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Coherent Electro-Optic Frequency Comb Lidar for CO₂ IPDA measurements: preliminary design and speckle issues

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Abstract: We report on the preliminary design of a dual electro-optic frequency comb (EOFC) lidar system for integrated path differential absorption (IPDA) measurements. We discuss the principle of gas concentration measurements by means of EOFCs in a dual comb spectroscopy (DCS) setup in the presence of speckle noise. Concentration measurements of a pure CO₂ gas cell are carried out using light backscattered from different surfaces. The precision of the concentration measurement is observed to depend on the roughness of the backscattering surface. Additionally, we present an example of remote surface characterization exploiting speckle noise correlation in a dual EOFC system. We manage to observe and quantify the roughness of a textile sample using a simple experimental setup.

Keywords: Coherent lidar, frequency comb, electro-optic, CO₂, speckle, surface characterization.

1. Introduction

Frequency comb (FC) based systems are attracting considerable interest in the field of remote sensing of atmospheric trace gases due to the possibility of interrogating gas absorption features with several evenly-spaced wavelengths. FCs generated by means of electro-optic modulators (electro-optic frequency combs - EOFCs) are highly tunable in terms of line-spacing and power distribution. This is particularly interesting for lidar applications, since the optical power can be concentrated in a small number of comb lines (in the order of 10) selected to cover an absorption feature of the target gas. EOFC-based systems could potentially overcome the disadvantages of traditional differential absorption (DIAL) lidar techniques [1], namely the time lag between the emitted wavelengths and the need of complex frequency stabilization systems. EOFC-based sensing methods rely on the dual comb spectroscopy (DCS) technique. Numerous demonstrations of gas spectroscopy using EOFCs can be found in the literature, reviewed for instance in [2].

In many previous works, applying the DCS technique for standoff measurements implied having mirrors at the end of the line-of-sight, reflecting the signal to the detector. However, real scattering targets (natural or artificial) and associated speckle effects must be considered for a wider range of applications. Therefore, with a view to developing an EOFC-based lidar for integrated path differential absorption (IPDA) measurements, recent works have addressed the impact of speckle noise on such a system [3]. The main conclusion of these works is that, in a dual EOFC lidar system, speckle noise may be correlated depending on the roughness of the backscattering surface. Speckle correlation has a beneficial effect on the IPDA measurement precision. Hence, the error in the gas concentration measurement depends on the roughness of the backscattering surface. In this paper, we shortly remind the principle of gas concentration measurements by means of EOFCs in the presence of speckle. Then we present an experimental setup optimized for CO₂ concentration measurements using light backscattered from rough surfaces. Finally, an example of remote surface characterization exploiting speckle correlation in a dual EOFC set up is presented.

2. Electro-optic frequency comb IPDA lidar for CO₂ measurements

We present a preliminary design of a continuous-wave (CW) bi-static lidar for CO₂ IPDA measurements. Figure 1 depicts the experimental setup. A distributed feedback laser diode (DFB-LD) emitting at 1572.0 nm is used to generate two mutually coherent EOFCs by means of a pair of phase modulators (PM). EOFC-1 is frequency shifted by means of an acousto-optic modulator (AOM) for dual

comb detection. The EOFCs are split into two arms in order to produce a measurement signal and a reference signal on two different photodiodes (PD).

The measurement signal results from the interference of EOFC-2 with EOFC-1, which has been previously absorbed by a CO₂ gas cell (750 Torr; room temperature; 0.8m in length), amplified by an Erbium-doped fiber amplifier (EDFA), collimated and backscattered by a spinning surface. Similarly, the reference signal arises from the interference of EOFC-2 with a branch of EOFC-1 which has not interacted with the gas sample. Signals are digitized, Fourier transformed and averaged. The line-spacings of EOFC-1 and EOFC-2 are set to 1500 MHz and 1505 MHz respectively. The AOM driving frequency is 80 MHz. Both the reference and the measurement signal produce a comb lying in the radio frequency (RF) domain.

The transmission profile of the CO₂ absorption line (@1572.0 nm) is obtained by computing the power ratio between the measurement and the reference RF combs. Inverting the measured transmission profile yields the central frequency of EOFC- 1 and the product p_c between the gas volume mixing ratio (VMR) in ppm and length of the gas column in meters, i.e., $p_c = VMR \times l_c$.

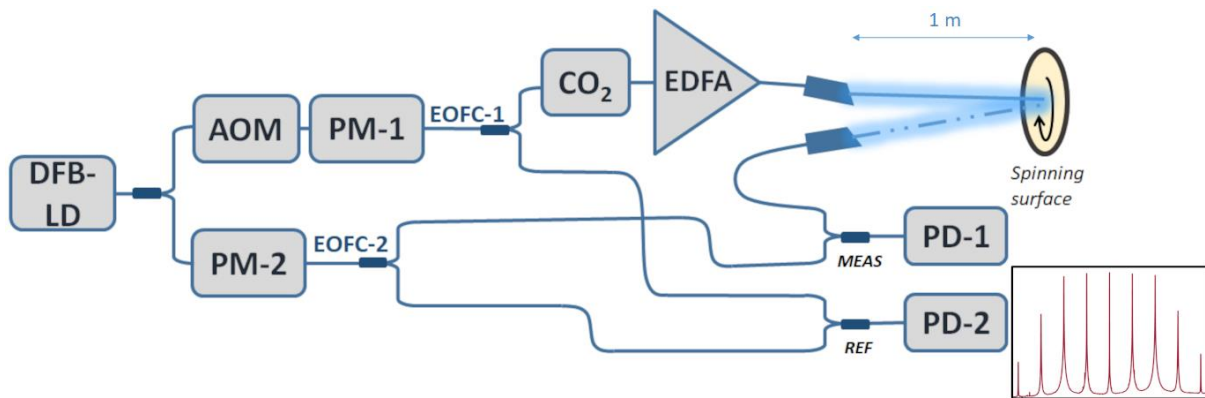


Figure 1. Experimental setup for CO₂ concentration measurements using backscattered light. The inset figure (bottom-right) shows the reference RF comb. DFB-LD, distributed feedback laser diode; AOM, acousto-optic modulator; PM, phase modulator; CO₂, gas cell; EDFA, Erbium-doped fiber amplifier; PD, photodiode.

We conducted measurements of the CO₂ gas cell transmission profile using two different backscattering surfaces: white paper and polyurethane foam. The surfaces were attached to a spinning platform in order to obtain a dynamic speckle noise. For each surface, we recorded 2000 spectra at a rate of around 60 spectra per second. Measurements were limited by speckle noise. The five central comb lines were taken into account when computing the transmission profile.

Figure 2-left presents the fit of the average optical depth to the HITRAN profile when using the foam as backscattering surface. Figure 2-right shows the statistical error in the estimate of p_c as a function of the averaging time for both surfaces. Speckle noise affecting the measurement RF comb lines was observed to be partially correlated from one comb line to another. For white paper, the correlation coefficient of speckle induced power fluctuations of adjacent comb lines, i.e., $|\Delta n|=1$, was $\rho_{\text{paper}}(|\Delta n|=1) = 0.94$ (with n the comb line index). For the polyurethane foam, we found $\rho_{\text{foam}}(|\Delta n|=1) = 0.83$. This difference in the speckle induced power fluctuations arises from a different surface mean roughness as stated in [3].

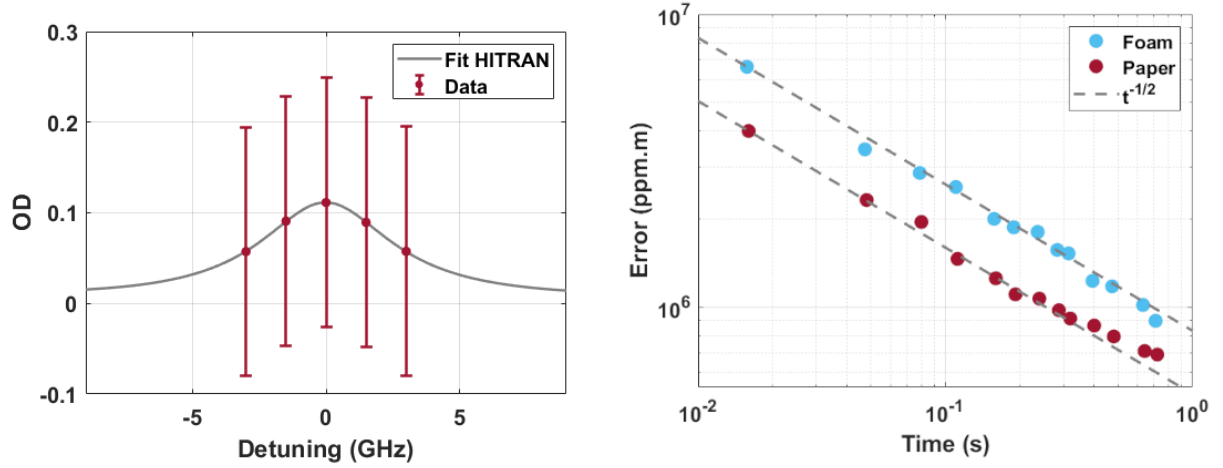


Figure 2. (Left) Fit of the average optical depth to the CO₂ absorption feature at 1572.0 nm. The error bars indicate the standard deviation after averaging over 30 spectra. (Right) Statistical error in the estimation of the p_c , for two backscattering surfaces, as a function of the averaging time. The error is computed as the standard deviation of 30 estimates.

Even if for both surfaces the measurement is speckle-limited, the error when using paper as a backscattering surface is reduced by a factor of 2 with respect to the measurement over foam due to a higher speckle correlation. For both surfaces the measurement follows the $t^{-1/2}$ trend. In this setup, the long-term achievable measurement precision is finally not limited by speckle noise, but by the use of two different interferometers and two different detectors. Future work will concentrate in the long-term stability of the gas concentration measurement.

3. Characterization of textile using a dual EOFC system

The use of an EOFC-based system exploiting speckle correlation for surface characterization has recently been proposed [3]. Assuming a Gaussian distribution for the scattering surface depth deviations, the correlation between the speckle-induced power fluctuations of two comb lines is given by:

$$\rho(\Delta n) = \exp\left[-\left(\frac{4\pi f_M \Delta n \sigma_s}{c}\right)^2\right] \quad (1)$$

Where Δn is the comb line index difference, f_M is the line-spacing of the EOFC and σ_s is the mean roughness (in meters) of the backscattering surface.

We present an example of remote surface characterization by means of a dual-EOFC system. The experimental setup is the same presented in Figure 1, without the CO₂ gas cell. Note that only the measurement interferometer provides information about the backscattering surface. The spinning surface, was replaced by a textile sample and the laser spot was manually swept along the sample. The displacement of the laser spot ensured speckle renewal. The power distribution of the measurement RF combs was recorded at a rate of 80 measurements per second. We computed the correlation coefficients between the powers of the RF comb lines over groups of 130 consecutive spectra. This resulted in a correlation measurement every 1.6 s. The correlation coefficients were then averaged over a rectangular window of 6 s so as to reduce edge effects.

Figure 3-left presents the averaged correlation coefficients as a function of time. Figure 3-right shows the mean roughness computed by fitting the correlation coefficients to a Gaussian function using Eq. (1). The line-spacing of EOFC-1 was set to 3GHz. A close-up photo of the textile sample is presented in the inset of Figure 3-right. The textile sample was composed of interspaced bands having different roughness. These roughness variations are reflected on the correlation coefficients. The laser spot diameter on the sample was 3 mm ($1/e^2$). We observe that this simple setup allows to quantify the roughness of a distant target, which might prove useful for material standoff control applications.

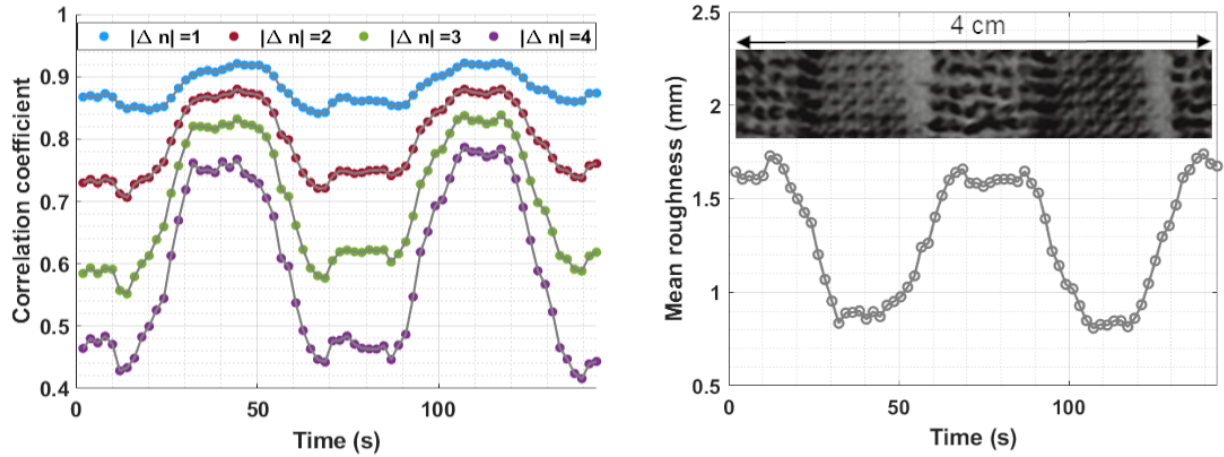


Figure 3. (Left) Correlation coefficients of the speckle power fluctuations as a function of time for different values of $|\Delta n|$, with n the comb line index, ranging from -2 to 2 for a 5-line comb. (Right) Mean roughness calculated from the correlation coefficients. The inset presents a close-up photo of the textile sample in inverted colors.

4. Conclusion

We have presented a preliminary prototype of IPDA lidar for characterizing CO_2 gas contents, based on the dual comb spectroscopy technique with combs generated by means of phase modulators. We measured the gas content of a pure CO_2 gas cell using the dual EOFC system at 1572.0 nm. The influence of the backscattering surface structure on the error of the measurement was experimentally demonstrated by conducting CO_2 measurements over two different backscattering surfaces.

Additionally, we carried out a remote surface characterization experiment, exploiting correlation of speckle noise in a dual EOFC system. We were capable of measuring the mean roughness of a textile sample 1 meter away from the laser collimator. This technique is appropriate for characterization of very distant or hard to access targets since the backscattered signal can be amplified thanks to the use of a local oscillator. However, since the surface characterization technique relies on a correlation calculation, the measurement requires a significant number of independent spectra. Further work is needed to identify future applications of this technique.

5. References

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