Pulsed Serrodyning Optical Transceiver Technology for Wind-Sensing Coherent Doppler Lidar

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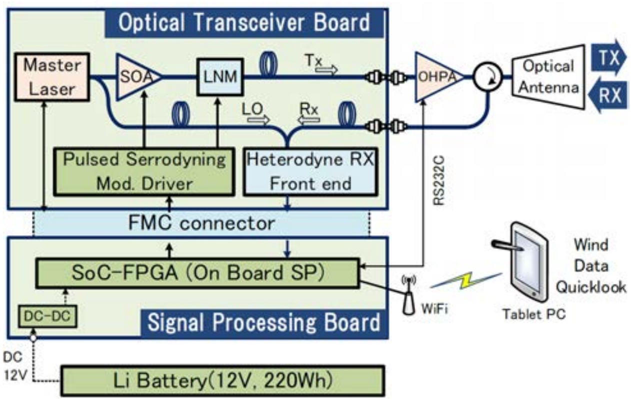
1. Introduction

Coherent Doppler lidar (CDL) systems are attractive sensors for wind sensing because they offer a method of measuring wind speed remotely under clear atmospheric conditions. An all-fiber CDL system using a 1.5-micron wavelength has many advantages, such as compactness, eye-safety, and reliability, thanks to the use of commercial off-the-shelf components for telecoms products[1]. The use of CDL is expanding rapidly for many wind energy applications[2]. Mitsubishi Electric released its first-generation commercial all-fiber CDL system in 2006, and the second-generation compact CDL, DIABREZZATM™, for assessing wind resources in 2014. An international standard for wind sensing with CDL was published recently[3], which will accelerate the spread of CDL for wind sensing. However, CDL is not small enough to be transported because an acoustic optical modulator (AOM) is used in optical transmitters.



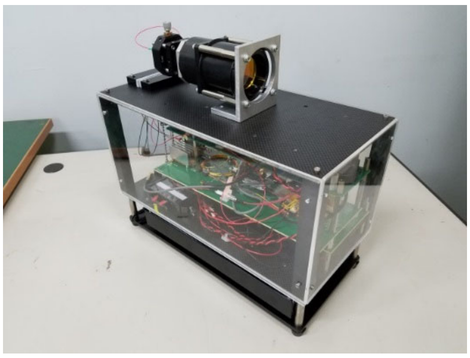


Fig. 1 Schematic block diagram and external view of the mobile Doppler lidar

For widespread use of CDL, compactness and transportability are essential. Accordingly, we have developed a new small optical transmitter using a semiconductor optical amplifier (SOA) and a lithium niobate optical phase modulator (LNM) with saw-tooth waveform, which provides pulsed serrodyne modulation[4].

2. System Configuration

Figure 1 shows a schematic block diagram and external view of the mobile coherent Doppler lidar. This new lidar has an all-in-one design consisting of an optical transceiver board directly connected with a signal processor, an optical high-power amplifier (OHPA), an optical antenna via a fiber circulator, and a lithium polymer battery. The dimensions are 39×29×16 (W×H×D) cm and the weight is 2.9 kg. The optical transceiver is combined a conventional fiber-optic heterodyning receiver with a newly developed coherent optical pulse seeder based on pulsed-serrodyning modulation. In the signal processing board a system-on-a-chip (SoC) solution has been adopted by using a large field programmable gate array (FPGA) with an internal processor core. Measured wind data can be displayed on a tablet PC via WiFi after on-board signal processing for wind speed estimation.

3. Optical Transceiver Unit

Figure 2 shows the block diagram and external view of the optical transceiver unit as a coherent pulse seeder combined with a heterodyne receiver. All fiber-optic components are commercial off-the-shelf components used for optical communication and have high reliability, being compliant with Telcordia GR468-core. An integrable tunable laser assembly (ITLA) is used as a master laser with a line width of 200 kHz and wavelength of 1550 nm. Its output is split into a local oscillator (LO) and a seed light to a pulsed serrodyning modulator which consists of a semiconductor optical amplifier (SOA), a lithium niobate optical phase modulator (LNM) and their drivers with digital-to analog converters (DAC). The pulsed serrodyning modulation is our newly developed technique to realize both pulse modulation and

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frequency shift without the double-pass acousto optic (AO) modulator currently used in our CDL system [3].

In the receiver section, optical return signals (RX) are phonically mixed with a LO signal, then detected as intermediate frequency (IF) signals at two balanced photodiodes (PD). In order to accommodate a bandwidth of 100 MHz corresponding to a Doppler frequency range of ±35 m/s, the heterodyning signal is sampled at the rate of 216 MSps with an analog-to digital converter (ADC) and transferred to the signal processing board.

4. Pulsed Serrodyning Modulator

Serrodyne frequency shifting is realized by applying saw-tooth phase modulation to the optical signals. Recently, the frequency shift of a few hundred megahertz required in CDL can be obtained with good quality by technological advances in high-speed driver electronics. Furthermore, SOA is promising for an optical pulse modulator with a small footprint if the issue of frequency chirp can be solved. We have newly developed a pulsed serrodyning modulation which realizes both frequency shift and compensation of frequency deviation in SOA(5). Figure 3 shows the temporal signals of pulsed serrodyning modulation for the optical intensity of a SOA and the optical phase of an LNM. The saw-tooth phase modulation is applied within only the pulse-on period, T1, over the pulse repetition interval (PRI). If the complete saw-tooth phase modulation with cycle of Tm is applied, the output optical frequency is shifted with an offset frequency of 1/Tm.

It is worth noting that no frequency shift occurs within the pulse-off periods because a saw-tooth signal is not applied. This leads to effective rejection of unwanted beat noise between optically internal reflections within the pulse-off periods and the LO signal in the heterodyne receiver without such a special pulsed modulator as a double-pass AOM with a high extinction ratio.

5. Experimental Results

In order to confirm whether the pulsed-serrodyning modulation works correctly, line-of-sight (LOS) wind Doppler spectra were evaluated in the case of pulsed-serrodyne modulation and that of single-pass AO modulation as a reference. The measuring conditions were as follows: a pulse-on period T1 of 500 ns corresponding to a range resolution of 75 m, a PRI of 250 μs, a saw-tooth cycle, and Tm of 6.17 ns corresponding to IF of 162 MHz as shown in Fig. 3. Figure 4 shows the LOS wind Doppler spectra at a distance of 500 m. In the case of single-path AO modulation the spectrum has a strong peak around zero Doppler velocity which may be caused by beat noise between a LO signal and internal reflection of leaky light within the pulse-off periods. This unwanted beat noise

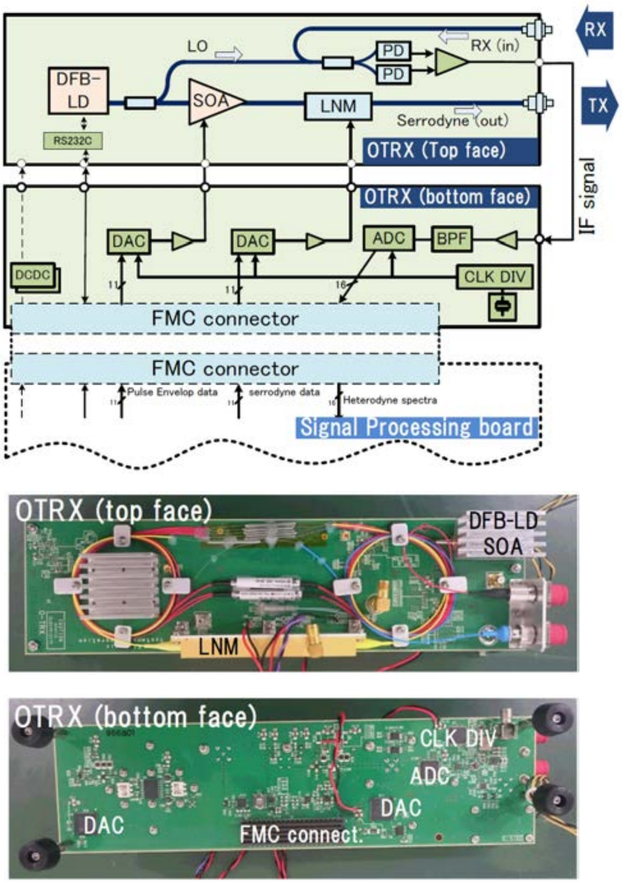

Fig. 2 Schematic block diagram and external view of the optical transceiver unit

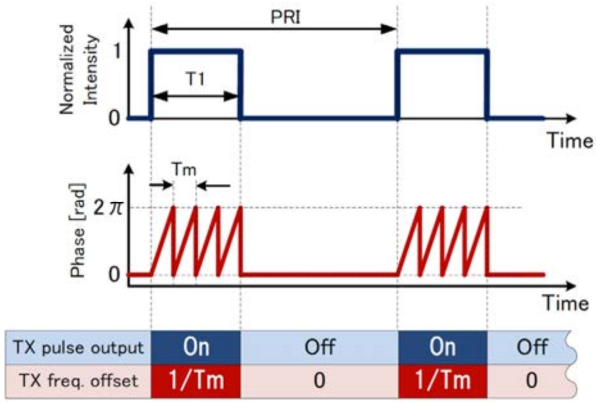

Fig. 3 Temporal signals of pulsed serrodyning modulation for the optical intensity of a SOA and the optical phase of an LNM

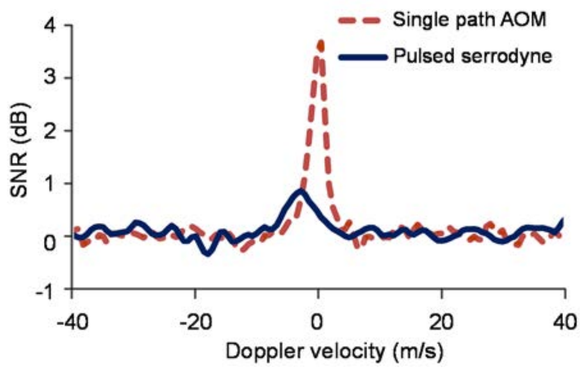

Fig 4 LOS wind Doppler spectra at distance of 500 m

makes it difficult to measure wind signals near the zero-Doppler velocity. Meanwhile, the spectrum of pulsed-serrodyne modulation has a peak at around −1 m/s without any noise peak at the zero-Doppler velocity.

Figure 5 shows the measurement data of the LOS wind velocity with respect to distance and that of their detectability. Theoretical calculation for detectability is also shown as a function of distance. The setting parameters are as follows: optical peak power of 30 W at a fiber end of an OHPA, aperture diameter of 50 mm, focusing distance of 500 m, and integration number of 4000. The back-scattering coefficient is assumed to be 8.3×10^{-8} $m^{-1}sr^{-1}$ taking into account the number of aerosols measured using a particle counter.

The measured detectability closely agrees with the theoretical curve, which indicates that the LOS wind velocities are measured up to 900 m because of the larger detectability than the detection limit of 7 dB.

Figure 6 shows the temporal variation of supplying power from fully charged batteries for continuous wind sensing under the same measurement conditions as in Fig. 5. In this figure, the present mobile CDL performed wind measurements for 5 hours 20 minutes without having to replace the battery. The average supply power was 31.4 W.

6. Conclusion

We have developed a new mobile coherent Doppler lidar for wind sensing with dimensions of 39×29×16 cm.

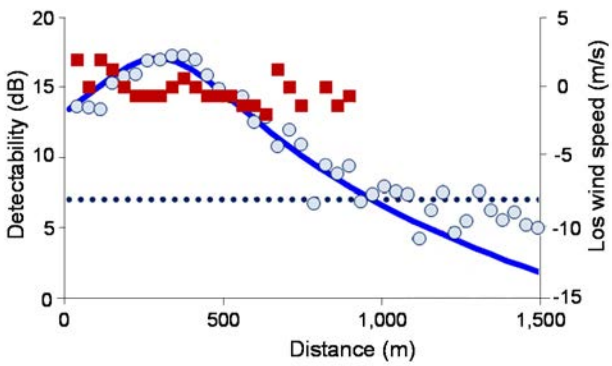

Fig 5 LOS wind velocity and detectability with respect to distance

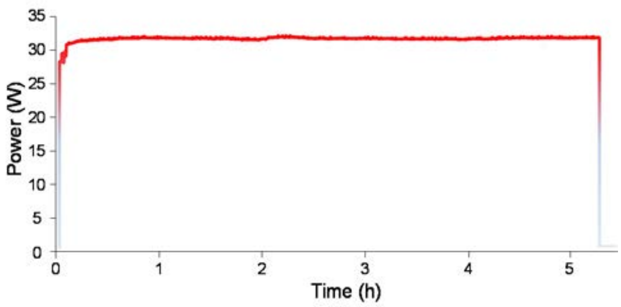

Fig 6 Battery supplying power under continuous wind sensing

Pulsed-serrodyning modulation makes it possible to realize both frequency shift and compensation of frequency chirp within the pulse-on periods of the SOA as pulse modulator. The new mobile lidar can be powered by a lithium battery and can continuously measure wind profiles for over 5 hours, thanks to the low power consumption of the optical transceiver and signal processor subsystem. Preliminary experiments have been performed by using this mobile lidar for line-of-sight wind velocities with the maximum horizontal range of more than 1 km.

7. References

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