Cost-effective Fully Fiber-based DIAL Utilizing Wavelength Modulation for Laser Locking

Nikita Kikilich[(a)], Erwan Negre[(b)], Kim Kalmankoski[(a)], Aarni Akkala[(a)], Michael Todt[(b)], Ewan O'Connor[(b)] and Juha Toivonen[(a)]

[(a)] Photonics Laboratory, Physics Unit, Tampere University, Tampere, Finland
[(b)] Finnish Meteorological Institute Helsinki, Finland
e-mail: nikita.kikilich@tuni.fi

Abstract: Recent advancements in Differential Absorption Lidar (DIAL) technology have led to the adoption of fully fiber-optic DIAL systems, offering superior robustness, reduced alignment sensitivity, and enhanced portability compared to traditional bulk-optic systems. These systems excel in environmental monitoring, atmospheric research, and industrial safety. Central to their performance is the stabilization of the laser's frequency against environmental perturbations, crucial for pinpointing gas absorption peaks. This study introduces Wavelength Modulation Spectroscopy (WMS) for frequency stabilization in fully fiber-optic DIAL system, highlighting its simplicity and cost-effectiveness over conventional laser frequency-locking methods for applications where extreme precision is not mandatory. We present a compact, portable fiber-optic DIAL system designed for measuring CO_2 concentrations with up to 10 ppm accuracy. The system ensuring laser wavelength stability below 140 MHz over several days, which contributes to the CO_2 maximum absolute error detection of 0.5 ppm at narrow absorption peaks (half-width ~5 GHz).

1. Introduction

Recent technological advancements in the field of Differential Absorption Lidar (DIAL) systems have led to significant improvements in the accuracy and reliability of gas measurements, critical for environmental monitoring, atmospheric research, and industrial safety applications. Traditional systems often relied on bulk-optic components, which, while effective, posed limitations in terms of robustness and ease of deployment. Fully fiber-optic systems replace traditional free space optics either partially or completely with fiber optics, leveraging the inherent benefits of optical fibers such as superior robustness and reduced sensitivity to alignment, thereby enhancing the portability of the instrumentation [1]. Fully fiber-optic DIAL systems operate on the principle of differential absorption, utilizing two distinct laser wavelengths — referred to as the 'ON' and 'OFF' wavelengths. The ON wavelength is precisely tuned to an absorption line of the target gas, while the OFF wavelength, close in frequency but outside the absorption line, serves as a reference to account for non-absorptive losses.

The stability of the ON wavelength is of paramount importance in DIAL systems. Any deviation in this wavelength can lead to significant errors in measuring the absorption characteristics of the gas, as it directly affects the system's ability to accurately identify gas absorption peaks. The Frequency Modulation Spectroscopy (FMS) method is commonly utilized in fully fiber DIAL applications [2, 3]. The accuracy of determining the gas content in these systems is less than 1 ppm, but they are difficult to implement and their parts are quite expensive.

In this study, we implement the WMS technique for stabilizing the ON-wavelength in fully fiber-optic DIAL system. WMS technique is simpler to deploy and more cost-effective compared to FMS in the systems where state of art accuracy is not needed. By implementing a low-frequency lock-in amplifier and using a reference gas cell, the system can achieve a stable measurement of gas concentrations with an accuracy of a few ppm.

2. Experimental setup and method

The DIAL principles involve emitting laser pulses at two distinct wavelengths 'ON' and 'OFF'. These laser pulses are directed into the atmosphere where they scatter off particles. The scattered light is then collected and coherently detected using a receiver. The intensity of the returned light at each wavelength is measured and compared — the difference in these intensities is used to calculate the concentration of the target gas in the path of the laser beam Figure 1.

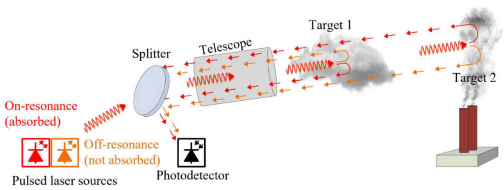

Figure 1. Basic principles of the DIAL

The core of the DIAL system consists of two high quality narrow band seed lasers, which are alternately switched using a fast optical switcher. These lasers are then amplified by a three-stage erbium-ytterbium amplifier. The output amplification stages based on large mode area optical fiber to achieve a higher output power. The whole optical path in the DIAL system is based on single-mode polarization maintaining fibers to maintain the same light path and coherence throughout the transmission and detection processes.

The ON-line laser's wavelength is carefully stabilized using a WMS technique. In this setup, the light from the ON-line laser diode is modulated by a low-amplitude (0.1 mA) sinusoidal signal and travels through a system of optical splitters before passing through a multi-pass gas cell. Here, the light undergoes amplitude modulation, which is then detected by a high-speed photodetector. The resultant signal is demodulated using a lock-in amplifier, producing an error signal. This error signal is used by a digital system to adjust the main current of the ON-line seed laser, thereby maintaining the laser wavelength at the peak absorption of carbon dioxide.

For laser stabilization, the first harmonic (1f) of the modulation frequency is used due to its direct representation of the first derivative of the absorption profile. This derivative peaks precisely at the center of the absorption line, providing a sensitive zero-crossing point that is optimal for detecting changes in gas concentration while being relatively immune to fluctuations in laser intensity and other non-absorptive losses. However, a notable challenge with the 1f signal is its susceptibility to residual intensity modulation (RIM), which can introduce an offset and potentially affect measurement accuracy. RIM results from the modulation of the laser intensity concomitant with wavelength modulation. In our setup, we have compensated for RIM by implementing precise phase adjustments in the lock-in amplifier [4].

The stabilization system of the central wavelength, include a main PID (Proportional, Integral, Derivative) controller for the first derivative error signal of absorption, a PID current controller, and a PID controller of the thermoelectric cooler Figure 2. These controllers work in concert to maintain precise control over the laser’s wavelength. Balancing the interactions between these controllers poses a challenge during system tuning.

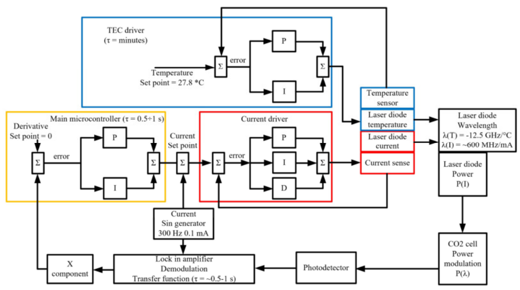

Figure 2. Functional block diagram of the stabilization system

The stability of the 'ON' central wavelength was evaluated over a two-day using two high-precision spectral analysis devices, the Bristol 771B Laser Spectrum Analyzer and the Thorlabs OSA207C. These instruments, which differ in their inherent noise levels and drift characteristics, allowed for an accurate assessment of wavelength stability. The maximum deviation observed from peak to peak, with a sampling frequency of about 0.5-1 seconds, was 140 MHz Figure 3.

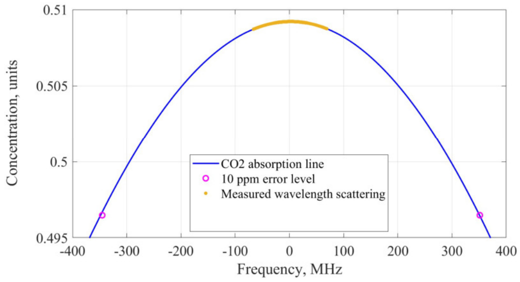

Figure 3. Measured wavelength scattering

This deviation translates to a maximum absolute error in the detection of carbon dioxide concentrations at the selected absorption peak of no more than 0.5 ppm. By increasing average time, this error can be significantly reduced, enhancing the reliability of the gas concentration measurements Figure 4.

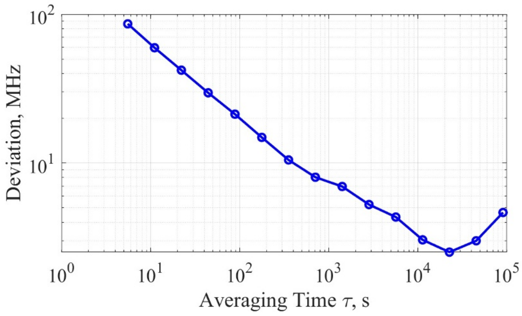

Figure 4. Allan's Variations

3. Conclusion

The stabilization of the central wavelength at the absorption peak of carbon dioxide has been successfully implemented in a fully fiber-optic DIAL lidar system using Wavelength Modulation Spectroscopy technique. The stability achieved with this setup, assessed over several days, showed peak-to-peak deviations not exceeding 140 MHz. This level of stability corresponds to a maximum absolute error in the detection of carbon dioxide concentrations of no more than 0.5 ppm. These results underscore the effectiveness of WMS technique in maintaining precise control over the laser wavelength, crucial for the accurate and reliable measurement of gas concentrations in atmospheric research and environmental monitoring. This achievement not only demonstrates the capability of fully fiber-optic systems in high-precision applications but also highlights the potential of WMS technique as a cost-effective and efficient method for enhancing the performance of DIAL systems.

4. References

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