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PERFORMANCES OF A HGCDTE APD BASED DIRECT DETECTION LIDAR AT 2 µM. APPLICATION TO DIAL MEASUREMENTS.

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ABSTRACT

A lidar receiver with a direct detection chain adapted to a HgCdTe APD based detector with electric cooling is associated to a 2.05 µm Ho :YLF pulsed dual wavelength single mode transmitter to provide the first atmospheric lidar measurements using this technology. Experiments confirm the outstanding sensitivity of the detector and hightligth its huge potential for DIAL measurements of trace gas (CO2 and H2O) in this spectral domain. Performances of coherent vs direct detection at 2.05 µm is assessed.

1 INTRODUCTION

CO2 is an unprecedented challenge for optic based remote sensing techniques, as its variation is rather small in the atmosphere. Typical natural variations due to its diurnal cycle (uptake by the vegetation, boundary layer dynamics) are around 5 % close to the surface but decrease to 0.1 % for turbulent linked fluctuations [1]. CO2 DIAL measurements requires indeed a high laser single shot signal to noise ratio (SNR). Although CO2 DIAL experiments emerged in the last decade [2,3], the technology faces two main challenges to get it: (i) a powerful dual wavelength single mode emitter and (ii) an efficient photodetector in the near infrared. Two spectral domains at 1.6 µm and 2 µm are relevant although higher optical depth at 2 µm enables more precision, flexibility and optimization of CO2 DIAL/IPDA measurements, ultimately from space.

In the framework of greenhouse gases studies, the LMD has developed a 2 µm DIAL emitter. Details of the laser may be found in [4]. The laser benefits from both fiber laser technology for compactness and reliability and free space operation to get high-energy pulses. LMD emitter delivers tens of millijoules and tens of nanosecond Fourier transform and diffracted limited beam pulses and can be operated at low or high repetition rates (100 Hz-10 kHz) depending the application.

To overcome the detector issue at 2 µm, LMD emitter was first associated with a coherent detection to make ground-based CO2 DIAL profiling in the atmospheric boundary layer [5]. However, recent advances in the field of HgCdTe APD may open the way to efficient direct detection [6,7]. The remarkable properties of HgCdTe APD (large gain, high efficiency, low dark current, close to unity excess noise factor, wide spectral range) make this technology especially suitable for very low intensity lidar signal detection. A dedicated APD for lidar application has been manufactured at CEA-LETI. This detector uses thermo-electric cooling (TEC) for space application. Some performances of the detector have been assessed in a precedent paper [8]. In the present paper we implement the detector in the LMD DIAL system to achieve first atmospheric lidar measurements at 2 µm using this technology. Preliminary CO2 DIAL measurements are presented and analyzed.

2 EXPERIMENTAL SET UP

2.1 HgCdTe APD detector prototype characteristics

The HgCdTe detector prototype developed by CEA-LETI is presented in Figure 1. The main characteristics are displayed in Table 1. The APD is located on several Peltier stages for electric cooling and positioned close to the transimpedance amplifier (TIA) to reduce parasitic capacitance. A dedicated substract on the APD surface acts as a high optical pass filter (> 800 nm). A quartz window serves as an interface between the detector vacuum box and lidar direct detection chain optical components.

The relevant detector characteristics for lidar detection are: a 180 µm active surface, a NEP of

75 fW/Hz$^{1/2}$ for a gain of 23 when polarized at 12 V and a total bandwidth (APD+TIA) of 20 MHz.

Table 1 HgCdTe APD main characteristics. NEP: Noise equivalent power, TEC: Thermoelectric cooler, TIA: transimpedance amplifier

APD	Diameter	180 µm
	Gain	23
	Operating voltage	12 V
	Operational temperature	180 K
	Equivalent capacitance	2 pF
	Excess noise factor	1.2
APD +TIA	Bandwidth APD APD +TIA	 > 60 MHz 20 MHz
	TIA gain	3.10^5 V/A
	NEP	75 fW/Hz$^{1/2}$

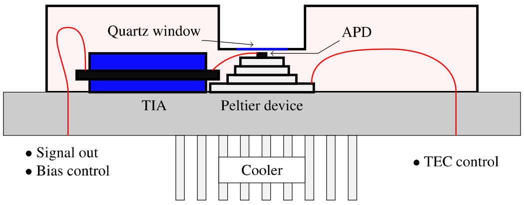

Figure 1 Sideview of the HgCdTe APD detector developed at CEA-LETI.

2.2 Direct detection DIAL experimental set-up at LMD

The APD was integrated in a lidar direct detection chain including a Cassegrain telescope, a diaphragm to control the field of view of the detection chain and different lens to image the telescope primary mirror on the detector surface. A 2-nm optical bandpass filter was also included to reduce the radiometric noise although the detector surface substrate already removed a big part of it for wavelength lower than 800 nm. The total transmission of the optical chain including telescope, lens and without the filter was estimated to be only 0.56 mainly due to the absence of dedicated coating an the telescope mirrors (telescope transmission is 0.8) and the optics. Given the size of the detector, the alignment of the optical components and the imaging on the detector surface is difficult to achieve although this is critical to obtain an operation in good conditions. This direct detection chain was associated with the LMD 2 µm dual wavelength single mode pulsed Ho:YLF emitter (Fig. 2). Some details may be found in Table 2. The ON wavelength is usually locked on the center of the R30 CO2 absorption line at 2050.967 nm although off-center locking is also possible using an additional DFB laser. The whole DIAL system was installed on the second floor of the LMD lab and the line of sight was practically horizontal.

Table 2 HgCdTe APD main characteristics. NEP: Noise equivalent power, TEC: Thermoelectric cooler, TIA: transimpedance amplifier

Emitter	Thulium fiber pump	
	Ho:YLF oscillator	
	Pulse Energy / Rate	10 mJ/ 1 kHz
	On/ Off wavelengths	2050.97/ 2050.26 nm
	Laser divergence after beam expander	0.3 mrad
Receiver	Telescope diameter	0.2 m
	Field of view	0.5 mrad
	Filter bandwidth	2 nm
	Detector	HgCdTe APD

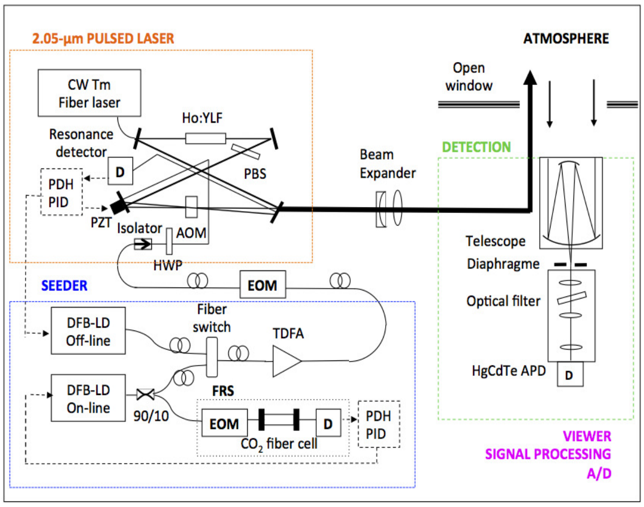

Figure 2 DIAL experimental set-up at LMD. The DIAL consists in a 2.05 µm pulsed oscillator, a dual-wavelength seeding module locked to a frequency reference system (FRS) and a direct detection. EOM: electro-optical modulator; AOM: acousto optical modulator; PID: proportional integral derivative; PDH: Pound Drever Hall; AOFS: acousto optic frequency shifter; TDFA: Thulium doped fiber amplifier; PBS: polarizer beam splitter; HWP: half wave plate; QWP: quarter wave plate; PZT: piezoelectric transducer..

3 PERFORMANCES

3.1 Lidar signal to noise ratio

Assuming the speckle noise is negligible (usually true in DIAL configuration) the lidar signal to noise ratio (SNR) may be written [6]:

$$SNR = \frac{P}{\sqrt{2h\ \ FB\left(P+P_{Bg}\right)+NEP^{2}B}} \qquad (1)$$

where P is the useful signal, P_{Bg} is the background signal which results mainly from the scattered solar radiation but also from some thermal radiation by components around the detector. F is the noise factor and B is the detection chain bandwidth.

The different sources of noise (shot noise, background, detector) were calculated for a single shot and compared with the lidar signal (background corrected) obtained in horizontal measurements (Fig. 3). For this particular case, there was no optical filter. Other measurements showed that the background noise is actually negligible when such a filter is used. Thus, Figure 3 shows that the single shot lidar SNR is detector NEP limited for a range longer than 0.6 km. A SNR of 0 dB is estimated at 3 km. It is worth pointing out that the SNR may vary by more than a factor of two during the day just due to the change in the atmospheric conditions and the particles content.

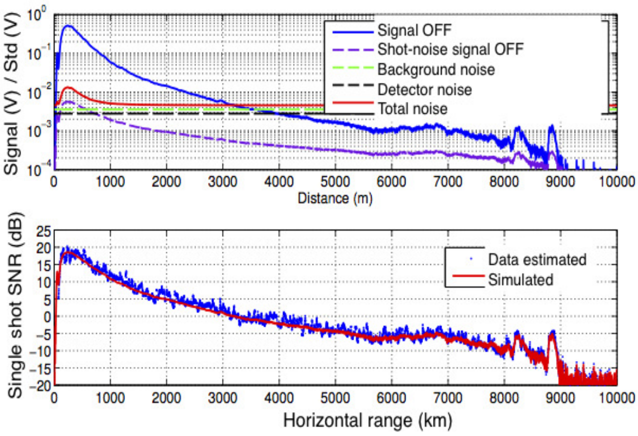

Figure 3 Different source of noise standard deviation (Std) estimated from the lidar signal and detector data. The lidar signal is averaged over 9000 shots for visualisation. The resulting SNR is calculated and compared with data estimated single shot SNR.

A longer data set was used to verify successfully that the SNR increases with the square root of the number of shots at least up to 4000 averaged shots.

3.2 Preliminary CO2 DIAL measurements

The DIAL configuration of the lidar was preliminary tested with the ON wavelength positioned in the center of the R30 CO2 absorption line at 2050.967 nm. Theoretically, this results in an optical depth of almost 0.65 for 1 km (and for 400 ppm of CO2 in standard conditions of temperature and pressure). Figure 4 displays the results.

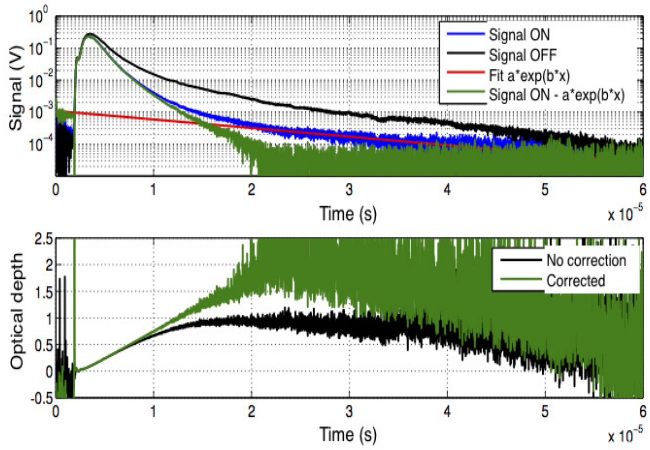

Figure 3 Lidar signals for the OFF and ON (CO2 line center) wavelengths and resulting optical depth due to CO2 absorption. An exponential fit of the ON-line data is used to correct from the slow decay of the signal with time. For range estimation, 1 µs corresponds to 150 m.

The main result is that, after 900 m, the calculated optical depth deviates significantly from an expected linear trend. An exponential decay of the signal is observed with a characteristic time of 16 µs. This parasitic signal is unlikely linked to the APD itself as its theoretical response time does not match [9] but seems rather to be linked to the optical set-up and an illumination on the edge of the detector. This may be corrected as shown in Figure 4 given that the ON-line signal is negligible after 3 km (97% of signal extinction with an absorption of 0.65 km^{-1}).

The DIAL system was also tested successfully with an ON-wavelength positioning on the wing of the CO2 absorption line (3 GHz off-set locking). For each case, the relative error on CO2 absorption coefficient was estimated and compared to previous results obtained in coherent detection [5]. The time and space resolution were fixed to 4 s and 100 m, respectively (Fig. 5).

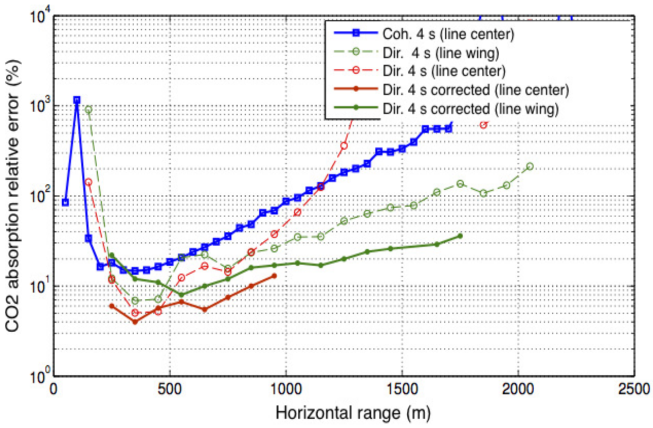

Figure 5 Relative error on CO2 absorption coefficient for a 100 m range gate and 4 s of time averaging (4000 shot-pair). The corrected data used the exponential correction described in Figure 4.

A reduction of the absorption enables to reach a longer range and a slower increase of the error with the distance as expected. Meanwhile the ON lidra signal is less sensitive to the parasitic signal. The direct detection shows a lower error at least by a factor of 5 than coherent detection (CO2 line center positioning).

4 CONCLUSIONS

A new direct detection chain at 2 µm using a HgCdTe APD prototype has been implemented and associated with a dual wavelength pulsed Ho:YLF oscillator. The performances of the lidar in terms of signal to noise ratio have been assessed. For the displayed data set, a SNR of 1 is obtained at 3 km mainly limited by the NEP of the detector. Preliminary DIAL measurements have been tested. The error budget on CO2 absorption coefficient estimate shows already a clear advantage of direct detection compared to coherent detection.

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