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William Patiño-Rosas, Nicolas Cézard. Dual comb integrated path DIAL lidar for gas monitoring: design and experimental implementation. SPIE Remote Sensing 2023, Sep 2023, Amsterdam, Netherlands. pp.127300J, 10.1117/12.2679438 . hal-04269101

HAL Id: hal-04269101

<https://hal.science/hal-04269101>

Submitted on 3 Nov 2023

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Dual comb integrated path DIAL lidar for gas monitoring: design and experimental implementation

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ABSTRACT

We report on the design of a dual comb-based fiber lidar system for integrated path differential absorption (IPDA) measurements. The system relies on the dual comb spectroscopy (DCS) technique using the lidar return from a hard target. Frequency combs are generated by means of electro-optic modulators. The working principle and architecture of the dual comb lidar are detailed. We present a proof of concept of the lidar system, and demonstrate the measurement of a water-vapor absorption line, utilizing a diffuse (non-cooperative) hard target located 200 meters away from the emitter.

Keywords: comb, lidar, speckle, water vapor, greenhouse gases

1. INTRODUCTION

In a context of climate change, remote gas sensing plays a significant role in environmental studies and air quality monitoring. In that scenario, differential absorption lidar technology (DIAL) has proven to be a robust remote sensing technique for studying atmospheric trace gases. In parallel, frequency comb (FC) based systems have gained considerable attention in the field of remote sensing of atmospheric trace gases due to their ability to probe gas absorption features using multiple evenly-spaced wavelengths.

This paper provides a brief overview of the principles behind gas concentration measurements using a dual comb-based system. Additionally, we highlight the challenges associated with utilizing diffuse targets in this context. We then discuss the architecture and design of a dual comb lidar system that operates with non-cooperative targets, comparing it with other architectures described in existing literature. Lastly, we outline the signal processing approach using sample signals from a target located at a distance of 200 meters.

2. INTEGRATED PATH DIFFERENTIAL ABSORPTION LIDARS

The working principle of DIAL involves emitting two laser pulses with slightly different wavelengths into the atmosphere. By analyzing the backscattered signals from either a solid surface (integrated measurement) or atmospheric particles (range-resolved measurement), it is possible to estimate the gas concentration within the atmospheric column. When a solid hard target, such as the Earth's surface, is used for the measurement, the technique is commonly referred to as integrated path differential absorption (IPDA).

In numerous applications, it has been demonstrated that employing more than two wavelengths can be beneficial for the gas measurements. Conducting multiple differential absorption measurements at several wavelengths can reduce systematic errors in gas concentration measurements and offer supplementary insights into the spatial distribution of the gas [1]. To generate multiple wavelengths, the laser frequency is usually swept across a discrete set of states. Furthermore, for airborne or spaceborne applications, it is vital that the various wavelengths are emitted very closely in time, in order to probe nearly identical atmospheric columns and interact with the same scattering surface [2].

On the other hand, the use of frequency combs (FC) also enables the probing of absorption features of the gas of interest at multiple wavelengths. By using FC-based systems, it becomes possible to overcome some of the above-mentioned

limitations of traditional differential absorption (DIAL) lidar techniques, as multiple evenly spaced frequencies are sent simultaneously in the same laser beam. The gas concentration measurement using FC is based on the dual comb spectroscopy (DCS) technique [3]. It can be used to probe multiple frequencies of a single absorption line, but if the spectral range of the FCs covers absorption features of different gases, it is also feasible to conduct multi-species gas monitoring using the same system.

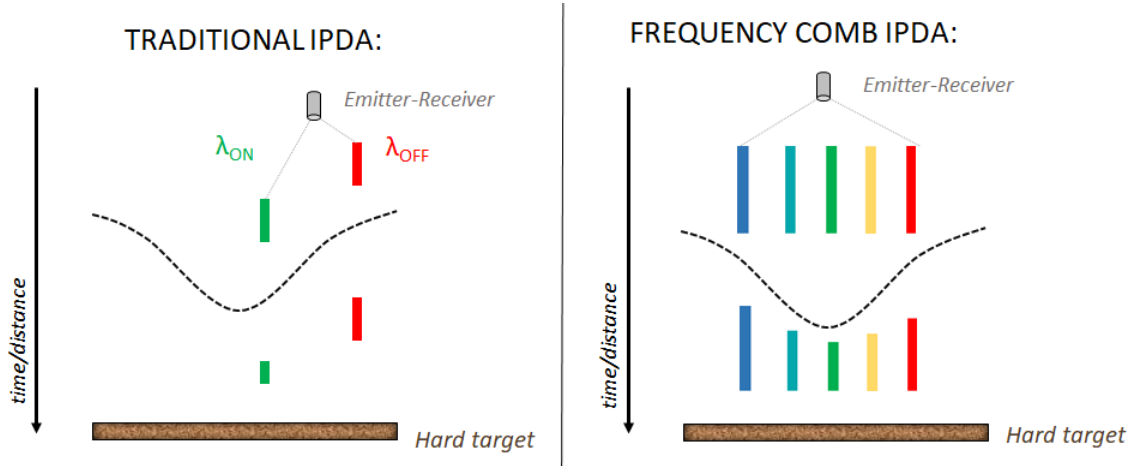


Figure 1. Schematic representation of a traditional (sequential) IPDA lidar compared to the concept of a frequency comb-based lidar. In a traditional lidar, the different wavelengths are emitted one after the other. Frequency combs allow probing the absorption features at several, evenly spaced, and simultaneous wavelengths.

3. DUAL COMB LIDAR ARCHITECTURE

Demonstrations of DCS have increased significantly in recent years, spanning from the ultraviolet (UV) domain to the mid-infrared. Various technologies have been used to generate the interfering frequency combs, such as mode-lock lasers, quantum cascade lasers, ring-cavity lasers, and electro-optic modulators. The latter, in particular, offer high tunability in terms of line-spacing and power distribution, making them well suited for lidar applications [4-6].

Two main architectures can be identified in the DCS experiments [3]: the symmetric configuration, where both frequency combs (FC) are employed to probe the sample, and the asymmetric configuration, where one FC is used to probe the sample while the other functions as a local oscillator (LO). The asymmetric configuration is more suitable for lidar measurements due to the LO's ability to amplify the lidar signal, which is importantly attenuated.

Recent studies have demonstrated open-path dual comb spectroscopy for analyzing atmospheric gases of interest to infer fluxes and quantify emissions [7]. Nevertheless, these works utilized retro-reflectors positioned at the end of the line of sight instead of natural (non-cooperative) hard targets, leading to high signal-to-noise ratio (SNR) signals without speckle. However, when employing diffuse hard targets, the optical power being distributed among the multiple comb lines restricts the feasibility of conducting gas measurements with a large number of comb lines.

Our approach differs from these studies. If the lidar is installed on a moving platform (plane or satellite), the use of retroreflectors is not possible, and scattering effects from diffuse targets cannot be neglected. When dealing with rough scattering targets, DCS signals are expected to exhibit a low SNR and be influenced by speckle [8]. However, by limiting the number of comb lines to a very small number (less than 10), we can conduct DCS and estimate the integrated path mean concentration.

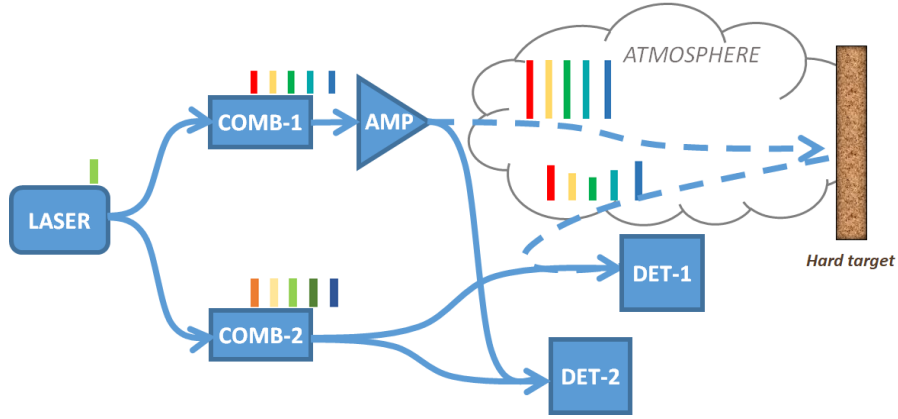


Figure 2. Schematic representation of a dual comb IPDA lidar. One comb is employed to probe the atmospheric column, while the other acts as a local oscillator to amplify the lidar return. Additionally, a reference dual comb signal is generated with the aim of normalizing the atmospheric measurement.

3. EXPERIMENTAL IMPLEMENTATION

We have developed a prototype of dual comb IPDA lidar, following the architecture outlined in Fig. 1. Two electro-optic combs (EOCs) were generated using two phase modulators driven by a pair of RF signal generators. Comb-1 underwent a frequency shift of 40 MHz through an acousto-optic modulator (AOM) working in pulse mode. This allowed us to generate 1 μ s laser pulses at a repetition rate of 250 kHz, resulting in a duty cycle of 25%. To amplify the pulses, we used an Erbium-doped fiber amplifier (EDFA). It is essential to maintain a high duty cycle since the EDFA is designed for continuous-wave operation. At the output of the amplifier, we obtained quasi-square pulses of 1 μ J. To generate a reference signal, 10% of the amplifier pulses were collected by a fiber coupler and fed into a second photodetector for normalization of the DCS measurement. The laser wavelength was fixed at 1530.24 nm, targeting an absorption feature of water vapor.

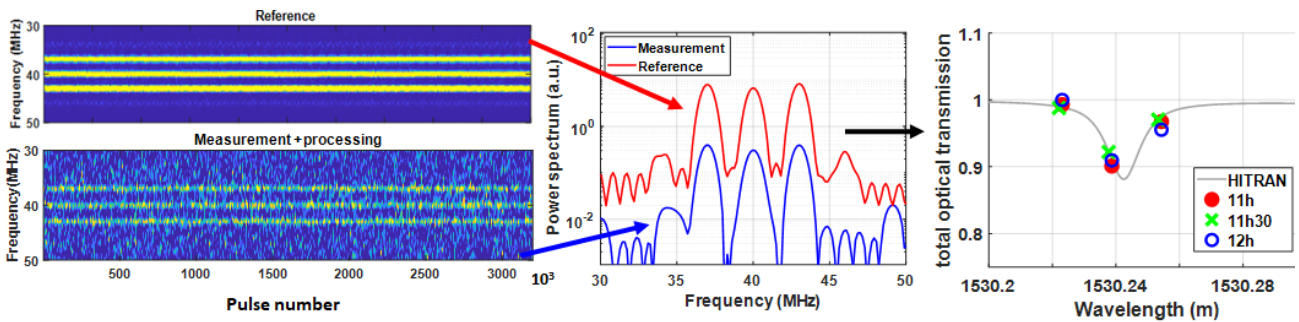


Figure 3. (Left) Spectrogram of the reference and lidar dual comb signals. (Center) Averaged power spectra for the atmospheric measurement and the reference dual comb signals. (Right)

Due to the relatively low pulse energy and high repetition rate, our system suffered from poor signal to noise ratio (SNR) and low ambiguity range (600m). For the initial proof of concept, the amplified pulse was directed towards a hard target located 200m away from the emitter. The signal processing involved locating the laser echo, computing its power spectrum, and removing the noise level. To improve the SNR, a significant number of signals were averaged. In Figure 3 (left), the spectrogram of the reference and measurement dual comb signals is presented after processing, where groups of 10^3 spectra were averaged. To maximize the SNR per comb line, only 3 comb lines were produced.

A total of 3.125×10^6 spectra were averaged, and the resulting averaged power spectra are shown in Figure 3 (center). The comb structure is centered at 40MHz with a line-spacing of 3MHz. By calculating the power ratio between the measurement RF comb and the reference RF comb, the transmission profile of the water vapor column at the comb wavelengths can be obtained (see Figure 3-right). This initial proof-of-concept allowed us to observe an absorption signature of approximately 10%, indicating the presence of water vapor. Finally, the measured transmission profiles were fitted to the theoretical absorption feature computed by means of the HITRAN-2023 database, using the temperature and relative humidity provided by the local weather service ($T=12^\circ\text{C}$, $\text{RH}=65\%$). Three different measurements conducted every 30 minutes are presented in Figure 3 (right). The measured profiles exhibit very good agreement with the theoretical transmission profile. Future work aims to evaluate the performance of the measurement system and explore its capability to probe longer atmospheric columns.

4. CONCLUSION & PERSPECTIVES

We have presented the design and proof of concept of a dual comb-based fiber IPDA lidar. The system utilizes the dual comb spectroscopy (DCS) technique with the lidar echo obtained from a hard target located 200m away from the lidar. The frequency combs were generated through electro-optic phase modulation of a continuous wave laser diode. Future perspectives for this work include increasing the laser power by using pulsed EDFA, to probe longer atmospheric columns and expanding the number of comb lines. Once the performance of the lidar prototype is evaluated, it might be exploitable in airborne applications.

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