx 10^{-10}$, for an observation time of 1 s, resulting in a frequency stability of few tens of kilohertz at the emission wavelength of 0.94 μm. To the authors' knowledge, this result is one order of magnitude better than what is currently obtained in similar stabilized systems [5], and two orders of magnitude better as compared to the typical frequency stability requirements of satellite dial systems. Moreover, a long-term frequency stability better than 10 MHz (3×10^{-8} in relative terms) was measured for integration times longer than 10^3 s.

The developed frequency stabilized laser is currently used as a master oscillator in the injection seeding experiments of high-energy gain-switched titanium sapphire laser. Moreover, this oscillator may find interesting applications as a frequency standard in coherent Doppler-Lidar systems, high-resolution spectroscopy of water vapour, and frequency metrology.

Acknowledgement

This work was supported by the European Space Agency—Alcatel Space Industries contract Breadboarding of a Water Vapour Transmitter.

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