Fast-switching system for injection seeding of a high-power Ti:sapphire laser

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A high frequency switching and tunable seed laser system has been designed and constructed for injection seeding of a high-power pulsed Ti:sapphire laser. The whole laser system operates as the transmitter of a scanning, ground-based, water-vapor differential absorption lidar (DIAL). The output of two seed lasers can be tuned in the wavelength range of 815–840 nm up to the power of 20 mW and switched between the online and offline wavelengths of the DIAL at frequencies of 0–1 kHz. The frequency stability of online and offline seed lasers is better than ± 20 MHz rms and the mode-hop-free tuning range is greater than 40 GHz with external cavity diode lasers. The advantage of this system for efficient injection seeding of the Ti:sapphire cavity is that it is modular, robust, fully fiber-coupled, and polarization maintaining.
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I. INTRODUCTION

Accurate measurements of water vapor using the differential absorption lidar (DIAL) method in the near infrared spectral region require single-frequency operation of high-power pulsed lasers[1–4] at two frequencies with a small frequency difference of about 50 GHz.[5] Injection seeding is one of the most efficient techniques for spectral narrowing of pulsed lasers and optical parametric oscillators.[4,6–12] Such narrow band lasers can also be used in different laser spectroscopic techniques such as laser induced fluorescence experiments.[6]

In DIAL measurements of water vapor, the required frequency stability of the online and offline frequencies should be on the order of 60 MHz.[13] Therefore, seed lasers with a short- and long-term frequency stability of the order of a few tens of megahertz are adequate for generating the on- and offline wavelengths (λ_{on} and λ_{off}) by injection seeding the pulsed laser. To lock λ_{on} accurately to the center of the desired water-vapor absorption line, the continuous tuning range for the seed laser must be larger than the width of the pressure-broadened water-vapor lines, which is about 5 GHz in the lowermost troposphere.[3,14,15] Therefore, the seed lasers need a mode-hop-free tuning range of at least 30 GHz.[3] Additionally, detailed DIAL end-to-end simulations revealed that for measurements with both a large range and high accuracy of the scanning DIAL system a high flexibility in wavelength selection is essential.[16,17] For instance, weak absorption lines are required for measurements in the horizontal direction. Stronger lines are more adequate for vertical soundings, at shallow boundary layer heights. Also to prevent errors due to insufficient knowledge of the atmospheric temperature profile, a proper wavelength selection requires to choose temperature insensitive absorption lines.[18,19] Suitable water-vapor lines that fulfill the observational requirements under all weather conditions have been identified in the wavelength region around 820 nm (Ref. 15) (see Fig. 1). The necessary flexibility in wavelength selection requires that the seed laser system should be tunable within the range of 817–821 nm. In order to achieve a high signal to noise ratio of scanning water-vapor measurements, the transmitter operates at a repetition rate of ≥ 250 Hz and an average output power of >6 W. Consequently, frequency switching at half of this rate is necessary for the injection seeding system. A robust and compact design continuous wave (cw) laser source as the injection seeder can be realized using external cavity diode lasers (ECDLs)[20] with an external grating in Littman–Metcalf configuration.[21]

In addition to the requirements on the tuning and stability behavior of the seed lasers, results of Ertel *et al.*[4] and Kallmeyer *et al.*[22] indicated that the output power of a suitable seed laser system should exceed 10–20 mW in order to meet the high spectral purity requirement for the pulsed Ti:sapphire (Ti:Sa) laser output. The spectral purity should be of $>99.5\%$ for accurate DIAL measurements.[9] In its present configuration, our Ti:Sa produced a higher pulse energy so that further measurements have to be performed to characterize the resulting spectral purity of the transmitter.[23] Corresponding results are in preparation and will be published elsewhere.[24]

Many techniques to injection seed pulsed Ti:Sa laser use narrow band cw Ti:Sa lasers or even pulsed dye lasers.[1,2,8,25]

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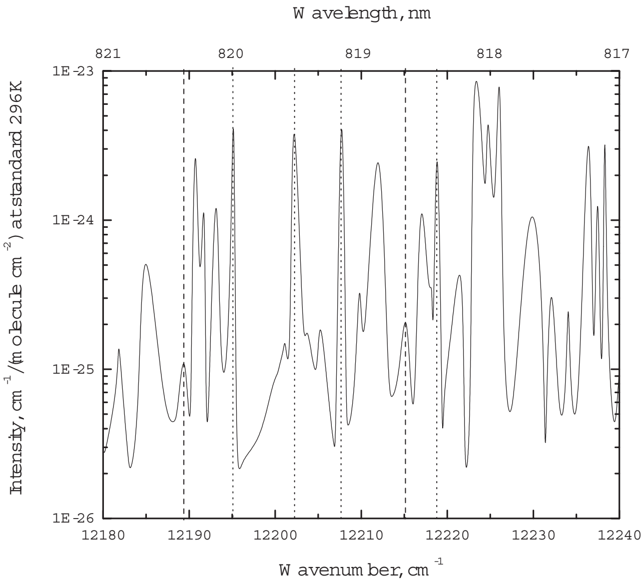

FIG. 1. Water vapor absorption lines at 820 nm, dotted lines: suitable for vertical sounding; dashed lines: suitable for measurements in horizontal direction.

However when a compact and robust setup is required, such as for DIAL applications, diode lasers are the preferred choice as the seed source.[26–29] In order to generate on- and offline wavelengths, several authors change the wavelength of the seed from pulse to pulse.[26,27,30] Others use two seed sources that are alternatively switched onto the Ti:Sa laser.[4] In our opinion, the latter technique has several advantages and is therefore used in this work. First it is easier to stabilize the lasers to their respective wavelengths. Also lasers can be tuned more reliably and have a broad tuning range such as ECDLs. Although it has been shown that ECDLs can be rapidly tuned, this requires more sophisticated techniques.[31]

Regarding the above requirements, we have designed a seed laser system whose output frequency stability is better than ± 20 MHz rms. It can be remotely tuned and locked to on- and offline wavelengths in the wavelength range of 815–825 nm by means of motor drives and piezoelectric transducers. The seed laser is operated with an output power of 20 ± 1 mW per channel and it can be switched between λ_{on} and λ_{off} at the frequencies between 0–1 kHz matched to the high repetition rate of the Ti:Sa laser. The tuning of the seeder is completely computer controlled by a program written in LABVIEW and $\lambda_{on}/\lambda_{off}$ switching is controlled by signals triggered by the Ti:Sa.

In contrast to previous publications which used free space optical components to steer the seed beam to the pulsed laser,[4,26–28,30] we designed a fully fiber-coupled system to provide maximum stability and modularity. In particular, a fast fiber-coupled, polarization maintaining multiplexer was used to switch the wavelengths. This design makes the seed injection system more compact and robust compared to the systems designed with bulk optical and optomechanical components. In principle, operation in harsh environments such as in aircraft is possible, although this was not the purpose here.

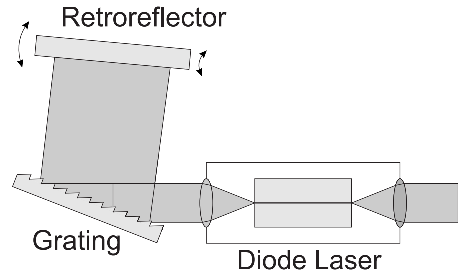

FIG. 2. Schematic structure of an ECDL in Littman–Metcalf configuration, the first order diffraction of the diode laser beam from a grating is reflected back into the diode by means of a retroreflector.

II. THE INJECTION SEEDER

A. Configuration

As stable sources for the injection seeding system, two ECDLs in Littman–Metcalf configuration are used (Fig. 2). In this configuration, the external cavity is defined by a reflection element and the front face of the laser diode. A diffraction grating inside the cavity is used for the wavelength selection. The first order diffraction from the grating is reflected back into the diode and a small part is coupled out via the zeroth diffraction order of the grating. The main part of the laser light coming from the rear face of the diode is collimated with a set of lenses.[21] ECDLs in this configuration can provide more power with respect to other configurations and since their output beams do not pass through beam steering components, the output beams can be easily coupled to an optical fiber.

Figure 3 shows the setup of the injection seeder. In this setup, laser1 and laser2 are ECDLs (Sacher Lasertechnik, Model TEC500 Lion) especially designed for operation in the wavelength range of 800–850 nm. Figure 4 shows the input/output as well as the tuning behavior of these lasers. The lasers are also equipped with piezoelectric transducers

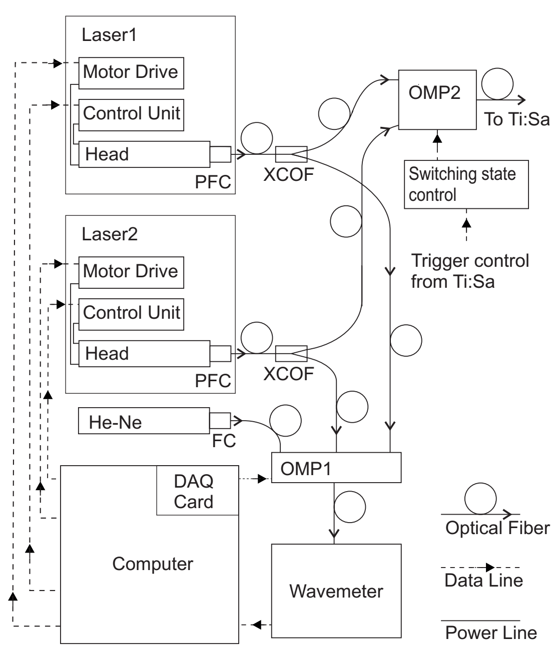

FIG. 3. The injection seeder setup, FC, precision fiber coupler, XCOF, OMP, and DAQ.

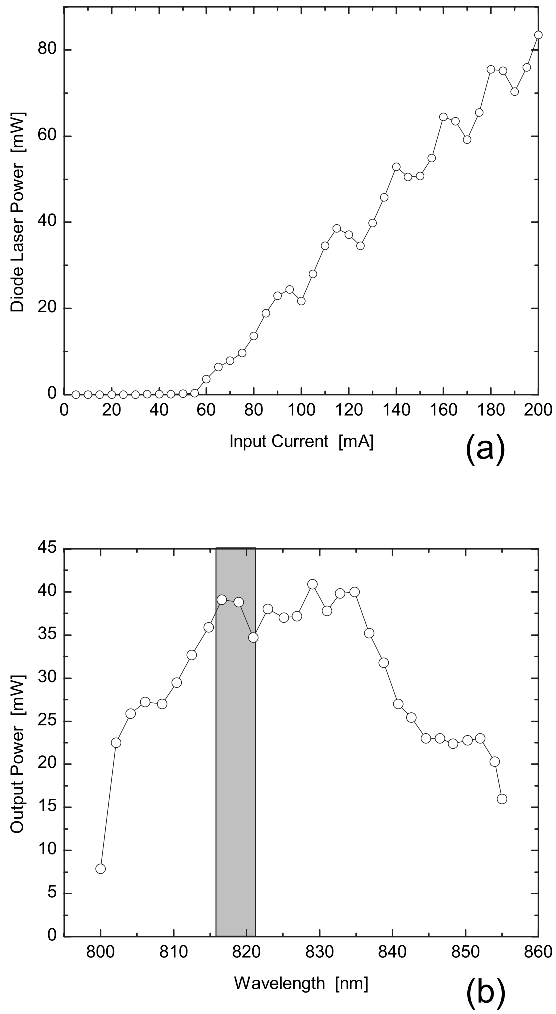

FIG. 4. Characteristics of diode lasers from Sacher Lasertechnik; (a) The input/output at 820 nm and (b) output power as function of wavelength (when tuned with the motor drive).

for fine adjustment of the retroreflector (Fig. 2). Using this component, the lasers have a mode-hop-free tuning range of approximately 30 GHz around the tuning frequency. This feature is necessary to lock the seeders to one of the water-vapor absorption lines. The outputs of the diode lasers are coupled to 99/1% single mode cross-coupled polarization maintaining optical fibers, cross-coupled optical fibers (XCOFs), by means of precision optical fiber couplers (FCs), (Toptica, Model FiberDock).

The 1% sides of the XCOFs are coupled to an optical multiplexer (OMP)1 (Sercalo, Model 4×1 optical switch) and after that to the wavemeter (HighFinesse, Model Angstrom WS/7). The responses of OMP1 to trigger signals of 250 and 500 Hz are shown in Figs. 5(a) and 5(b). It should be noted that OMP1 is used in the stabilization process of the diode lasers and it should switch to different input channels in scales of a few seconds. Therefore its response behavior in Fig. 5 is quite acceptable. The wavemeter also has a satisfying stability behavior. Even though the manufacturer reported a 10 MHz resolution for this device, our measurements show that the wavemeter stability during 30 min of recording, was better than ±5 MHz when a frequency stabilized He–Ne laser (SIOS, Model SL 03) was applied to it.

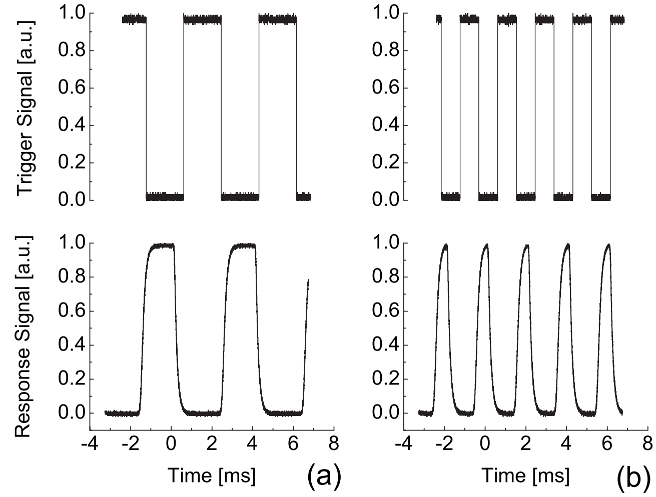

FIG. 5. Response time behavior of OMP1 (bottom) to trigger signals (top) of frequency: (a) 250 and (b) 500 Hz.

The wavemeter measurements are transferred to a 1.7 GHz personal computer (PC) through a universal serial bus (USB) port while the PC controls the OMP1 via a data acquisition (DAQ) card (National Instruments, Model PCI-6221). The control units of the diode lasers are also controlled by the PC through the USB ports. The third input of OMP1 feeds with the stabilized He-Ne laser for frequent calibration of the wavemeter readings.

The 99% ends of the XCOFs are coupled into a 2×1 high frequency and polarization maintaining OMP (CIVCOM, Model 2×1 ultrahigh frequency optical switch), OMP2. OMP2 is controlled by trigger signals from Ti:Sa with a maximum frequency of 250 Hz and the switching is done via transistor-transistor logic (TTL).

Figure 6(a) shows the switching response time of OMP2 measured by means of a fast photodiode. Figure 6(b) depicts the crosstalk measured using an optical spectrum analyzer (Ando, Model AQ6317B). As can be seen, the response time is less than 5 μs (10%–90%) and the crosstalk is less than 30 dB. Although the crosstalk could only be measured in static operations, we have no reason to believe that it would behave differently when switched. The short response time and very low crosstalk make this switch a proper choice for multiplexing the λ_{on} and λ_{off} wavelengths and injection to the Ti:Sa laser. The long-term stability of the switch is still under investigation.

Using single-mode polarization maintaining optical fibers for steering the laser beams and coupling them to different components, makes the optical alignment of different components such as switches, lasers, and fiber-splitters independent of each other. This makes the vibration isolation of the system easier and makes it rugged. The whole seed laser system is mounted in two 19″ racks (Knürr, Model Doubleprorack) and the vibration-sensitive components such as lasers and wavemeter were installed on a vibration isolated optical bread board. The advantages of a rugged, fiber-coupled seed laser setup in airborne operation has recently been successfully demonstrated.[32] In particular, since the wavemeter reading shows a slight pressure dependence, it is important to stabilize the seed lasers to an absolute frequency

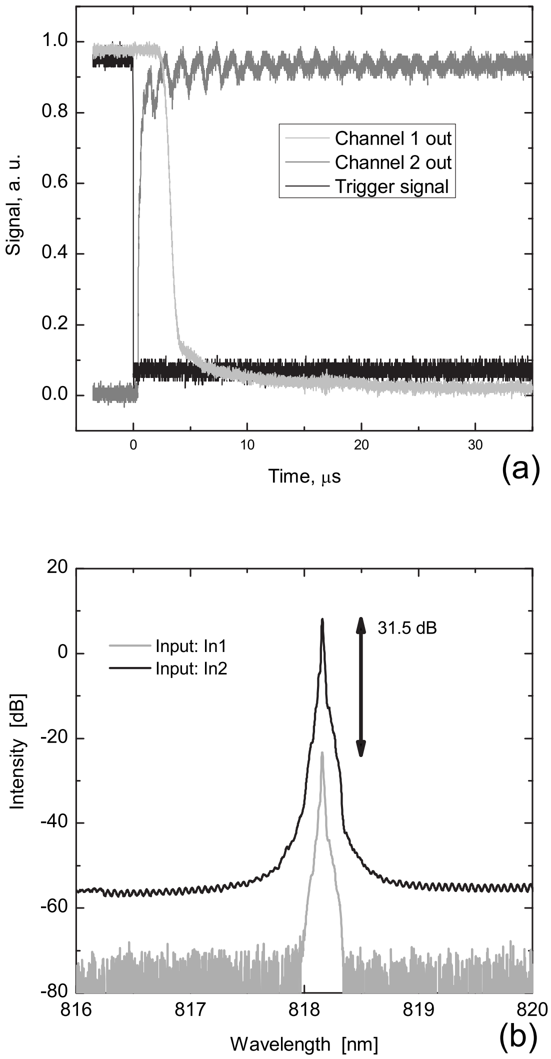

FIG. 6. Characteristics of OMP2, (a) response time behavior for inputs to channels 1 and 2 and (b) crosstalk between channels 1 and 2 when channel 2 is on by the trigger signal.

reference. In our setup, as described in the following chapter, this is performed by regular calibration of the wavemeter to the stabilized He–Ne laser. Therefore, an airborne operation of the seed laser setup in principle should be possible.

B. Stabilization

The OMP1 switches between the He–Ne, laser1, and laser2, respectively. This happens by applying TTL signals via the DAQ card to the two digital inputs of the switch.

The tuning procedure is performed in three steps. In the first step, laser1 and laser2 are tuned to λ_{on} and λ_{off} via their motor drives within ± 5 GHz. In the next step, a triangular voltage ramp is applied to the piezo controllers of laser1 and laser2 to take their frequencies to within ± 0.5 GHz of their set frequencies. As the frequencies of the diode lasers satisfies these conditions, the third step will be started. The third step is a stabilization loop. In this loop the wavemeter first reads the He-Ne frequency through OMP1 as a reference. These readings compensate for possible wavelength drifts of the wavemeter. After the wavemeter calibration, the frequencies of laser1 and laser2 are stabilized to λ_{on} and λ_{off} through a proportional-integral-derivative (PID) control program to

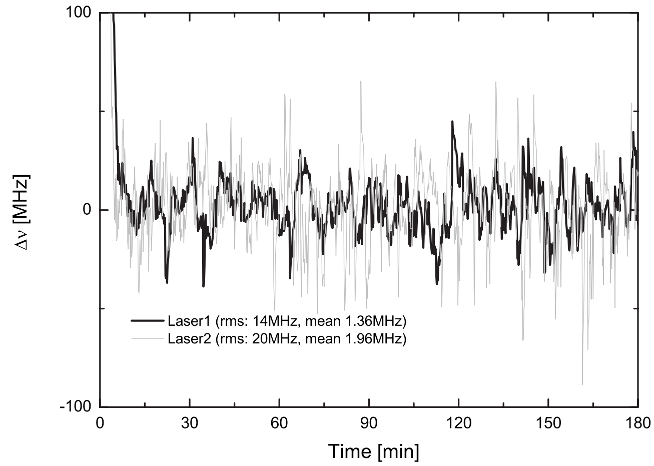

FIG. 7. Typical stability behavior of the diode lasers during more than 180 min of operation of the seeder, laser1 to λ_{on} laser2 to λ_{off}.

within ± 20 MHz of accuracy. In the PID control program, the difference between the set frequency (ν_{on} or ν_{off}) and the wavemeter readout for frequencies of laser1 or laser2 counts as the error signal. Product of the error signal and a proportionality constant (the PID P-part) adds as a correction to the applied voltage on the piezo controllers of laser1 and laser2. The I- and D-parts of the PID programs are adjusted for more stable and smooth tuning of the ECDLs frequencies. The tuning accuracy of the lasers is determined by the limits of the wavemeter resolution and the sensitivity of the piezoelectric power supplies.

III. RESULTS

As described in Sec. II, we have used two ECDLs in Littman–Metcalf configuration (Fig. 2) for high frequency (up to 1 kHz) injection seeding to a Ti:Sa laser that is the transmitter of a DIAL for water-vapor measurements.[33] In this system, a fast switching and polarization maintaining OMP controls the switching of the λ_{on} and λ_{off} wavelengths up to a frequency of 1 kHz so it can well respond to the 250 Hz trigger signal from the Ti:Sa. The tuning and stabilization of the diode lasers are controlled via a PC when a wavemeter reads their frequency through an OMP. In this arrangement a frequency stabilized He–Ne laser has been used as a reference for frequent calibration of the wavemeter. The whole injection seeding system is fiber coupled via polarization maintaining fibers and mounted in 19″ racks.

Figure 7 shows a typical stability behavior of the seeder outputs during more than 180 min of operation. In Fig. 7, laser1 was locked to ν_{on}=365.544 331 THz (λ_{on} =820.126 131 nm) as the online frequency and laser2 to ν_{off}=365.744 331 THz (λ_{off}=819.677 661 nm) as the offline frequency. After settling the stabilization loop, it keeps the lasers stable to within 20 MHz (rms) (see Fig. 7). During this measurement, the wavemeter showed a stability of better than ± 5 MHz as recorded by means of the He–Ne laser. Thus, both lasers show an acceptable frequency stability especially in long-term recordings. The setup in Fig. 3 provides an output power of 20 ± 1 mW at the fiber output for injection seeding to the Ti:Sa laser when the trigger input to OMP2 can have a frequency of 0–500 Hz.

In summary, the main features of the designed injection seeding system are its high frequency switching into the considered on- and offline wavelengths, ruggedness due to coupling all the lights into the polarization maintaining single mode optical fibers and use of ECDLs. Use of ECDLs in the setup also provides continuous stable tuning and locking of λ_{on} and λ_{off}. Currently, the seeding system is being integrated into the water-vapor DIAL system.

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