Improvements of performance in all-fiber Coherent Doppler LIDAR (CDL) system with considering non-linear optical effects

Toshiyuki ANDO[(1)], Masashi FURUTA[(2)], Hisamichi TANAKA[(2)], Tomoya MATSUDA[(2)], Masahiro NAGASHIMA[(2)], Shumpei KAMEYAMA[(1)], and Yoshihito HIRANO[(1)]
[(1)]Mitsubishi Electric Corporation, Information Technology R&D Center
[(2)]Mitsubishi Electric Corporation, Communication Systems Center
E-mail: Ando.Toshiyuki@ap.MitsubishiElectric.co.jp

Abstract

Portable Coherent Doppler LIDAR (CDL) has been developed as a commercial product for measuring wind profile at middle range up to 1500m. Downsizing in the new CDL system has been effectively realized by small portion of packages, which is based on the all-fibre optical transceiver / receiver unit combined with a PC based signal processing unit including a FPGA pre-processor and with a compact optical antenna. Usability has also been improved with quick-looking screens (LOS velocity, PPI, RHI, Doppler spectra, and wind vector) as well as touch-panel interfaces. This paper is presented the Spectrum broadening of transmitted optical pulses due to the non-linear effects inside an optical fiber, which are observed during preparations of operating parameters in this new CDL

Introduction

All-fiber Coherent Doppler LIDAR (CDL) using wavelength of 1.5 micron has such many advantages as its eye-safety, its reliability for various environmental conditions and its flexibility for components' layouts [1,2]. Mitsubishi Electric has been developed a commercial prototype of all-fiber CDL system since 2004, which successfully made confirmations of its highly measuring accuracy based on simultaneous measurements with a conventional ultrasonic anemometer [3]. In 2005 commercial product of all-fiber CDL system (LR-05FC series) has been manufactured [4], which successfully achieved reductions not only of its dimensions but also for manufacturing cost less than 50% of the prototype system[5].

While it is well known that non-linear optical effects in an optical fiber give some limitations in measuring performances. Stimulated Brillouin Scattering (SBS) makes output optical pulses be back scattered to a fiber amplifier and then propagated again as amplified pulses which may lead damages on fiber optic components. For this, the output optical pulse has been operated with its peak power to be kept less than the SBS threshold of 10~15W. Self-Phase Modulation (SPM) is also known as a non-linear effect which induces the frequency chirp within a transmitting optical pulse, leading to offset errors on the measured wind velocities. As to this SPM influences, it has been clearly confirmed that these errors can be compensated by subtracting offset values which analytically estimated from temporal profiles of output optical pulses [6]. In the practical point of view the output power set as much as possible to obtain better Signal- to Noise Ratio (SNR), however, at peak power near the SBS threshold some temporal instabilities often occur in output pulses. These instabilities may give some degradations of optical coherence in a transmitting pulse. In the present paper influences of this instabilities in optical pulse shapes were studied.

Overview of System configuration and functions

Figure 1 shows that the outer look image of the new CDL system. The system consists of a main container (53(W)x65(H)x56(D)cm, 46kg), and an optical antenna(15(W)x15(H)x30(D)cm, 7kg) connected with an optical fiber cables, and a tripod(2kg). A main container includes a fiber-based optical transmitter/ receiver (T/R) unit, a PC based signal processing unit, and its power supply in a 19 inch 10U rack case with casters which enables us to be easily carried it as well as quickly setup(≦～5minutes) on observation sites. The total power consumption is designed less than 500VA, which makes it possible to be operated by an automobile's power outlet with a commercially available DC-AC converter. By changing the scanning scheme the system has four measuring modes as follows: Line Of Sight(LOS) wind velocity with a fixed beam direction, sectored (±20deg) Plan Position Indicator (PPI) mode with a horizontally linear beam scanning, sectored Range Height Indicator(RHI) mode with a vertically linear beam scanning, and Velocity Azimuth Display(VAD) mode with a conical beam scanning. Note that a center direction in the scanning range (center angles of azimuth and elevation) can be automatically obtained by using a digital magnetic compass mounted on an optical antenna (optionally installed), translated into each beam direction with wedge rotating angles.

In this new CDL it has been considerably improved its usability with simultaneously refreshed quick-looking screens (LOS velocity, PPI, RHI, Doppler spectra, and wind vector) as well as touch-panel user interfaces. Figure 2 shows that an example of screen image (anemometer mode), which indicates horizontal wind speed direction, and vertical wind speed with respect to the measuring range. The refresh rate of these screens is up to a few Hz depending on the scanning rate. It is also noted, a real-time monitor of

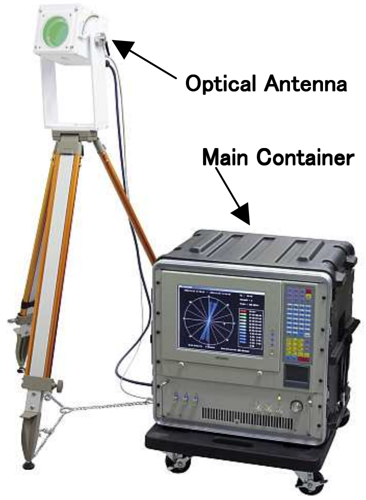

Fig. 1 Outer look of the Portable CDL system

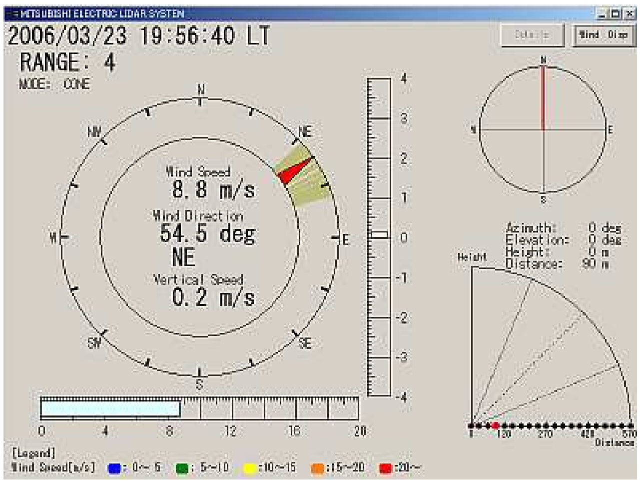

Fig.2 Example of quick look screen (anemometer mode)

Doppler spectra enables us to be quickly comprehended whether the observation could be correctly performed on site. Furthermore measuring results are simultaneously stored in the disk drive as time series data files with a spread-sheet format, and are easily displayed back again by loading these files.

Figure 3 shows that the block diagram of the new CDL system. The optical TRX unit is combined a MOPA (Master Oscillator Power Amplifier) transmitter with an optical heterodyne receiver in which all optical components are connected by polarization maintaining fiber. The optical parameters of the system are follows: The wavelength of 1.54 μ m, pulse duration of 200, 500 and 1000ns, Pulse Repetition Frequency (PRF) of 4kHz (16kHz optional), transmitting pulse energy of 1.8~4.6 μ J, and aperture diameter of 60mm.

PC based signal processing unit with a Field Programmable Gate Array (FPGA) pre-processing

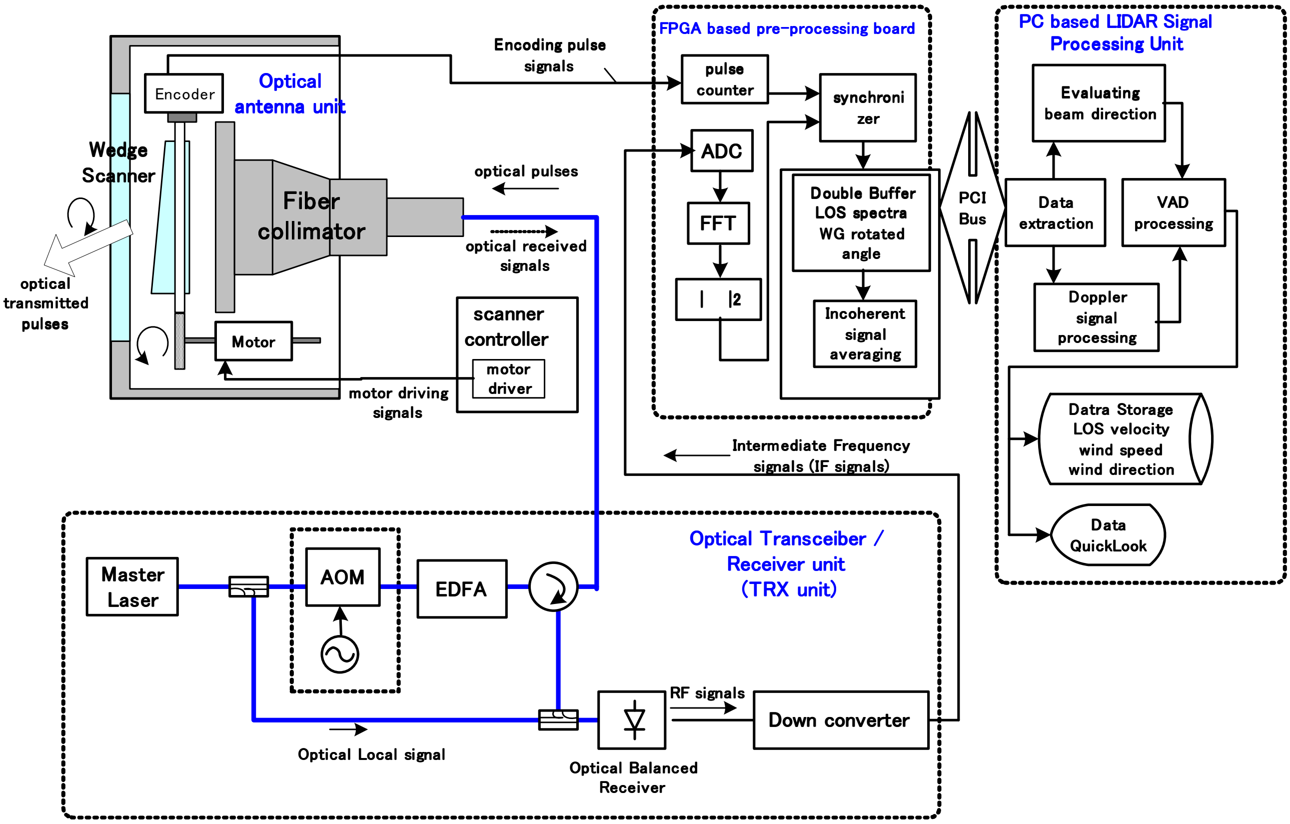

Fig.3 Block diagram of the Portable Coherent Doppler LIDAR (LR-FC series) system

board enables to be performed 256-points Fast Fourier Transform (FFT) of 20 range gates with sampling rate of 216MS/s at PRF up to 16kHz. Details of the system components and their functions were described [5].

Spectrum broadening of transmitted pulses near SBS thresholds

In our previous study, the SPM induces some offset in the center frequency of Doppler spectra as the average of the instantaneous frequency deviations over a single pulse duration[6]. In the SPM the instantaneous frequency deviations are appeared to be proportional to temporal variation of the output optical power through the fiber. Actually larger offsets are appeared in the Doppler frequency under the short pulse rather than the long pulse, because of the steeply temporal variation of the output power at short pulse. While, the distortions are observed in temporal pulse shapes of output pulses at their peak power close to the SBS threshold. These distortions are mainly appeared as a dip caused by in the pulse profiles. It is reason why the SBS backscattered pulses reduces forward amplified pulses in the EDFA (gain depression). According to the dip due to SBS effects, SPM may increase the frequency deviation at the dip. Figure 4 shows that the temporal profiles of the output pulses and their spectra with a local signal at output powers near the SBS threshold. The beat spectra are obtained by FFTs of 1usec-gated data of digitized beat signals at sampling rate of 1.2 GS/s. The output powers are (a) 14.9W, (b)13.6W, respectively. A dip in the pulse shape was observed at 0.1 μs after rising edge in fig.4(a). As to the beat spectra, temporally stable spectrum in fig.4(b) has been observed with its spectrum width of about 2 MHz, whereas the spectrum width in fig.4(a) has found to be spread about 3～4 MHz with temporal instability because of the stochastic properties of SBS.

In order to confirm whether this spectrum broadening is caused by temporal average of the SPM induced frequency deviations over a pulse duration, we have simultaneously acquired the spectrum widths of input and output pulses of an Erbium Doped Fiber Amplifier (EDFA). Figure 5 shows that 30-minutes time series of the output peak powers and their spectrum widths before and after amplified by EDFA. Output powers are set as same as those in fig.4. It is clearly found that the spectrum width of output pulses in fig. 5(a) has been broader than that in fig.5(b), whereas spectrum widths of input pulses for EDFA have a same width of 2MHz under both condition of output peak power. This means that the spectrum broadening has been mainly occurred nothing but output pulses after amplified by EDFA in the case where a dip has been appeared in the output pulses. Output power of (a) 14.9W, (b) 13.6W, corresponding to fig.4 (a) and (b), respectively.

The bottom plots represented spectrum widths of beat signals b/w local and seed pulse for EDFA.

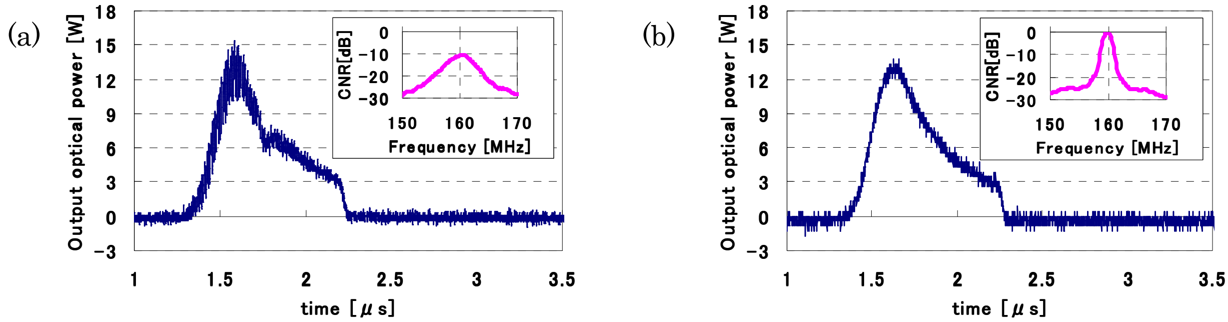

Fig.4 Pulse shapes of output optical pulses and their beat spectra near the SBS threshold
Output optical powers are (a) 14.9W, (b) 13.6W.

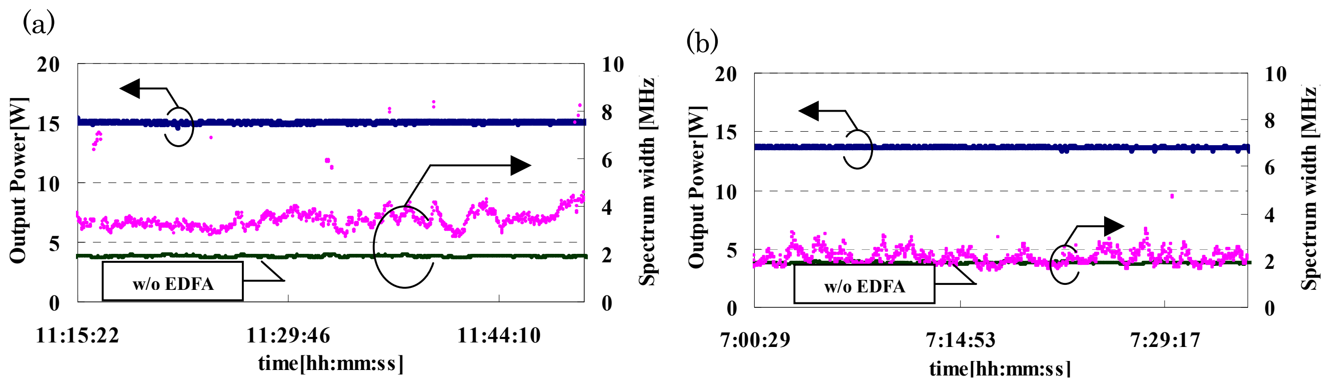

Fig.5 30 minutes time series data of output peak power and spectrum widths of beat signals between local and transmitting optical pulse.

Figure 6 shows that the histograms of the spectrum widths of transmitted optical pulses as shown in fig.5. The cumulative averaged values of spectrum widths, Δν ,are estimated as 1.96MHz at output power, Po of 13.6W, and 3.50MHz at 14.9W. It is found that the averaged spectrum width in the output pulse of the EDFA at output power of 13.6W has been marked as same as that of input pulse of EDFA. Note that the spectrum width in fig.5(b) has also temporally fluctuated nevertheless the temporal profile is smooth as shown in fig.4(b). These results suggest that the output pulse power should be carefully set by taking into account of temporal variation of the spectrum width.

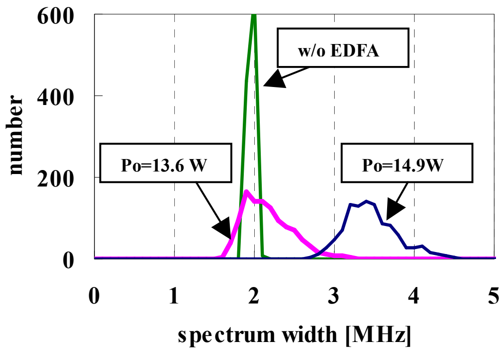

Fig.6 Histograms of the spectrum width of transmitting optical pulses

In the theoretical point of view of the CDL, the Signal to Noise Ratio (SNR) of the Doppler spectra for measuring wind is presented as following CLR equation [8],

$$SNR(L) = \frac{\eta_D(L)\lambda \cdot E \cdot \beta \cdot K^{2\frac{L}{1000}} \cdot \pi \cdot D^2}{8h \cdot B \cdot L^2}$$

where h is the Planck's constant, E is the transmitting pulse energy, B is the bandwidth, β is the atmospheric backscatter coefficient, K is the atmospheric transmittance, λ is the wavelength, D is the effective aperture diameter, and L is the measuring distance. $\eta_D(L)$ is the system efficiency depending on the beam focusing distance, wavelength and transverse coherent length [8].

According to the above equation, the SNR is proportional to the value of E/B for the same atmospheric and system conditions. Furthermore, if the variations in wind speed are negligibly small, this E/B value may be approximately proportional to Po/Δν , because E is obtained by Po multiplying pulse duration. In the present experiments, the values of $10\log[P_o/\Delta\nu]$ at output power of 13.6 [W] was evaluated greater than that at output power of 14.9 [W] by the difference of 2.1[dB] even if few power in output pulses.

This means that the criterion of the measuring performance for CDL system may be estimated by the pulse energy to spectrum width ratio with respect to each of pulse condition, and that it should be maximum by changing the peak power of output pulses.

Conclusion

Portable Coherent Doppler LIDAR (CDL) has been summarized as a commercial product (LR-05FC series), about its system configuration and its measuring functions. Then spectrum broadening of transmitted optical pulses has been studied to set operating parameters of this new CDL. It has been turned out that the SBS induced temporal distortions in the output pulses as well as the spectrum broadening within a pulse duration caused by SPM. The measuring performance for CDL system may be estimated by the criterion of pulse energy to spectrum width ratio which should be maximum by changing the peak power of output pulses. This criterion has been applied to the new CDL system, and effectively made the spectrum widths in output pulses to be kept as much as that of the master laser, leading to maximum SNR for Doppler spectra. It is also worthy to note that this study may be much useful not only for customizing the operating conditions to various deployments (e.g. different length of fiber cable between optical transceiver and antenna) but also for making a diagnosis on the system performance for various environmental conditions on site.

References

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