

Frequency-Comb-Based LiDAR Architecture for Greenhouse Gas Sensing

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Abstract—This work presents a numerical analysis of two LiDAR architectures for greenhouse gas sensing, with a focus on the detection of CO_2 and CH_4 . The simulations were performed using the Lumerical Interconnect software. The first architecture evaluates a conventional IPDA LiDAR system, in which the laser wavelength is switched between spectral regions inside and outside the gas absorption bands. The second architecture proposes the use of an optical frequency comb, enabling the simultaneous investigation of different wavelengths associated with the spectral signatures of the gases. The results indicate that both topologies allow the effects of gas absorption on the received signal to be identified. Furthermore, in the frequency-comb-based architecture, cross-correlation analysis enabled the simultaneous differentiation between CH_4 and CO_2 , demonstrating the potential of the proposed approach for multispectral LiDAR systems applied to environmental monitoring.

Keywords—Frequency comb, greenhouse gas sensing, IPDA LiDAR, multispectral LiDAR.

I. INTRODUCTION

Greenhouse gases (GHGs), such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), play a central role in the Earth's radiative balance by absorbing and re-emitting infrared radiation in the atmosphere. However, the continued growth of anthropogenic emissions has intensified global warming, reinforcing the need for accurate monitoring of these species [1]. From a geophysical perspective, the atmospheric distribution of GHGs is highly variable in both space and time, as it is influenced by meteorological conditions, atmospheric transport, temperature gradients, pressure fields, and surface characteristics. These factors directly affect gas dispersion and concentration patterns, making it challenging to obtain reliable measurements with high spatial resolution and sufficient temporal representativeness [1].

In this context, remote sensing techniques have become well established as fundamental tools for the detection and quantification of atmospheric gases, particularly those based

on Light Detection and Ranging (LiDAR) [2], [3], [4]. This technology relies on the emission of laser radiation and the analysis of the backscattered signal to retrieve information about the propagation medium, thereby enabling the remote characterization of atmospheric composition. In geophysical applications, LiDAR offers important advantages, including high spatial resolution, real-time operation capability, and non-contact measurement, which make it particularly suitable for environmental monitoring and for the investigation of atmospheric processes and dynamics [2], [3].

Among the LiDAR techniques applied to gas detection, Differential Absorption LiDAR (DIAL) is particularly relevant [2], [5]. This method employs two distinct wavelengths: one tuned to an absorption line of the target gas and another positioned outside this absorption feature. The difference in signal attenuation between these wavelengths makes it possible to estimate gas concentration along the optical path and to retrieve range-resolved concentration profiles. This approach is especially useful for local and regional measurements, where spatially resolved information is essential for analyzing gas distribution in the atmosphere [2], [5].

Another widely used technique is Integrated Path Differential Absorption (IPDA), which is also based on differential absorption but provides the path-integrated concentration along the laser beam trajectory rather than a range-resolved profile [6], [7], [8]. Unlike DIAL, IPDA does not reconstruct concentration as a function of distance, but it is well suited to large-scale applications, such as airborne and satellite-based measurements for greenhouse gas monitoring over extended areas [6], [7].

Recent advances in LiDAR systems have incorporated modulation schemes, digital signal processing, and high-sensitivity detectors to improve signal discrimination, enhance the signal-to-noise ratio, and increase measurement accuracy [3], [9]. These developments have expanded the applicability of optical gas sensing systems, enabling low-concentration gas detection and operation in more complex scenarios, including multi-species sensing and dynamic environments [9].

The effectiveness of a remote gas sensing system depends not only on suitable absorption lines, but also on the adopted modulation and signal processing strategy. In this sense, random modulation and correlation-based processing can improve return-signal discrimination and support both gas identification and the estimation of the absorbing region location [9].

Motivated by this perspective, this work investigates two optical sensing configurations for CH_4 and CO_2 detection following an IPDA approach, based on the attenuation accu-

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mulated along the complete optical path. The first architecture corresponds to a conventional IPDA LiDAR system with wavelength switching across the gas absorption bands, whereas the second proposes a numerical optical frequency-comb-based approach for simultaneous multispectral analysis.

The main contribution of this work is the numerical comparison of two LiDAR-based architectures for CH₄ and CO₂ sensing, using random modulation and cross-correlation for gas identification and optical path delay estimation.

This paper is organized as follows. Section II presents the adopted methodology, including the system model, the gas absorption lines, the proposed architecture, and the signal processing procedures, such as cross-correlation calculation. Section III discusses the obtained results, including the spectral analysis, power levels, and time-domain signals, with emphasis on the simultaneous sensing of different gases. Finally, Section IV summarizes the main conclusions of this work.

II. METHODOLOGY

A. Gas Absorption

In the context of spectroscopy, each gaseous species exhibits absorption bands or lines at specific wavelengths. This property allows the interaction between the optical beam and the gaseous medium to produce spectral signatures that can be exploited for species identification and remote sensing. Figure 1 presents four configurations: no absorption, absorption in the simultaneous presence of CH₄ and CO₂, absorption due only to CO₂, and absorption due only to CH₄. Figure 1a illustrates the absorption lines of CO₂ and CH₄, adapted from the spectral data reported in [10]. In turn, Figure 1b presents synthetic absorption lines representing, in one case, an environment containing only CO₂ and, in another, an environment containing only CH₄. Based on these absorption lines, simulations were carried out in Ansys Lumerical for each of the configurations considered.

B. Cross-correlation

To identify the presence of a gas in a given environment and estimate the location of the region where absorption occurs, random modulation is applied to the transmitted signal, while cross-correlation is calculated between the transmitted and received signals. This approach enhances the detection of the returned signal by quantifying the similarity between the emitted and detected waveforms, as discussed in [11]. The discrete-time cross-correlation between the signals $x[n]$ and $y[n]$ is expressed as

$$R_{xy}[\ell] = \sum_{n=-\infty}^{\infty} x[n] y[n + \ell], \quad (1)$$

C. Proposed Analysis

Figure 2 presents the two schematics investigated in this study, both implemented in Lumerical Interconnect [12]. Figure 2a shows the first configuration, in which the optical carrier is modulated at two distinct wavelengths at different time instants. For this purpose, a tunable laser is employed.

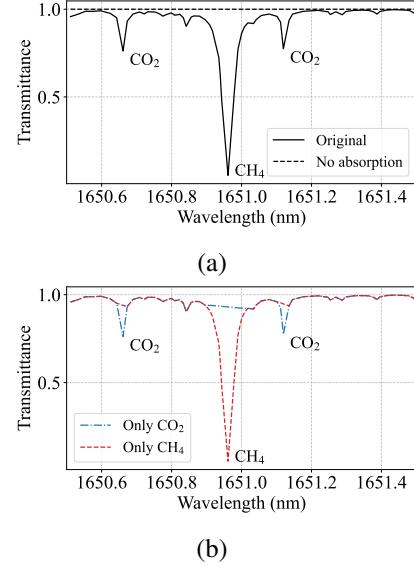


Fig. 1: Gas absorption profiles considered in the simulations: (a) CH₄ and CO₂ transmittance spectra with the no-absorption reference [10]; (b) synthetic absorption responses for environments containing only CO₂ or only CH₄.

The wavelength is controlled by the applied voltage, allowing different wavelengths to be generated at different time instants. Initially, the laser wavelength is adjusted to a region outside the absorption band of the target gas, resulting in low signal attenuation. Subsequently, the wavelength is tuned to the gas absorption region, under which the optical loss becomes significantly higher. Random signal modulation is performed by means of a pseudo-random binary sequence (PRBS) generator in conjunction with an amplitude modulator. The delay block represents the optical propagation time to the gas-containing region. Through cross-correlation of the transmitted and received randomly modulated signals, this delay is estimated from the correlation peak, enabling the absorbing region position to be inferred. It is also worth highlighting the S-parameters block included in the schematic, into which the absorption response shown in Figure 1 is incorporated.

Figure 2b presents a second approach, in which three wavelengths are transmitted simultaneously, corresponding to the high-absorption regions of CO₂ and CH₄, as well as to a low-absorption region for both gases. These wavelengths are generated by amplitude modulation of the optical carrier with a sinusoidal signal, whose frequency determines the spacing between the resulting optical components. To implement this configuration, power splitters associated with optical band-pass filters were employed. For each wavelength, random intensity modulation of the optical signal is applied. Similarly to the first setup, the S-parameters block should also be emphasized, since it incorporates the absorption response of the gases under consideration.

III. RESULTS

This results section is divided into two subsections. The first subsection presents the results obtained for the first setup,

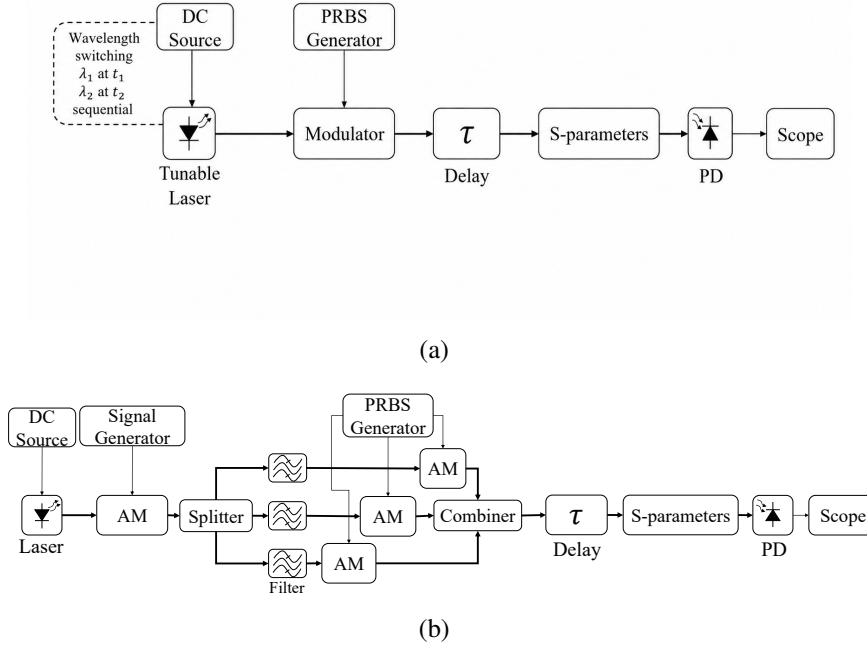


Fig. 2: Proposed LiDAR configurations: (a) wavelength-switching setup using a tunable laser; (b) simultaneous multispectral setup based on an optical frequency-comb approach. The delay block represents the optical propagation time to the gas-containing region.

whereas the second subsection addresses the results related to the second setup.

A. Setup 1

Figure 3 shows the three wavelength configurations investigated after random modulation. The cases presented correspond to the laser tuned to the CO_2 absorption region, to the CH_4 absorption region, and to a spectral region where neither gas exhibits absorption. The spectra after the S-parameter block, which represents the gas absorption response, are also shown.

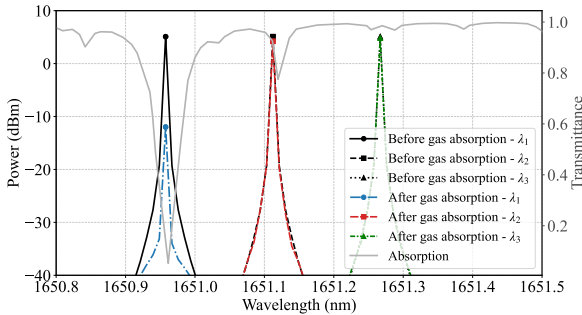


Fig. 3: Optical spectra before and after gas absorption in Setup 1 for CH_4 , CO_2 , and low-absorption reference wavelengths.

Figure 4 presents the cross-correlation results for wavelengths inside and outside the absorption region of each gas. The imposed delays of 1 ns, 5 ns, and 10 ns emulate different

optical path lengths, and the peak displacement confirms that the proposed processing can estimate the propagation delay and infer the absorbing region position. Gas-induced attenuation also affects the received signal intensity and the correlation peak amplitude. These results confirm the feasibility of the proposed correlation-based sensing approach.

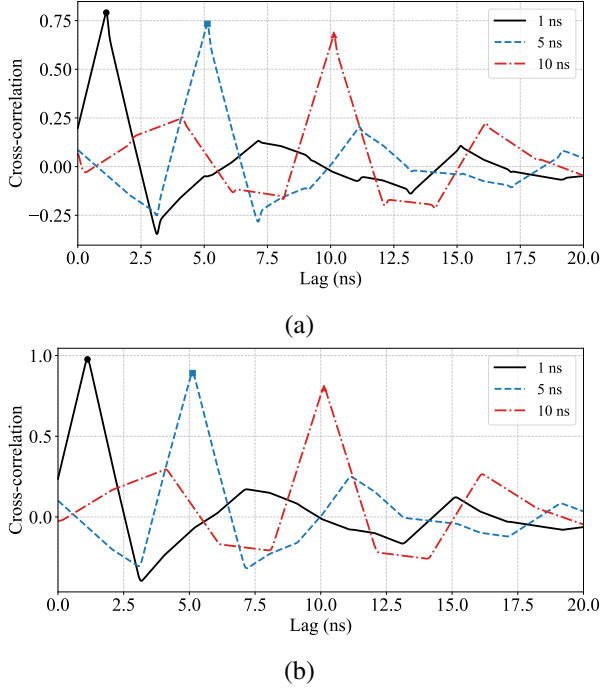
B. Setup 2

For Setup 2, a laser with its wavelength fixed at the region of maximum CH_4 absorption (λ_1) was used. By employing a sinusoidal waveform generator operating at 17 GHz, it is possible to generate an optical signal with a wavelength located in the CO_2 absorption region (λ_2), as well as another optical signal with a wavelength outside the absorption regions of the gases. Figure 5a shows the generated frequency comb and the gas transmittance spectra. In this work, frequency-comb equalization techniques were not investigated. Figure 5b shows the signals after being split by the splitter component and filtered by optical bandpass filters, as illustrated in Figure 2b. It is important to highlight that the signal with the highest power is associated with the region of strongest absorption. This condition was considered to enable signal detection even in the presence of CH_4 , which introduces significant attenuation.

Considering the four S-parameter configurations of Figure 1, the APD-detected signals were evaluated after low-pass filtering, as shown in Figure 6. The distinct temporal responses indicate that the received waveform depends on the gas absorption scenario, enabling the identification of the gas condition.

TABLE I: Correlation peak results and estimated delays for Setup 2.

Delay (ns)	Correlation peak			Estimated delay (ns)		
	CO ₂	CH ₄	CO ₂ and CH ₄	CO ₂	CH ₄	CO ₂ and CH ₄
1	5.10e-04	1.96e-04	1.77e-04	0.96	1.03	1.03
5	4.37e-04	1.76e-04	1.60e-04	4.79	4.87	4.87
10	4.26e-04	1.68e-04	1.52e-04	9.59	9.67	9.67


 Fig. 4: Cross-correlation results for Setup 1 under optical delays of 1, 5, and 10 ns: (a) CH₄; (b) CO₂. The peak position indicates the estimated propagation delay.

The cross-correlation was then calculated between the gas-free received signal, used as reference, and the CO₂, CH₄, and CO₂+CH₄ cases. Figure 7 shows the results for optical delays of 1 ns, 5 ns, and 10 ns. The correlation peaks are spaced by approximately 2 ns, consistently with the 0.5 Gb/s PRBS modulation rate. Differences in peak magnitude are associated with the attenuation introduced by each gas condition: the CO₂-only case presents the highest peak because it is the least attenuated and, therefore, remains closer to the gas-free reference signal. In contrast, the CH₄ and CO₂+CH₄ cases produce lower correlation magnitudes due to stronger absorption effects. Thus, the peak magnitude provides information for gas-condition identification, while the peak position is used to estimate the optical path delay, as summarized in Table I.

IV. CONCLUSIONS

This work presented a numerical analysis and comparison of two LiDAR architectures for greenhouse gas sensing, focusing on CO₂ and CH₄ detection. The results show that both topologies enable the identification of gas absorption

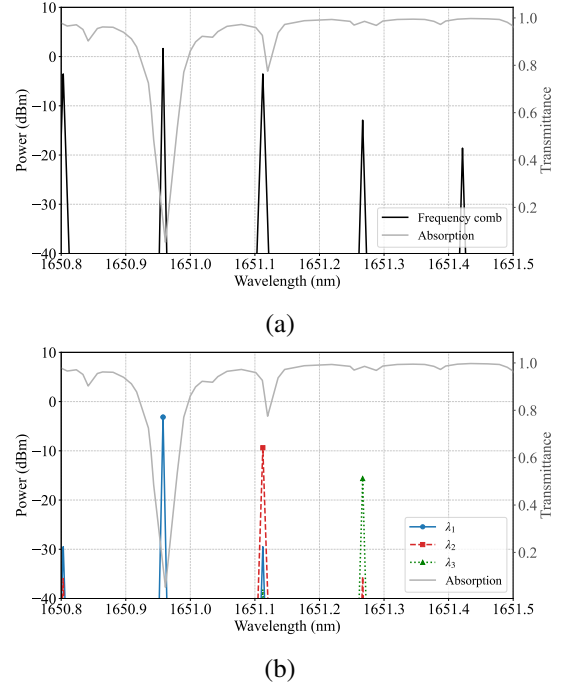
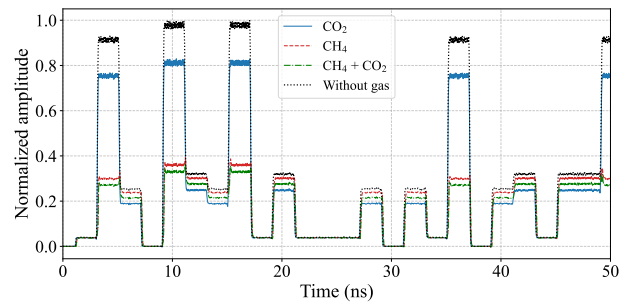

 Fig. 5: Optical spectra for Setup 2: (a) generated frequency comb; (b) filtered components associated with CH₄, CO₂, and the low-absorption reference region.


Fig. 6: Normalized received time-domain signals after APD detection and low-pass filtering for different gas absorption scenarios.

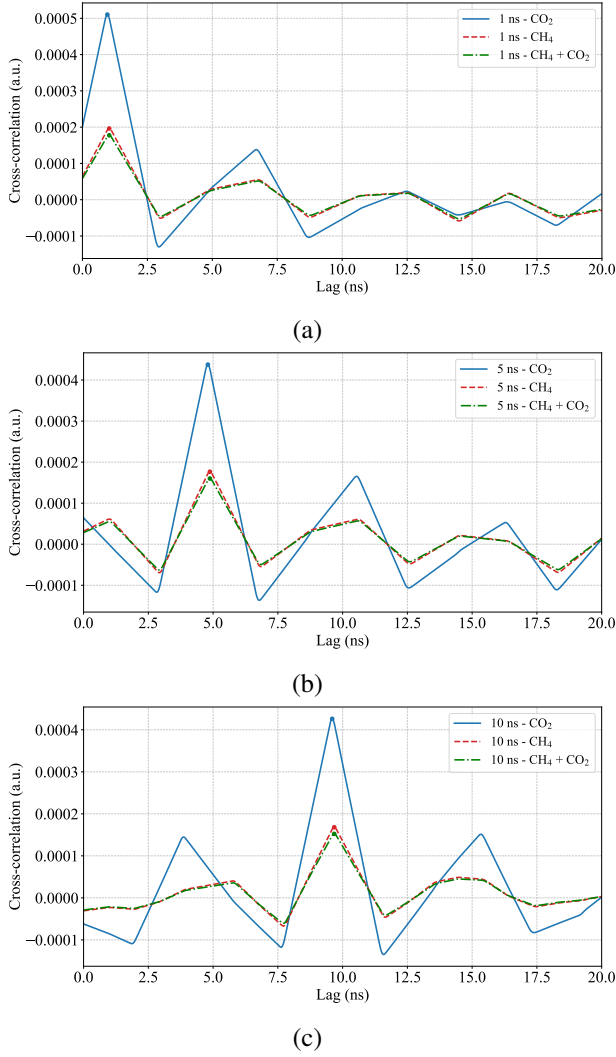


Fig. 7: Cross-correlation results for Setup 2 under different gas conditions and optical delays of (a) 1 ns, (b) 5 ns, and (c) 10 ns. Peak position indicates delay, and peak magnitude depends on gas absorption.

effects on the received signal and the estimation of the round-trip optical propagation delay through cross-correlation. In the conventional IPDA architecture, the absorption regions of CO_2 and CH_4 are investigated sequentially by switching the laser wavelength between the selected spectral regions. This configuration provides a simpler sensing approach, but requires consecutive measurements for the analysis of different gases. In contrast, the frequency-comb-based architecture simultaneously interrogates multiple wavelengths associated with CO_2 , CH_4 , and the low-absorption reference region. Consequently, this architecture enables simultaneous multispectral gas-condition identification, although it requires additional optical components and a more complex implementation. Therefore, the main advantage of the conventional architecture is its simpler configuration, whereas the frequency-comb architecture offers simultaneous multispecies sensing. Although the numerical results confirm the feasibility of both approaches, practical implementation still requires addressing

issues such as frequency-comb stabilization, receiver noise, atmospheric effects, and operation under lower signal-to-noise ratio (SNR) conditions. Future work will investigate more realistic propagation scenarios, experimental validation, robust signal-processing techniques for improved gas detection under stronger signal degradation, and the influence of gas concentration on the absorption response and sensing performance.

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