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A COMPACT, ALL SOLID-STATE COHERENT DOPPLER Nd:YAG LASER RADAR FOR WIND PROFILING

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1. Introduction

Coherent Doppler laser radars have proven to be useful for remote wind velocity measurement. Most coherent laser radar systems have employed CO_2 lasers[1]. Since Kane et al.[2] first demonstrated the feasibility of a Nd:YAG coherent laser radar for wind field measurement in 1987, solid-state coherent laser radars with wavelengths of 1~2 μm have been rapidly developed in the past decade[3~5]. Solid-state lasers with their shorter wavelengths offer the advantages over the longer wavelengths such as CO_2 lasers (9~11μm) of small beam divergence, and better range resolution for the same wind velocity resolution.

In these coherent laser radar systems, a laser diode (LD) pumped cw master oscillator combined with a flashlamp-pumped pulsed laser amplifier[2,3] or an injection-seeded, flashlamp-pumped slave laser with a cw master laser[3,4] was used. In the case of a cw oscillator combined with pulsed amplifier scheme, extremely high optical gain of the laser amplifier is necessary to obtain enough laser output. In the case of injection-seeding scheme, a long laser cavity is usually necessary to obtain long duration of laser pulses 100~500 ns. The laser pulse duration is a main factor to limit the velocity measurement resolution of laser radar systems.

In this paper, a compact all solid-state coherent Doppler Nd:YAG laser radar system at wavelength of 1.06 μm is reported. This coherent laser radar scheme uses a LD-pumped, long pulse Q-switched, and single frequency Nd:YAG laser oscillator combined with a laser amplifier as the transmitter and a cw $Nd{:}YVO_4$ microchip laser[6] as the local oscillator. The laser pulse duration can be varied from 60~220 ns by changing the LD-pumping energy of the Nd:YAG master oscillator. This laser radar system has characters of small laser volume of 40X20X10 cm^3, simple construction and is developed for measuring the tropospheric wind velocity from the ground with high velocity resolution.

2. Laser Radar System

Figure 1 shows a schematic of the compact all solid-state coherent Doppler Nd:YAG laser radar system.

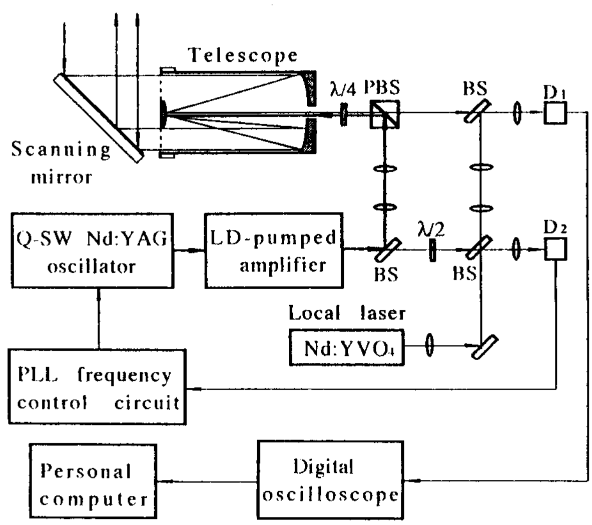

Fig.1 Schematic of the 1.06 μm Nd:YAG coherent Doppler laser radar. An LD-pumped, Q-switched Nd:YAG master oscillator with a LD-pumped, pulsed Nd:YAG amplifier and a $Nd{:}YVO_4$ microchip local oscillator are used in the system. (PBS, polarization beam spliter; PB, beam spliter; D_1, signal detector; D_2, reference detector.)

The laser transmitter consists of a single-LD side pumped, Q-switched Nd:YAG master oscillator and a three LD-pumped laser amplifier. In order to obtain long pulse duration laser output, the master oscillator was designed to exhibits uniformly distributed low single-pass gain and a long cavity lifetime with a short cavity length (180 mm). The laser pulse duration varies with the LD-pumping energy. When the laser pulse duration changes from 60 to 220 ns, the pulse output energy varies from 400 to 100 μJ. The single longitudinal mode is selected by an etalon, and an iris of 1 mm diameter is used to obtain TEM_{00} transverse mode. The amplifier is a multi-pass structure and is side-pumped by three LDs with the total energy of 75 mJ and the output obtained is 8~10 mJ.

The local oscillator of the coherent laser radar system is a cw $Nd:YVO_4$ microchip laser with the output of 10 mW.[6] The PLL feedback control loop is used to lock the frequency of the pulsed Nd:YAG master oscillator by changing the cavity length to the frequency of the local $Nd:YVO_4$ microchip laser with an offset frequency (intermediate frequency) of 50~150 MHz. This offset frequency can be changed by adjusting the reference frequency applied to the PLL. The pulse-to-pulse offset frequency drift is less than 0.5 MHz.

The laser radar system uses a Cassegrainian telescope to transmit the laser beam and collect the return signal. The laser beam is off-axially transmitted to the atmosphere by the telescope, avoiding the back reflection of the laser beam by the secondary mirror of the telescope. Two InGaAs PIN photodiode detectors, with a response time of 2 ns, are used in the system as signal and reference detectors. The output signal of the reference detector is fed to the frequency control circuit to stabilize the offset frequency. The output of the signal detector is sent to the signal processing unit to obtain the wind velocity.

The signal processing unit consists of a Tektronix 320 digital oscilloscope with sampling rate of 500 Ms/s and an IBM ThinkPad 750CS personal computer. The discrete Fourier transform (DFT) is a simple signal processing method and the fast Fourier transform (FFT) algorithm is used to obtain the range-resolved, radial wind velocity.

Detailed specifications of this coherent Doppler laser radar system is summerized in Table 1.

Table 1 Summary of Nd:YAG coherent Doppler laser radar system specifications.

<u>Transmitter</u>	
Laser:	LD-pumped, Q-switched Nd:YAG master oscillator, LD-pumped Nd:YAG amplifier
Wavelength:	1.064 mm
Pulse energy:	8-10 mJ
Pulse duration:	60-220 ns
Repetition rate:	30 Hz
<u>Receiver</u>	
Telescope:	Cassegrianian, 18 cm diameter
Detector:	InGaAs PIN Diode, 1 mm diameter, 2 ns response time
Local oscillator:	cw $Nd:YVO_4$ microchip laser, 10 mW output power
<u>Signal Processor</u>	
Offset frequency:	50 - 150MHz
Frequency stabilization:	< 0.5 MHz
Digitizer:	Tektronix 320 digitizing oscilloscope

3. Estimation of Velocity Resolution

The FFT is a spectral analysis algorithm for processing the signal frequency and is widely used in coherent Doppler laser radars to estimate radial wind velocity. First, the return signal detected from a single pulse is digitized to generate the range resolved time series of the sample. This time series is then Fourier transformed to form the periodogram (sample power spectrum). Second, the independent periodograms obtained from different pulses scattered from the same scattering volume are averaged to form the accumulated periodogram. The spectral peak is determined from this accumulated periodogram to estimate the wind radial velocity.

The FFT Doppler processor velocity error or velocity resolution can be obtained from Ref. 7 after small modification, and is given by

$$\sigma_v(R) = \upsilon_{Ny}\left(\frac{1}{M}\right)^{1/2} \times\left[\frac{W}{4\sqrt{\pi}} + \frac{2W^2}{SNR_W(R)\sqrt{N}} + \frac{1}{12SNR_W^2(R)N}\right]^{1/2}, (1)$$

where $\upsilon_{Ny}=\lambda/2T_S$ is the Nyquist velocity, T_S is the sampling time spacing, M is the number of digitized samples in the range gate width Tg (= MT_S), N is the average number of pulses, W is the ratio of the velocity spread to the Nyquist velocity ($\delta\upsilon/\upsilon_{Ny}$, $\delta\upsilon$ is the velocity spread of the radial wind in the scattering volume), $SNR_W(R)$ is the wideband signal-to-noise ratio of the return signal from range R.

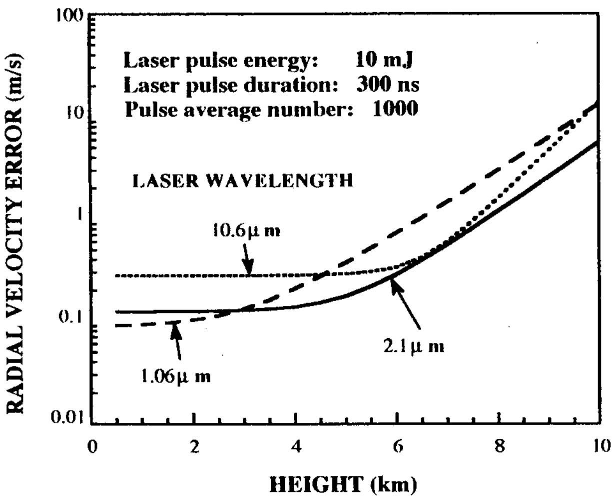

Fig. 2 Calculated radial wind velocity error versus height at wavelengths of 1.06, 2.1 and 10.6 μm in the presence of the weak atmospheric turbulence ($C^2_n(1m) = 10^{-13} m^{-2/3}$).

The radial velocity errors have been calculated as a function of height and compared at the laser wavelengths of 1.06, 2.1 and 10.6 μm as shown in Fig.2. In the calculation, exponential decreasing mode of the aerosol density with height [8] and λ^{-2} wavelength dependence of β are assumed[9] and in the presence of the weak atmospheric turbulence ($C^2_n(1m) = 10^{-13} m^{-2/3}$). The laser pulse duration is 300 ns for three wavelengths with the pulse-duration limited range resolution of 45 m and the pulse average number is 1000. Only the velocity spread due to the pulse dauration is considered.

The results shows that at the lower height the 1.06 μm Nd:YAG coherent Doppler laser radar offers higher velocity resolution. By increasing the pulse average number, even higher velocity resolution can be obtained.

4. Conclusion

An all solid-state coherent Nd:YAG laser radar was designed and constructed. This laser radar system is compact and easily movable, and gives better range and velocity resolution. We are using this coherent Doppler Nd:YAG laser radar system to measure the wind profile in the lower tropospheric atmosphere.

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