Coherent wind LIDAR based on a coherently-beam-combined pulsed laser source

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Introduction

Coherent wind LIDARs are increasingly used for climatic condition and turbulence assessment with applications in wind farm projects optimization or aircraft security during take-off and landing. Laser pulses are sent through the atmosphere and wind speed is measured using Doppler-induced frequency shift on the backscattered laser light. Laser sources with excellent spatial beam quality, narrow linewidth and typical pulse duration ranging from ~100 ns to 1 µs are required. Pulsed master oscillator power fiber amplifier (MOPFA) at 1.5 µm are well adapted, versatile sources but with peak power limited to a few hundreds watts by nonlinear effects in standard fibers.

In this paper, we report on a coherent wind LIDAR based on a pulse laser source made of two coherently-beam-combined amplifiers. LIDAR performance is compared using the combined-amplifier and the single-amplifier of the same power. The carrier to noise ratio (CNR) and wind speed accuracy of both operating modes are presented.

LIDAR setup

Coherent beam combination (CBC) allows improving the output power of a LIDAR by using more than a single fiber amplifier. To achieve this, two or more amplifiers injected by the same pulsed oscillator are coherently combined in a singlemode beam using a controller to compensate phase differences. We have recently achieved the operation of a combined-source in 100 ns-pulse regime with peak power of 208 W, using two single-sources limited to 95 W and 123 W, respectively [1]. Beam quality and spectral linewidth were maintained.

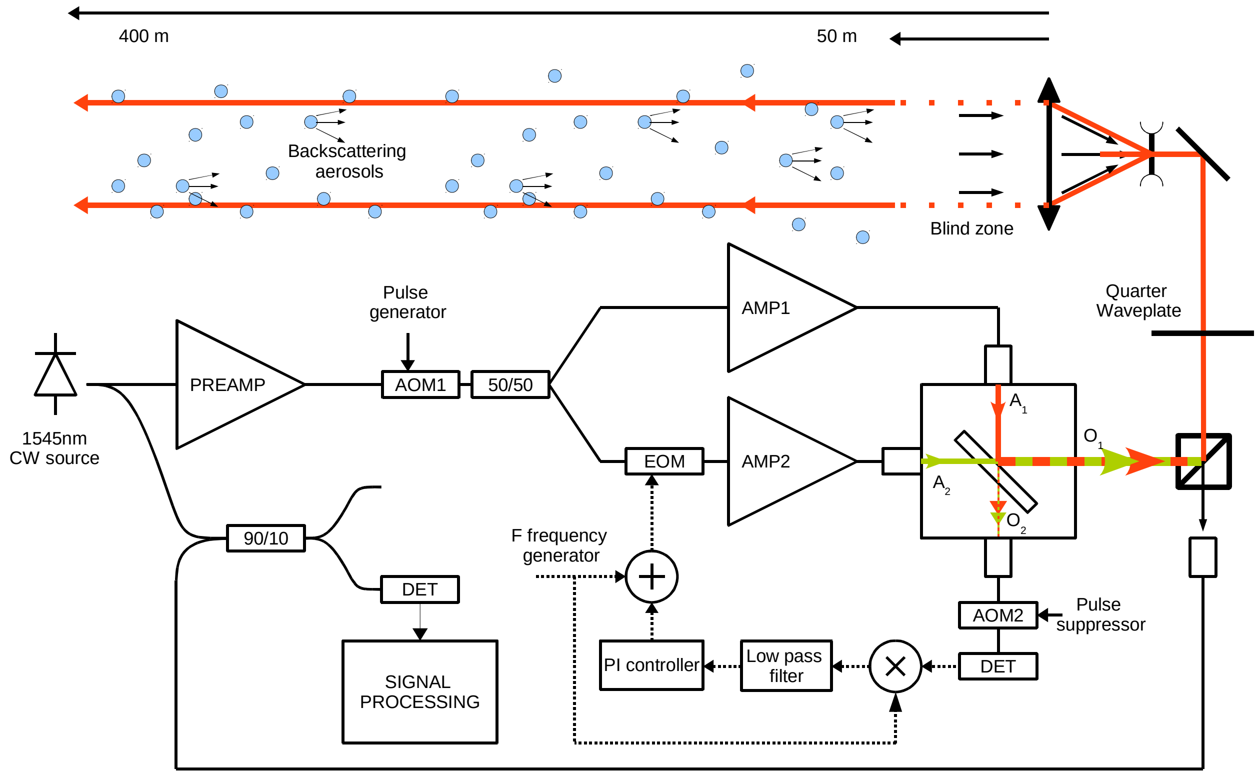

Figure 1 **:** LIDAR setup coherently combined pulsed laser sources

We have implemented this source in a wind LIDAR system as shown in Figure 1. The local oscillator is first split in two beams, one beam is pulse shaped by the acousto-optic modulator AOM1, this beam is split again in two beams which are then amplified by two identical fibered amplifiers AMP1 and AMP2. Both amplifiers beams are collimated (A_1 and A_2) and are combined on output O_1 and sent into the atmosphere after collimation with a lens diameter of the order of several cm. Output O_2 is minimized by the LOCSET phase control system. Aerosols present in the atmosphere will backscatter a very small part of the laser beam. Thanks to a quarter waveplate, the backscattered beam is separated from the transmitted beam by a polarizing splitter, and coupled into a singlemode fiber. The coupled light is mixed with the local oscillator and the resulting light is detected for further signal processing.

The phase control principle lies in a small phase modulation at a given frequency f_{mod}, introduced by the electro-optic phase modulator EOM at one amplifier (AMP2) input. This phase modulation translates into a small intensity modulation at outputs O_1 and O_2. A photodetector is placed on output O_2 in order to detect the intensity modulation at f_{mod} frequency, thanks to a frequency mixer and a low pass filter. A proportional integral controller adds a voltage offset to the input of the electro-optic phase modulator. The intensity modulation at f_{mod} frequency is minimized by the controller through this voltage offset. The output O_2 intensity is thus minimized or maximized, depending on the controller setting. In this setup, the controller is set to minimize the intensity at O_2 and maximize the intensity in O_1 by power conservation rule. One should note the acousto-optic modulator AOM2 is used as a pulse suppressor. Phase control is applied between the pulses. We observe no additional phase noise during the pulse emission [1].

CNR and windspeed comparison

We compare the performance of the wind LIDAR driven by a single-amplifier (30 W peak power) and the same wind LIDAR driven by two combined amplifiers (30 W peak power total output). The peak power was limited to 30 W in both cases for the sake of comparison. Pulses duration is 240 ns both for single-amplifier and combined- amplifier operations. The LIDAR is alternatively operated in single- amplifier and combined- amplifier modes, with fast (6 s) switching time, in order to probe the atmosphere in the most similar state for both modes.

The pulse repetition rate (PRF) is 10 kHz in both modes. The backscattered signal is acquired for each pulse and its frequency shift is analysed for 7 distances ranging from 100 m to 400 m. The carrier to noise ratio (CNR), defined as the ratio of the power contained in the signal to the power contained in the noise over the full detector bandwidth, is estimated as well as the wind speed by a Maximum Likelihood Estimator (MLE). Then the CNR and the estimated speed are averaged over 8192 pulses, corresponding to 0.8s acquisition. Figure 2 shows on the right the evolution of the CNR averaged over 1000 s versus distance in both modes. The standard deviation is also indicated as error bars. The two curves are close, showing that there is no degradation of the CNR when using combined-source instead of single-source.

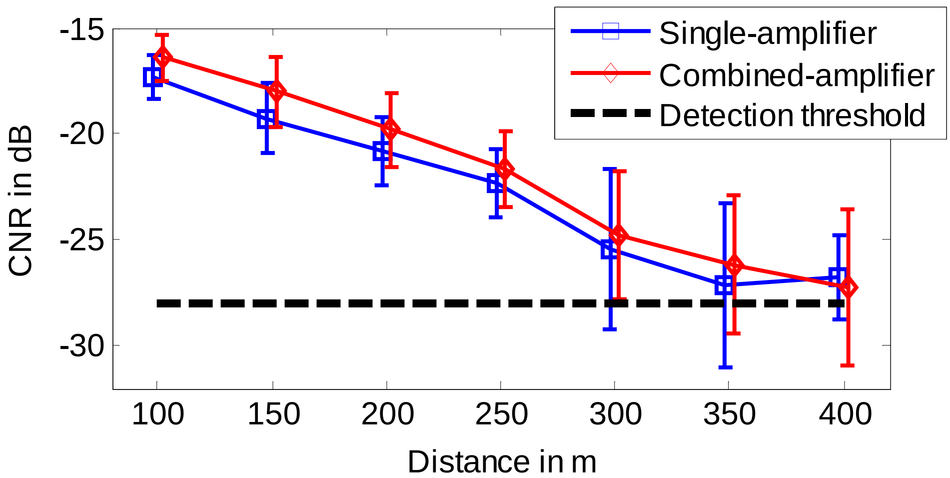

Figure 2 : estimated CNR versus distance, error bars show CNR standard deviation over 1000 s

Figure 3 shows the estimated wind speed every 6 s, alternatively measured with the combined- amplifier and with the single- amplifier. The two curves are consistent and follow the evolution of the atmospheric wind speed.

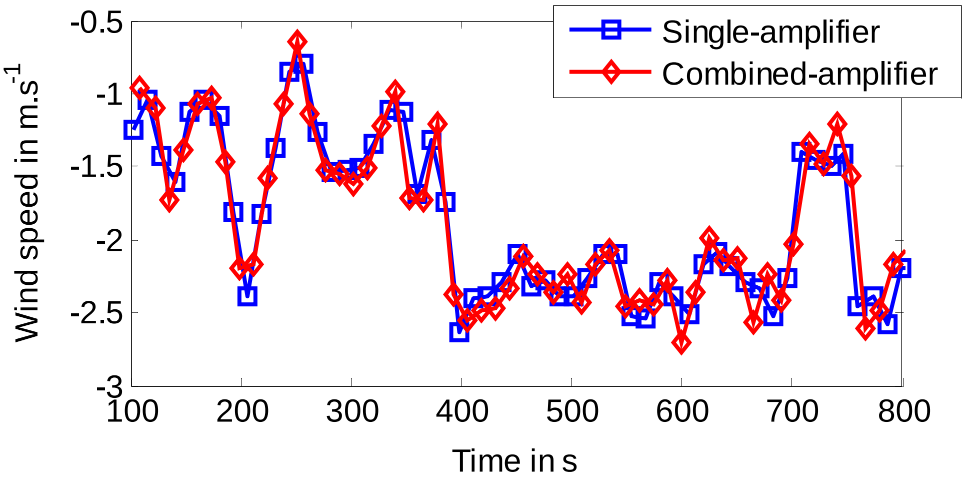

Figure 3 : estimated wind speed versus time for a distance of 100 m

A way to estimate the uncorrelated wind speed error level of a LIDAR is to compute the periodogram of wind speed data obtained by the LIDAR (see [2]). Figure 4 shows the periodogram of windspeed data, for single amplifier mode on left handside, and combined amplifiers mode on right handside. Both modes were operated under 30 W peak power. The two wind speed data sets were 10 min long, and LIDAR operation was no longer interleaved, in order to minimize time between wind speed measurements (3 seconds). LIDAR data is divided in ten sets of 1 min. A periodogram is processed for each 1 min data set, and the ten periodograms are accumulated before being displayed. This choice seems to be a good trade-off, as it provides smoothed periodograms with a reasonably low cut-off frequency (16.7 mHz).

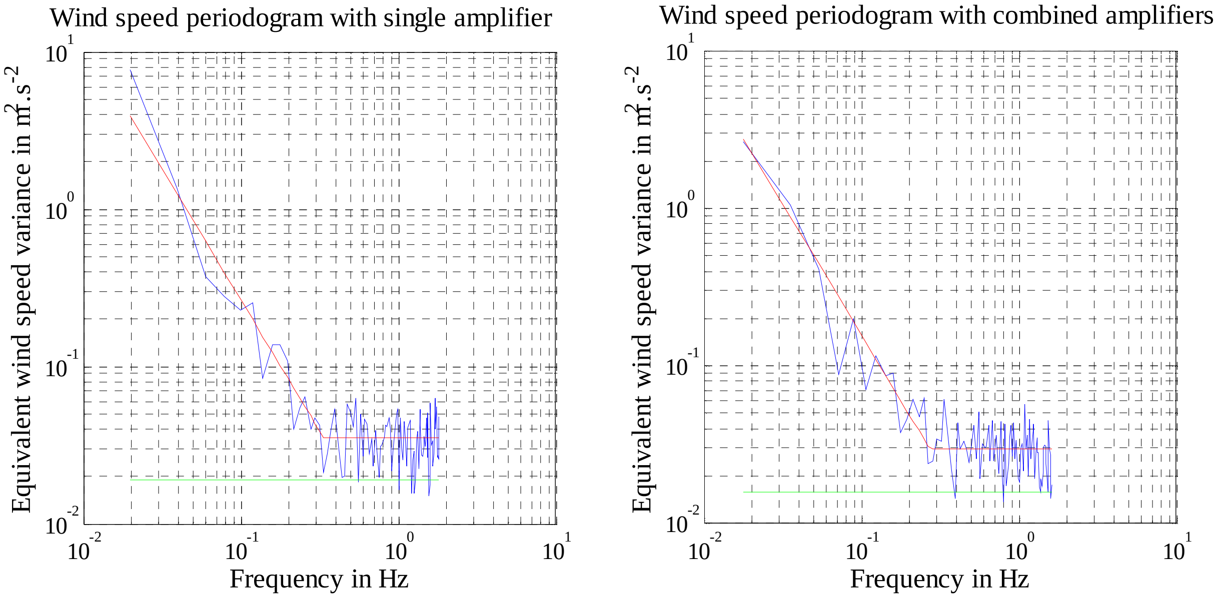

Figure 4 : Periodograms of estimated wind speed (left: single amplifier, right: combined amplifiers)

At low frequencies (from 16.7 mHz to 0.3 Hz), LIDAR data (blue curve) exhibit the Kolmogorov -5/3 power slope due to the ambient wind turbulence. At higher frequencies (from 0.3 Hz up to 16.7 Hz), LIDAR data show a flat noise level which is the consequence of the LIDAR uncorrelated wind speed error level.

The broken line in red shows the result of LIDAR data fitting of both regimes (-5/3 power law and constant level) considering the chi² periodogram statistics.

The scale of the y axis doesn't show the wind speed power spectral density (in $m^2.s^{-1}$), but the equivalent wind speed variance (in $m^2.s^{-2}$). The equivalent wind speed variance scale is equal to the wind speed power spectral density scale, multiplied by the measurement bandwidth. Displaying this equivalent variance scale is useful, since one can immediately identify LIDAR accuracy with the equivalent wind speed variance given by the flat noise level of LIDAR data periodogram. In single amplifier mode, LIDAR accuracy is 0.19 $m.s^{-1}$, which is very similar to the 0.17 $m.s^{-1}$ of accuracy obtained with combined amplifiers mode.

The remaining plain green line displays the averaged Cramér-Rao Lower Bound (CLRB) value for wind speed accuracy. The formula used for computation of the CLRB is taken from [3] (referred as "periodogram CRB"). A CLRB value is computed for each wind speed measurement, using the parameters (carrier to noise ratio, Doppler shift and frequency broadening) yielded by the maximum likelihood estimator. All CLRB variance values, from the 10 min long data set, are then averaged before being displayed in Figure 4. Performance of the maximum likelihood estimator is found to be equal to 140 % of the value of the averaged CLRB in terms of standard deviation.

Conclusions and prospects

Coherent beam combination is a scalable technique for improving output power of single-frequency laser pulsed sources used in LIDAR and other field. Preliminary results, undertaken with single mode fibered amplifiers, have shown the compatibility of coherent beam combining with pulsed coherent wind LIDAR. Coherent beam combination opens a way for improvement of LIDAR measurement range, which can be cumulated with improvements done on peak power of pulsed fibered amplifiers for even greater pulsed fibered LIDAR performance.

References

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[2] R. Frehlich, S. M. Hannon, S. W. Henferson, "Coherent Doppler Lidar Measurements of Wind Field Statistics", Boundary-Layer Meteorology, **Vol. 86 (Issue 2)**, pp 233-256 (february 1998).

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