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DFB laser frequency stabilization unit at 1572 nm

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ABSTRACT

A frequency stabilization unit was developed to stabilize high power laser diodes for differential absorption lidar. Three distributed-feedback (DFB) lasers were used in this approach. To achieve the required frequency stability, two opto-electrical feedback loops for on- and off-line channels were coupled to the third opto-electrical loop for CO_2 locking. A master DFB laser is locked to the selected CO_2 absorption line using a single pass reference cell and a custom feedback loop based on a commercially available equipment (LaseLock 4 Channel). The master DFB stabilization range is around 18 kHz at the interval of 23 s, measured with a frequency comb. The light emitted from the master laser is then fed into the on- and off-line frequency locking loops (phase-lock loops) and it is used to stabilize the beat note of the on-line and off-line channels with respect to the master laser frequency. The offsets read 350 MHz with tunable range of 150 MHz and fixed 10 GHz for ON- and OFF-line signals, respectively.

Keywords: frequency stabilization, wavelength stabilization, laser locking, frequency locking, lidar, CO_2 detection

1. INTRODUCTION

Nowadays, the society agrees that the long-lived atmospheric species, with carbon dioxide (CO_2) among the others, are the main driver of the climatic changes we are starting to suffer[1]. Therefore, more accurate knowledge about the sources and sinks of these gases is of high interest. Most of the knowledge comes from the in-situ measurements (ground), airborne, and spaceborne data. However, the global approach does not really exist[2]. In the recent years the advances in technologies led to development of active methods for gas sensing based on light detection and ranging (lidar) which can be used from space, like MERLIN mission, which is in preparation[3]. The most common differential absorption lidar (DIAL) and integrated path differential absorption lidar (IPDA) are using two wavelengths for detection[3-5]. First one, online wavelength (ON) is close to the maximum of absorption whereas the offline wavelength (OFF) is set in a vicinity of the absorption line, where the gas absorption is negligible[5]. The laser sources used in such devices are usually high peak power solid-state lasers[6] or hybrid master-oscillator power-amplifier (MOPA) lasers where the master-oscillator is a semiconductor laser, while power-amplifier is an optical fiber-based amplifier[4]. However, they are bulky with low wall plug efficiency which is a main concern for the space-born applications. Therefore, monolithically integrated MOPA were also used as a proof-of-concept in the random modulated continuous wave (RM-CW) IPDA lidar[7, 8]. These devices show high output power together with excellent beam quality, and high wall plug efficiency[9, 10].

Light sources used in DIAL or IPDA require a frequency stabilization since the ON and OFF-lines instability leads to increase of the errors in the estimation of the CO_2 concentrations. Different techniques were proposed to stabilize semiconductor lasers. Starting from locking to the wavelength meter with PID loop changing the current of the laser[11] leading to an Allan deviation of 10^{-10} in 1 s time interval and 10^{-12} for 1000 s time interval using the external cavity diode laser (ECDL). Another approach is to use a Fabry-Perot etalon (FPE), an optical resonator which transmits light at frequencies that are integer multiples of its free spectral range. Using ECDL, a relative stability of $1,5 \cdot 10^{-11}$ was achieved for integration time longer than 15 min[12] or $2.6 \cdot 10^{-10}$ in 0.16 s integration time[13]. Although this method is easy to implement, it shows some drawbacks ie. the amplitude modulation (AM) couples in the error function, the AM cannot be distinguished from the frequency modulation (FM) and it is limited by the response time of the Fabry–Perot cavity[14].

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Therefore, another technique using FPE, but removing the aforementioned limitations was proposed, and it was called a Pound-Drever-Hall technique[14], which gained very high popularity. A laser's frequency is measured with a Fabry–Perot cavity, and this measurement is fed back to the laser to suppress frequency fluctuations. Since this method is based on the derivative of the reflection coefficient it is easy and straightforward to decouple the frequency measurement from the laser's intensity and to know immediately at which side of the resonance the laser is on. An additional benefit of this method is that the system is not limited by the response time of the Fabry–Perot cavity. In the original work this method delivered better than 100 Hz stability, and the modern implementations[15] can lead to sub-Hz stability as $2\cdot10^{-15}$. Next technique is the direct stabilization to the absorption line of the gaseous species of interest. In the simplest form the light is sent to the gas cell and the absorption is measured with a photodiode (PD) and applying modulation and lock-in detection, the wavelength of the laser is controlled by the feedback electronics to keep absorption at constant level or at a maximum[16]. It is the most accurate method for wavelength locking since the absorption lines are well known and stable, providing absolute stability. Other technique that allows the locking of a laser to a controllable wavelength, by means of a radio frequency (RF) reference signal, using a previously locked laser as reference while keeping the wavelength stability of this reference laser is the optical phase-lock loop (OPLL). This method allows having a laser locked to an arbitrary wavelength with the best possible accuracy using for example a gas cell for wavelength stabilization of the reference laser. Then, by changing the RF reference signal frequency, the stabilized wavelength can be tuned to an arbitrary value[17]. The relative stability can be achieved even down to 10^{-15}.

In this paper we present a frequency stabilization unit (FSU) with a master laser (ML) locked to the CO_2 absorption line and two slave lasers offset by means of OPLLs, for stabilizing an on-line laser (ONL) shifted about 350 MHz with a tuning range of 150 MHz and an off-line laser (OFL) shifted about 10 GHz from the ML wavelength. This device can be used for stabilizing monolithically integrated MOPAs. In the section 2 we give an overview of the design and manufacturing, followed with a description of the experimental setup and methods. Next, we present the results and discuss them in the section 3 with summary and conclusions in the section 4.

2. DESIGN AND EXPERIMENTAL

The scheme of the system is shown in the Figure 1 left, the customized electronics from TEM Messtechnik used for laser locking is presented in the top right, and the realization of the FSU in the bottom right with elements indicated by capital letters. The system is all-fiber design with no free space parts except the CO_2 cell, although the cell is fiber-coupled. The CO_2 cell is a 150 mm long single pass spectroscopic reference cell without temperature stabilization (B). The wavelength used for stabilization is 1572.017 nm where relatively strong CO_2 line exists. The lasers used in this approach are distributed feedback (DFB) lasers emitting at 1572.06 nm from Agilecom. The devices are assembled in the butterfly package with maximum output power of 12 dBm coming out of polarization maintaining (PM) optical fiber (A) and TEC elements which allows temperature control. After each laser, an optical isolator is used to avoid reflections which are deteriorating the locking efficiency. 80% of the light from ML is sent through the absorption cell and it is detected on a large area photodiode in the final design (we have tested detectors with area of 1.3 mm^2, 3 mm^2, and 19 mm^2. The size of the photodiode is quite important to assure homogenous coverage of the PD´s area by the beam full of speckles, which can deteriorate the detection, hence stabilization, if the PD area is too small. In this implementation a top-of-fringe stabilization is applied, which uses a modulation technique and phase-synchronous detection. In brief, the laser frequency is modulated, hence the transmitted laser beam is detected by a photodiode and passed through the feedback loop, which makes detection of the beat note, producing an error signal, proportional to the deviation from the CO_2 line center. The rest of the light from ML is divided in two parts by 50/50 coupler and is injected to the OPLL for ON and OFF-line detection (F). The RF components which were used are all commercial of-the-shelf components like amplifiers, mixers (E), RF signal generators, ON-line (C) and OFF-line (D) photodiodes. The signals are sent to the customized version of the LaseLock 4 channel, which is sending the control signal to the LD and TECs (G). The fast and slow PID control loops were used in this application. Part of the light is used for monitoring of the lock via external means (I). Since this FSU should be used for stabilizing monolithically integrated MOPAs, there is also an input which allows for such connection (H). The advantage of this design is following, after minimizing the frequency drift of ML, both ONL and OFL should follow the stability of the ML considering the quality of the RF electronics used in PLLs, ie. low noise, flat response.

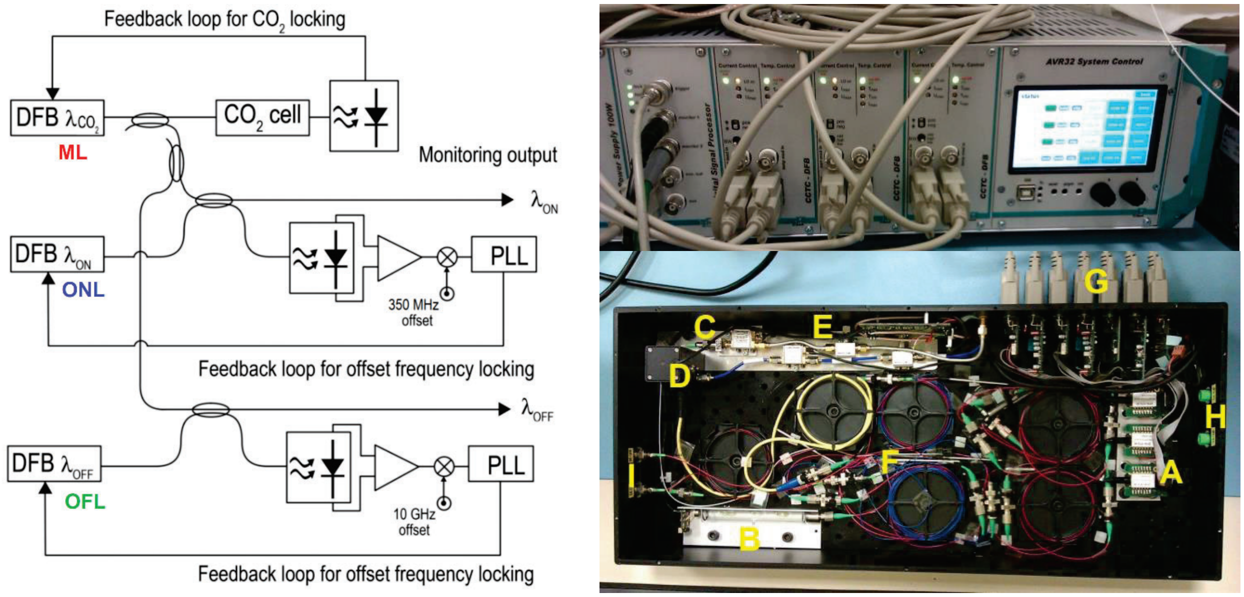

Figure 1. Scheme of the frequency stabilized unit (left), locking electronics LaseLock 4 channel from TEM Messtechnik (top right) indicating three locked lasers, and FSU with following components: A – three built-in DFB lasers, B – CO_2 cell, C – ON-line photodiode, D – OFF-line photodiode, E – RF section (amplifiers, mixers, and signal generator inputs), F – optical section (optical fibers, couplers, and isolators), G – LD and TEC inputs, lock-in outputs, H – input for MOPAs, I – ON- and OFF-line monitor output.

The experimental setup is shown in Figure 2. It consists of FSU and a self-referenced optical frequency comb (OFC) (Menlo systems FC1500 Optical Frequency Synthesizer) with absolute long-term optical frequency stability of about 800 Hz, used for frequency monitoring.

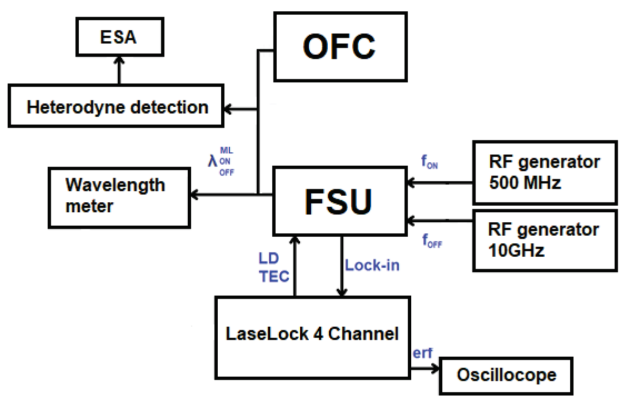

Figure 2. Scheme of the measurement setup for frequency stabilization.

First, the ML was locked to the CO_2 line and then the beat note was produced between ML and OFC which was measured on the electrical spectrum analyzer (ESA). Then the ONL was locked to ML and again the beat note was produced this time between ONL and OFC. Finally, in the same manner the beat note between OFL and OFC was produced. The stability of the lasers was monitored during the short periods of time up to 30 min and long-term overnight measurements, resulting in sampling during about 10 h. The short time monitoring was used to fine tune the PID loops to increase the stability of the locked lasers. One of the important optimization steps was the normalization of the error function. Since we are using a single pass cell the absorption is very weak (see Figure 3) so the slopes above the absorption line and at the absorption lines have very similar values. To overcome this problem, a constant offset has been introduced to bring the error function to zero level (red arrow in Figure 3). The point is that with changing the amount of light at the photodiode the slope is changing thus moving the error function up or down thus disturbing stability. This is because the signal is not normalized. Therefore, the normalization of the signals (i.e. measuring of the average power and dividing the input signal over averaged power) was introduced which brought the error function always to 0 as indicated by the blue arrow on Figure 3. In the next section, the influence of this optimization will be given in more details.

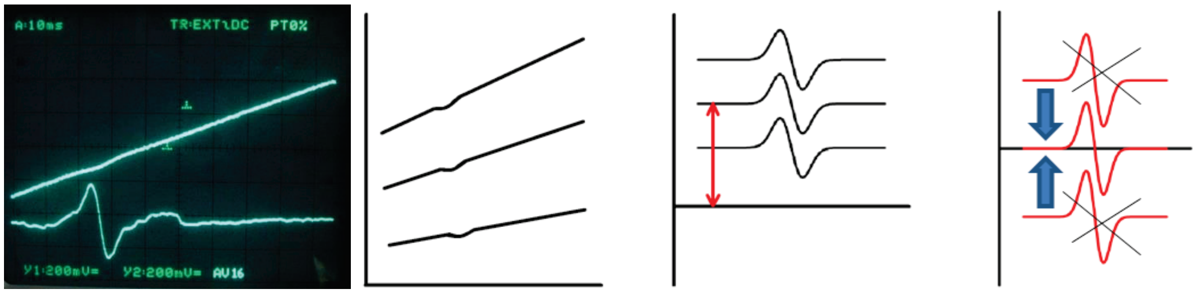

Figure 3. From the left: oscilloscope image of the L-I curve with absorption and corresponding error function; L-I curves with different light amount on photodiode; corresponding not normalized error functions and offset error functions.

3. RESULTS AND DISCUSSION

After locking the ML laser to the CO_2 line, the beat note between the ML and OFC was measured in the short-term measurements up to 1000 s, which were used to fine tune the FSU. Optimization of the setup led to 67 kHz stability obtained from the Allan plots. After optimization, the long-term measurements were performed. Figure 4 (left) shows the raw data for not normalized signals. It can be clearly seen that after 15000 seconds the frequency oscillates around a value of about 1147 MHz. We assign these oscillations to the temperature change in the lab by means of air conditioning since the CO_2 cell is not temperature stabilized. Lack of normalization is introducing larger instabilities, and this is very important factor since the area of the detector is only 3 mm^2, which is probably too small to provide homogeneous detection of the beam with speckles. After raw data analysis we have found that the stability was of 95 kHz in the 10 s as can be seen in the Allan variance plot in the Figure 4 (right), which were higher than the short-term values. PSD analysis of the signals revealed that in case of the long-time measurement there is some flicker noise detected whereas during the short time measurement only the white noise is present.

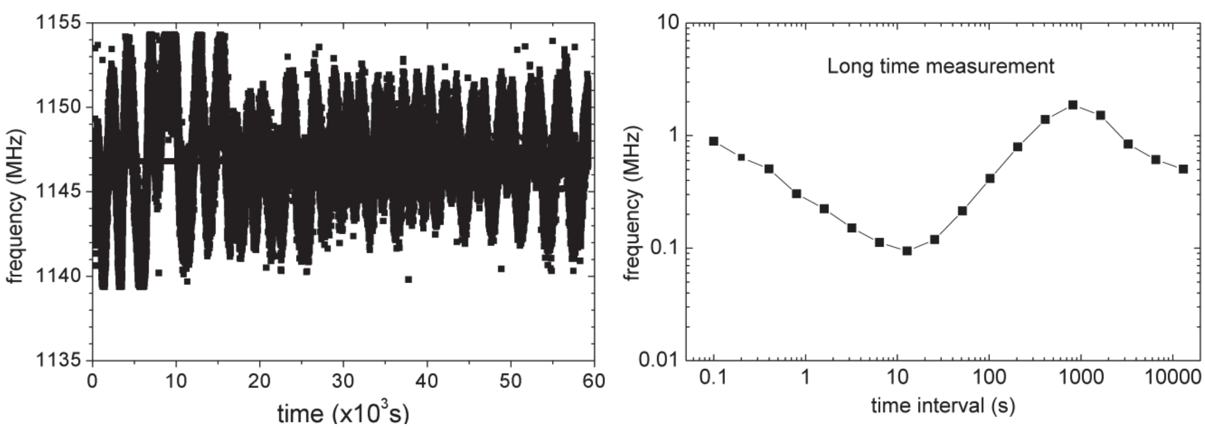

Figure 4. Stabilization of the ML laser locked to the CO_2 line: raw data (left) and Allan deviation (right). Not normalized signals and 3 mm^2 PD area.

After exchange of the 3 mm^2 photodiode to the 19 mm^2 one and the normalization of the signals again the long-term measurements were performed, and the raw data are shown in the Figure 5 (left). This time, the oscillations due to the air conditioning in the lab are very weak, although still visible. The amplitude of these oscillations is of about 2 MHz. However, the short-term measurements reveals that the RMS value is less than 300 kHz. This time the PSD analysis shows that the ML exhibits white noise in both, short- and long-term measurements. Allan deviation of the long-term overnight measurements is shown in Figure 5 (right). The stabilization is of about 18 kHz at the interval of 23 s and stays around 20 kHz up to 50 s. This confirms that increasing the size of the photodiode improved the homogenization of the speckle pattern at the photodiode area, and the normalization of the error function removed the ambiguities in the signal detection.

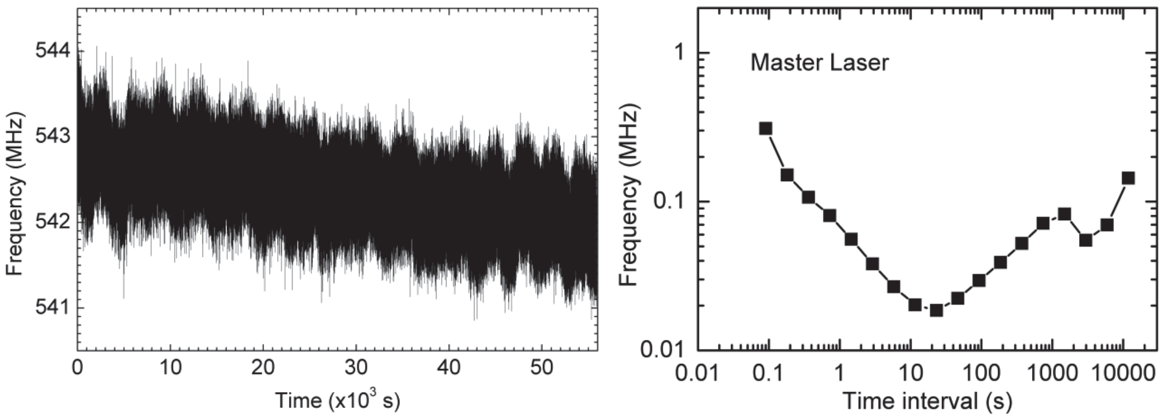

Figure 5. Stabilization of the ML laser locked to the CO_2 line: raw data (left) and Allan deviation (right). Normalized signals and 19 mm^2 PD area.

Figure 6 shows Allan deviation of the ONL and OFL locked to the ML and referenced to the OFC. These measurements were performed during the lidar measurement campaign in February with the rapid changes of the atmospheric conditions, which strongly influenced the stability since the CO_2 cell was not temperature stabilized. Therefore, Allan deviation reads 147 kHz in 1.5 s time interval and 53 kHz in 3 s time interval for ONL and OFL, respectively. The PSD analysis shows a white noise in case of short-term stability. However, it changes to flicker noise for ONL during the overnight measurement.

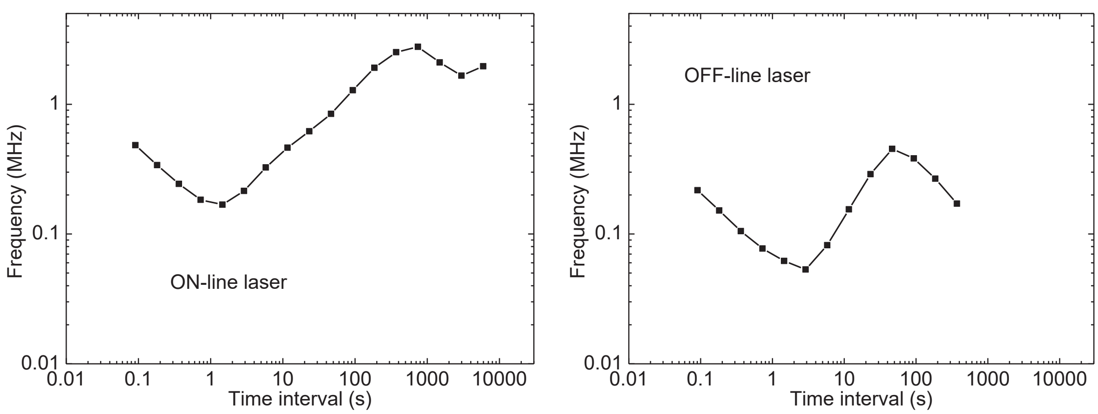

Figure 6. Stabilization of the ONL (left) and the OFL (right) both locked to the master laser.

4. SUMMARY AND CONCLUSIONS

We presented a frequency stabilization unit for laser stabilization for IPDA lidars. Three DFB lasers were used: master laser locked to the CO_2 line and two OPLL offset lasers for measurement of the ON- and OFF-lines. The stabilization of the lasers was measured by means of the optical frequency comb. The measurements of the master laser were performed in the laboratory conditions, thus allowing for optimization of the locking loop, including the PID control, signal normalization, and PD sizes. The measurements of the ONL and OFL were performed in the uncontrolled weather conditions which strongly influenced the results since the CO_2 cell had no temperature stabilization. Therefore, the optimization of the ONL and OFL loops was not possible due to the constraint of the measurement campaign. The direct improvement of the system will be the introduction of the temperature stabilized CO_2 cell in the next upgrade of FSU.

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