Innovative Fiber-Laser Architecture Based Compact Wind Lidar

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Abstract: This paper describes an innovative, all-fiber, compact, and eyesafe coherent lidar system developed for wind and wake vortex sensing applications. The all-fiber lidar, with modular architecture, incorporates an integrated 3D scanner that provides user programmable, continuous 360 degree azimuth and 180 degree elevation scan angles. Operating at 1.54 microns, the lidar allows pulsewidth agility from 50 - 400 ns with a variable PRF of up to 20 KHz. The wind lidar is air cooled with overall dimensions of 30 cm x 46 cm x 60 cm and is designed as a Class 1 system. This lidar is capable of measuring wind velocities greater than 120 +/- 0.2 m/s over ranges greater than 10 km and with a range resolution of less than 15 m. In this paper, the key features of lidar instrumentation and its functionality are discussed followed by results of recent wind forecast measurements on a wind farm.

Keywords: Coherent lidar, wind lidar, all-fiber lidar, 3D scanner

1. Introduction

The ability of coherent lidar systems to produce a continuous, real-time 3D scan of wind velocities via detection of backscatter of atmospheric aerosols in clear-air conditions and at long stand-off distances with relatively low pulse energy gives this technology a clear advantage over other atmospheric monitoring technologies. Lidar systems have proven their value in the remote measurement of spatially resolved atmospheric wind velocities in a number of applications, including the detection of clear-air turbulence, wind shear, microbursts, and aircraft wake vortices [1,2]. The technically mature and commercially proven wind lidar system in the world is the solid-state laser based WindTracer® lidar systems. WindTracer® lidar, first built in 1998 by Coherent Technologies, Inc. (CTI) (now known as Lockheed Martin Coherent Technologies, LMCT), have effectively been used worldwide for more than a decade to detect hazardous winds and aircraft wakes. However, emerging optical fiber laser and fiber amplifier in combination with 3D printing technologies are anticipated to further enhance the wind lidar architecture and expand its utility to various other applications including wind farming. These technologies have the potential to provide a versatile system by reducing overall size, weight, and power (SWaP), and significantly lowering downtime of current solid-state laser based systems. Besides cost advantage, these systems with low SWaP and long range capability could operate in demanding environments and provide a viable path for airborne and space borne applications. Accordingly, to overcome the disadvantages of current systems to a large extent, an eye-safe wind lidar with all-fiber architecture using commercial-off-the-shelf (COTS) components was developed. In this paper, the wind lidar system known as Windimager™, developed by Sibell Optics under NASA SBIR funding [3,4] with emphasis to enhancing range, sensitivity, system efficiency and reliability, while simultaneously reducing SWaP requirements, is discussed.

2. All-Fiber Wind Lidar Architecture

Figure 1 illustrates the wind lidar system architecture with optical and electrical interconnects. It can be physically separated into four modules: (1) the Scanner Head assembly, (2) the UPS unit, (3) the

Environmental Control unit, and (4) the Computer / DAQ unit. Each sub-assembly is an environmentally sealed unit and the four modules can be assembled into the full sensor system in a matter of minutes. The optical interconnects are the polarization maintaining single mode optical fibers. The Scanner Head Assembly consists of the fiber transmitter system, the telescope, and the hemispherical scanner itself, all housed within the scanner dome. The heart of a lidar sensor is the laser transmitter system and is shown in Figure 2 along with the transmit telescope (both part of the Scanner Head Sub-Assembly). Each major component of the sub-assembly is a fiber-coupled, self-contained unit that can be easily replaced, without the necessity of re-alignment if the component should fail. The Fiber Transmitter System is configured as a fiber-based Master Oscillator/Power Amplifier (MOPA) architecture. It consists of COTS components including a seed laser, a CW pre-amplifier, a pulse slicer, and a single mode CW EDFA as the first fiber preamplifier. Pulsed operation is accomplished by chopping the MO output by the acousto-optic modulator (AOM). The first preamplifier is then followed by a custom designed second fiber preamplifier and a Large Mode Area (LMA) EDFA. The fiber reels holding optical fibers are printed nylon parts. The novel fiber-amplifier network, beam-combined provides over 400 μJ of energy per pulse and the system can run between 3 kHz – 20 kHz. The MO provides an extremely narrow linewidth (3 kHz) and low RIN (-145 dB/Hz). The telescope used in this system is a Dall-Kirkham type with an aperture size of 114 mm and 25x magnification. Unlike all other scanners that use mirrors and rotating wedges to steer beams of light, the Windimager™ scanner rotates the light source itself – specifically the fiber lidar/telescope assembly. This design has several advantages. Most significantly it reduces the overall complexity of the unit, which in turn improves reliability. In addition, optical scatter and polarization losses are eliminated, thereby improving the lidar performance. The Windimager™, also features two unique components that improve the sensitivity, range and performance of the sensor. The first component is the use of a balance detector for both the monitor and the signal detection and the second one is a fiber coupled optical switch that is placed between the DFB output and the AOM to prevent a reflected acoustic pulse-generated optical signal. The "Back-Propagated Local Oscillator (BPLO)" alignment using quad cell allows performance optimization on the fly. The custom designed detector and its novel use to obtain optimum beam alignment is a significant advancement in the maintainability and manufacturability of lidar systems. The detector's frequency response is flat to within 2 dB over 250 MHz. The detector electronics is capable of detecting as few as 8 photons, which is within an order of magnitude of the theoretical limit.

The lidar system is air cooled with overall dimensions of 30" (W) x 46" (L) x 60" (H). The compact modular design allows for easy transport and rapid setup. Its features include: improved system sensitivity, continuously variable pulsewidth, compact packaging in a standard 19-inch rack, reduced complexity coupled with high-end components to maximize reliability, a unique 3D wind data display to enable easy interpretation of atmospheric conditions, and compact, rugged, modular and lightweight construction to allow for easy deployment in a variety of harsh environments. Some of the key features that separates it from the currently available free-space and fiber LIDAR systems are:

- Rapid fire rate that allows for quick and detailed atmospheric profiling
- Pulsed fiber laser technology yields excellent range and wind velocity accuracy
- Variable pulse width operation that adapts for various modes of wind measurements
- Reduced complexity coupled with high-end components maximizes reliability
- Compact, rugged, modular and lightweight construction allows for easy deployment in a variety of harsh environments
- Fiber optic, 1.55 μm architecture is easily upgradeable to higher power and greater range configurations while still remaining eye-safe
- Real-time data-processing and display update
- User GUI allows multiple application-based operating modes and scan scenarios.
- Custom 3D wind data display enables easy interpretation of atmospheric conditions
- All conduction or convection thermal control – no liquid cooling
- Significantly less expensive than systems with comparable performance

- High electrical efficiency allows the system to run on battery power up to 24 hours.

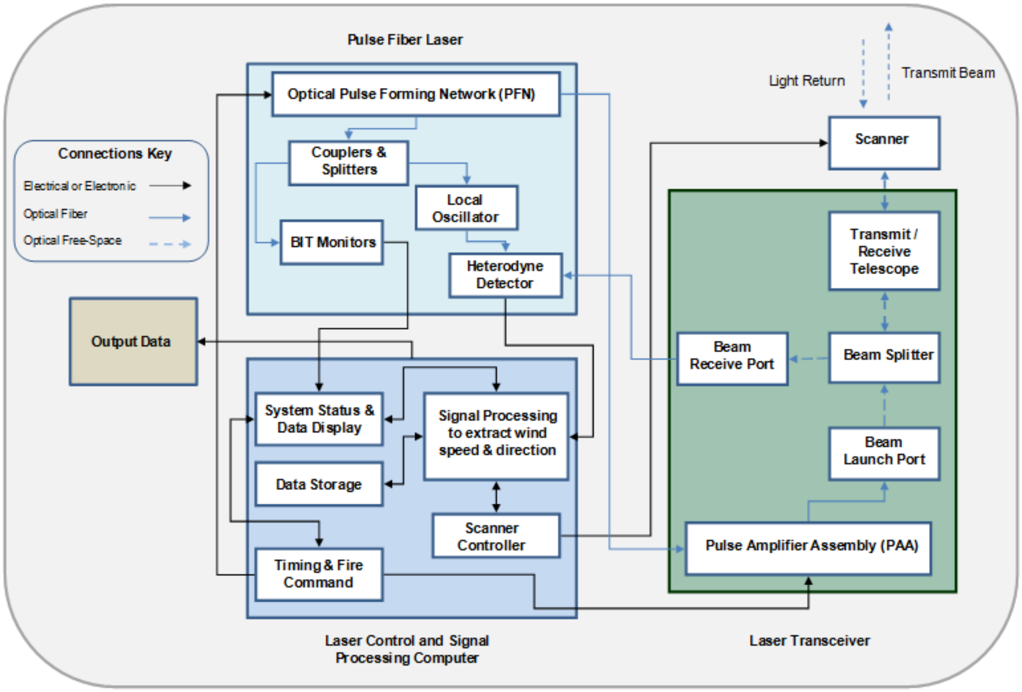

Figure 1. General system architecture of the Windimager™ lidar system.

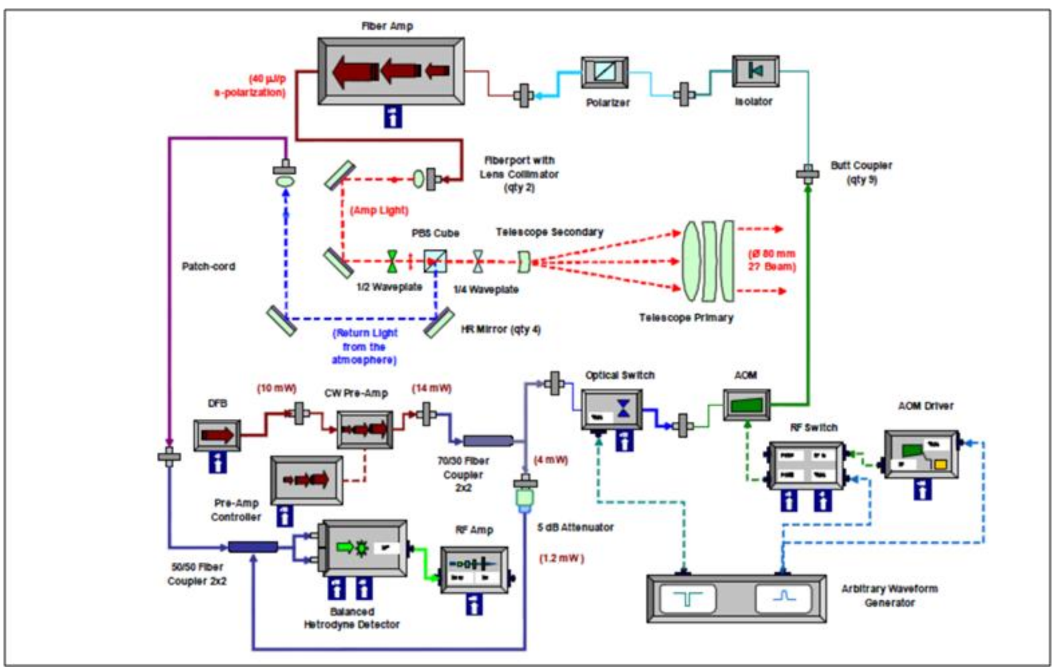

Figure 2. Block diagram of the fiber-coupled transmitter and telescope architecture.

Table 1 lists the overall specifications and Figure 3 shows the wind lidar system. Previously, heat maps (Range, km vs. Wind speed, m/s characteristics) representing horizontal single line-of-sight (LOS) returns collected by the Windimager™ lidar located facing the Rocky mountain range near Boulder, CO from a distance greater than 9 km, and BPLO alignment and other system aspects have been discussed in detail [5,6]. In the following section, the performance of the Windimager™ lidar which was successfully tested on a wind farm on the Southeast coast of Aruba for wind field forecasting purposes is discussed.

Table 1. Specifications of the all-fiber wind lidar.

Transmitter:	
Typical Horizontal Detection Range:	400m to 10km
Minimum / Maximum Detection Range:	50m / 15km
Maximum Radial Velocity:	" 127m/s
Velocity Accuracy:	" 0.2m/sec
Range Resolution:	7.5m (minimum), adjustable
Wavelength:	1547nm " 3nm
Output Beam Diameter (1/e ^{2}):	80mm
Laser Classification:	Class 1
Pulse Temporal Profile:	Near Gaussian
Output Pulse Options :	

Pulse Width (ns)	Pulse Energy (uJ)	Rep Rate (Hz)	Output Power (mW)
50	35	20,000	700
90	70	15,000	1050
170	115	10,000	1150
200	140	8,000	1120
330	220	5,000	1100
400	240	4,000	960

Scanner	
Elevation Scan Range / Rate:	360 ƒ continuous, 40 ƒ / sec (max)
Azimuth Scan Range / Rate:	360 ƒ continuous, 40 ƒ / sec (max)
Unidirectional Repeatability:	0.002 degrees
Min Incremental Motion:	0.001 degrees
Absolute Positional Accuracy:	" 0.01 degrees
Scan Resolution:	Up to 10,000 points / PPI scan
Scan Modes:	PPI, RHI, complex group motion, or combination
Scan Patterns	User Programmable
Rotation Stages MTBF:	20,000 hours
Optical Clear Aperture:	101 mm

Signal Processor:	
Operating System:	MS Windows
Graphical User Interface: System	NOTUS Data Collection
CPU:	Intel Core i7-820QM, 1.73 GHz
Memory:	4 GB DDR3
Hard Disk Drive:	Up to 24 TB, RAID array
Digitizer Card:	750 MS/s sample rate, 16 MB RAM, 8 bits/sample
Timing:	GPS, IEEE-1588 or IRIG-B
Additional Sensors:	GPS, Compass (Optional)
Input Devices:	Ethernet
Network:	100BaseT
Size & Weight:	
System Dimensions:	30-in (W) x 46-in (L) x 60-in (H)
System Weight:	800 lbs (364 kg)
Environmental:	
Operating Temperature:	-40° to +55° C
Storage Temperature:	-25° to +40° C
Cooling System:	Air-cooled
Power Requirements:	
Input Power:	1100 W Max, 550 W Typical
Service Circuit Req:	20 Amps
Voltage (single phase):	100-250 VAC, 50/60 Hz

Figure 3. The Windimager™ lidar unit. Left Picture: (1).Hemispherical scanner, (2). Air cooled unit. Right Picture The internal arrangement. (1).The lidar transceiver chassis. (2). The UPS unit

4. Wing Energy Harvesting

With the system running at 4000 Hz and the pulse averaging set to 1000 shots, PPI maps similar to the one shown in Figure 4 are generated. With an average wind speed of 32 km/h for example (typical for Aruba), the system gives a 17 minute advance warning of sudden drop offs in wind speed. In the event that the wind speed increases abruptly, from 32 to 80 km/h for example, then the system will give a 7 minute advance warning - which is enough time to pitch the turbine blades and prevent possible damage to the gear boxes. Further validation tests are progressing.

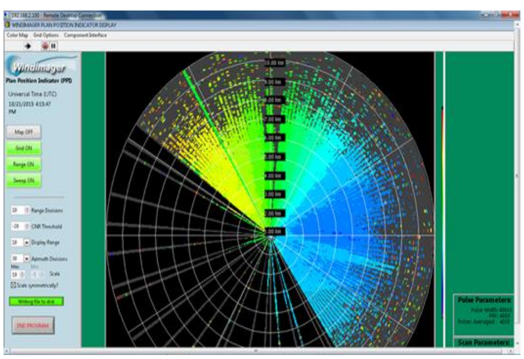

Figure 4. A wind map generated in an Aruba wind farm.

4. Summary and Conclusions

The salient features of the development of an all-fiber, modular, compact architecture based 1.55 micron wind lidar with an integrated, novel 3D hemispherical scanner for wind sensing and wake vortex applications are presented. Successful field test results carried out for wind forecasting on a wind farm in Aruba are presented. The compact all fiber, Windimager™ class of technology system has the potential to provide a developmental path for several applications including wind field forecasting for wind energy harvesting.

5. References.

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