Front. Optoelectron. China 2011, 4(4): 411–414
DOI 10.1007/s12200-011-0148-7

RESEARCH ARTICLE

A speed measurement system utilizing an injection-seeded Tm:YAG laser

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Abstract A speed measurement system utilizing a stable single frequency Q-switched Tm:YAG laser was presented in this study. The maximum pulse energy of the laser was 2.38 mJ with the pulse repetition rate of 100 Hz. Using the speed measurement system, the revolving speed of a rotating target could be measured by optical heterodyne detection technique and the maximum measurement error was 0.68 m/s.

Keywords speed measurement, optical heterodyne, Tm:YAG, seeding injection

1 Introduction

Eye-safe 2 μm coherent Doppler wind lidar has a wide range of applications [1–3]. High stable single frequency Q-switched 2 μm lasers are required in coherent Doppler wind lidar systems for the measurement of wind field. Injecting a continuous wave (CW) single-frequency laser into a Q-switched laser is a useful method for obtaining stable single-frequency Q-switched laser [4–6].

Several seeding injection techniques have been developed over past few decades. The Q-switch build-up time technique was one of the earliest approach for seeding injection [7]. The disadvantage of the Q-switch build-up time technique was its limited capability to suppress external disturbance. The Pound-Drever-Hall method was another efficient seeding-injection method, but the setup was usually complex [8]. The ramp-hold-fire technique was widely used since it was developed, due to its capability of suppress significantly high disturbance and simple setup [9,10]. Compared with other methods, the ramp-hold-fire technique was more suitable for the stable operation of the injection-seeded single-frequency 2 μm laser. Utilizing the ramp-hold-fire technique, the frequency fluctuation of the injection-seeded laser was reduced and the speed measurement accuracy was improved.

The application of an injection-seeded Tm:YAG laser in speed measurement system was described in the following sections. The optical heterodyne detection technique used to measure the line-of-sight velocity of a rotating target was also discussed. Compared with the incoherent detection technique, the sensitivity of the measurement system by using the optical heterodyne detection was much higher [11]. Utilizing the speed measurement system, the revolving speed of a rotating target was obtained and the maximum error was 0.68 m/s.

2 Experimental setup

Experimental setup used in this study consisted of master laser, slave laser and speed measurement system, as shown as Fig. 1. The master laser was a diode-pumped double-diffusion-bonded monolithic Tm:YAG nonplanar ring oscillator (NPRO), reported by our group years ago [12]. The NPRO Tm:YAG laser had the advantages of high stability and narrow line width. The master laser was isolated from the slave laser by an optical isolator, and the laser beam was split by polarizing beam splitter (PBS) into two parts, one part for seeding injection, the other part for the speed measurement system as a reference signal. In order to match the mode of the master laser with the mode of the slave laser, a coupling system was employed.

The slave laser was a double-end pumped acousto-optic (AO) Q-switched Tm:YAG laser. Two fiber-coupled 785 nm laser diodes were used as the pump source. The output beams from both laser diodes were focused into the Tm:YAG crystal through coupling lens (CL). The waist diameter of the pump beam in the Tm:YAG crystal was about 300 μm. The size of Tm:YAG crystal was φ 4 mm×10 mm. In order to obtain linearly polarized laser, a polarizer was inserted into the cavity as a reflector. The input mirror (IM) and two 45° dichroic flat mirrors (45° HR) were coated with anti-reflection (AR) at 785 nm

Received May 06, 2011; accepted June 29, 2011

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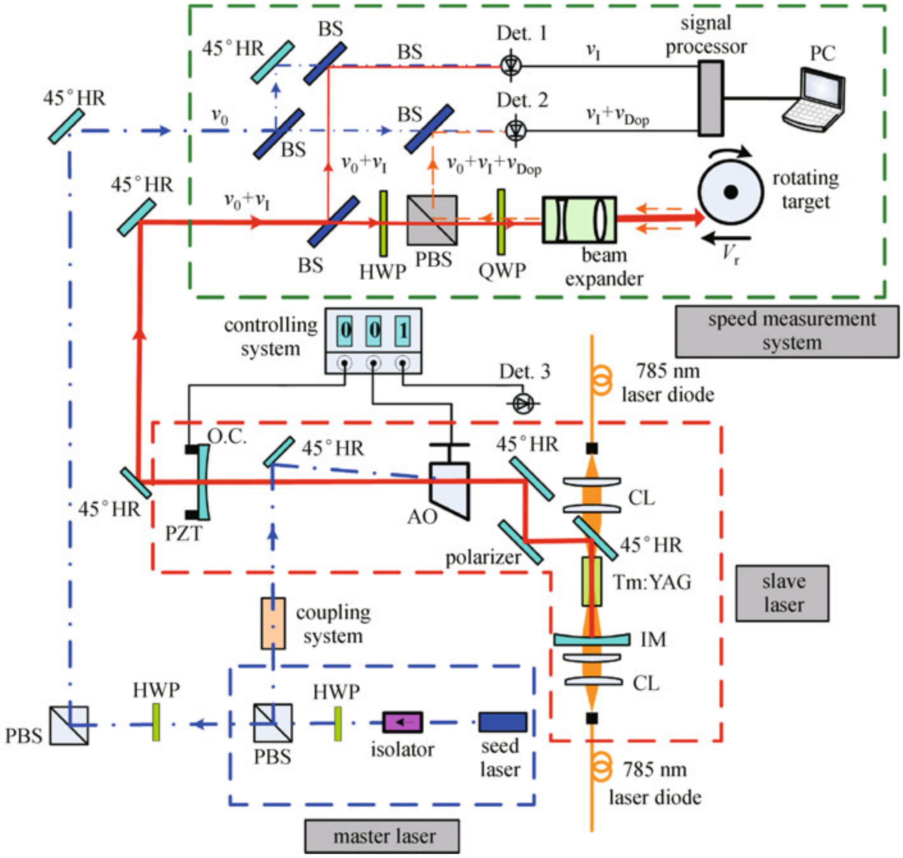

Fig. 1 Schematic of the 2 μm injection seeded Tm:YAG Q-switched laser and the coherent detection part of the speed measurement

and high-reflection (HR) at 2 μm. The output coupler (O. C.) was a plano-concave mirror with 500 mm radius of curvature. The output coupler was mounted on a piezo-electric transducer (PZT) which was driven by the ramp voltage to change the cavity length. The slave laser was Q-switched by a fused-silica, acousto-optic modulator with 27.4 MHz operating frequency. Diffraction appeared when the radio frequency power was turned on, and the master laser was focused into the slave laser through the diffraction of the Q-switch module.

In order to realize the ramp-hold-fire technique, an active controlling system was designed to make the slave laser resonate with the master laser. The ramp-hold-fire process had been described in Ref. [10].

The revolving speed of a rotating target was measured using the 2 μm injection-seeded Tm:YAG laser. As shown in Fig. 1, a portion of the laser pulse ($\nu_0+\nu_I$) was transmitted onto the rotating target through a beam expander. The reflected signal was Doppler-shifted by the revolving speed of the target and the Doppler-shifted frequency (ν_{Dop}) was proportional to the line-of-sight speed of the rotating target (V_r). The reflected signal was separated from the outgoing laser pulse by a quarter-wave plate (QWP) and a PBS. The reflected signal was photo-mixed with the master laser on Det. 2.

3 Optical heterodyne technique and experimental results

The Doppler-shifted frequency ν_{Dop} was measured by optical heterodyne measurement of the reflected signal and the reference signal. The process of heterodyne detection was shown in Fig. 2. The electric fields of reflected signal and reference signal were expressed as

$$E_1(t)=A_1(t)\exp\left[i2\pi(\nu_0+\nu_I+\nu_{Dop})t\right]+c.c., \quad (1)$$

$$E_2(t)=A_2\exp\left[i2\pi\nu_0 t+i\phi(t)\right]+c.c., \quad (2)$$

where A_1 was the electric field amplitude of the reflected signal. A_2 was the electric field amplitude of the reference signal. $\phi(t)$ was phase perturbations of the reference signal relative to the reflected signal. $c.c.$ was complex conjugated.

The detected signal contained the sum and difference frequency of the reflected signal and the reference signal. The sum frequency could not be detected due to the limited bandwidth of the detector. But the difference was an intermediate frequency (IF) signal that could be detected accurately. The intensity of the detected signal (I) was expressed as

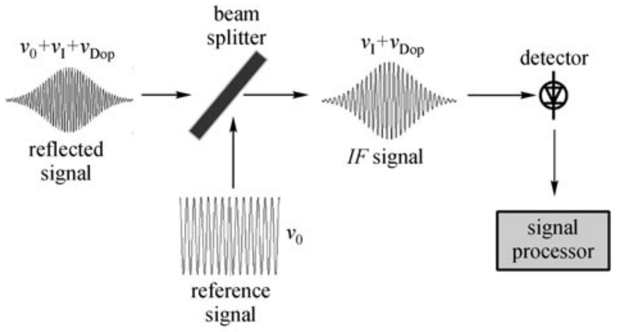

Fig. 2 Schematic of the optical heterodyne method

$$I \propto A_1^2(t) + A_2^2 + A_1(t)A_2\cos[2\pi(\nu_I+\nu_{Dop})t+\phi(t)]. \tag{3}$$

The first and second terms in Eq. (3) were the direct current. The third term was the IF signal which contained the Doppler-shifted frequency ν_{Dop}. In our system the frequency ν_I was:

$$\nu_I = \nu_{AO} + \delta\nu, \tag{4}$$

ν_{AO} was the frequency shifted by the AO Q-switcher which was constant. $\delta\nu$ was frequency jitter of the slave laser caused by injection seeding which varied with time.

In order to eliminate the measurement error determined by $\delta\nu$, two detectors were used in the speed measurement system. As shown in Fig. 1, a portion of the master laser (ν_0) photo-mixed with slave laser output ($\nu_0+\nu_I$) on Det.1 and reflected signals ($\nu_0+\nu_I+\nu_{Dop}$) on Det. 2. The detectors converted the frequencies of laser pulse and reflected signals into intermediate frequencies ν_I,$\nu_I+\nu_{Dop}$ respectively. The *IF* signal between the master laser and slave laser detected by Det. 1 was indicated in Fig. 3. Fast Fourier transforms (FFT) was used to calculate the spectrum of *IF* signals and the intermediate frequencies were determined. The frequency jitter $\delta\nu$ was measured using the FFT method. As shown in Fig. 4, 1000 shots of the intermediate frequencies detected by Det. 1 were memorized by the signal processor and the frequency jitter was 1.07 MHz (rms). Figure 5 was the spectrum of the *IF* signals detected by Det. 1 and Det. 2. The Doppler-shifted frequency ν_{Dop} was obtained from the difference between the intermediate frequencies. The measurement error caused by $\delta\nu$ was eliminated. The line-of-sight speed of the rotating target was obtained as

$$V_r = \frac{\lambda}{2}\nu_{Dop}, \tag{5}$$

where λ was the laser wavelength.

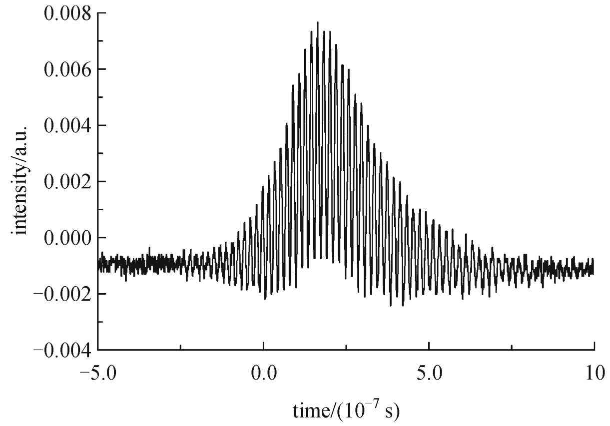

Fig. 3 *IF* signal between master laser and slave laser

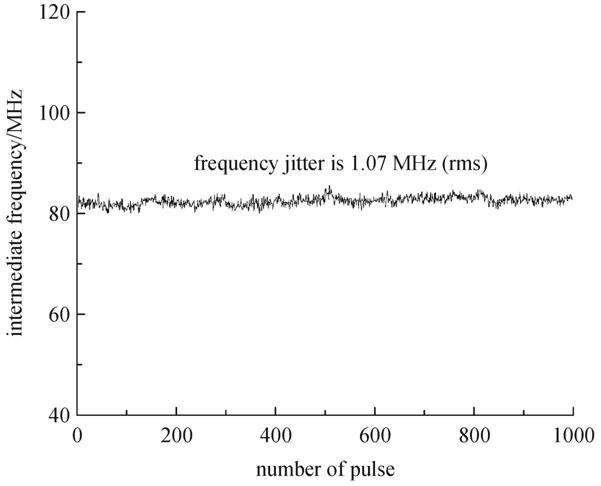

Fig. 4 Frequency jitter of slave laser

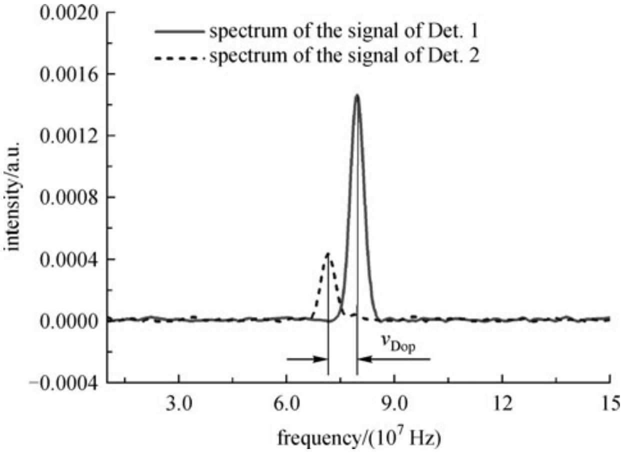

Fig. 5 Spectra of signals detected by Det. 1 and Det. 2

The output parameters of the injection-seeded Tm:YAG laser had been reported by our group [13] The maximum single-frequency pulse energy was 2.38 mJ with a pulse repetition rate of 100 Hz. The line-of-sight speed of the rotating target was obtained by using the speed measurement system discussed above. As shown in Fig. 6, the measured speed agreed well with the real speed and the maximum measurement error was 0.68 m/s.

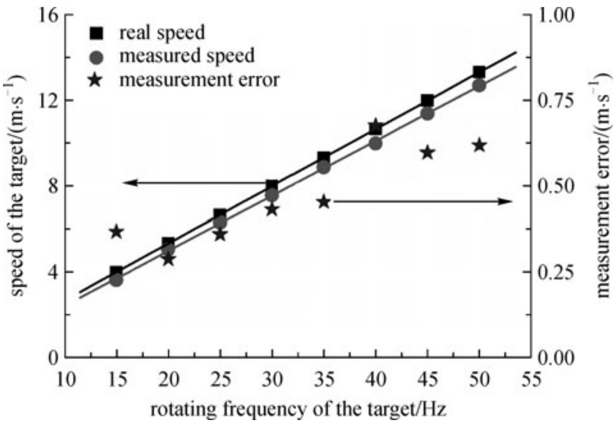

Fig. 6 Real and measured speed of the revolving target

4 Conclusions

A speed measurement system using coherent detection technique was reported. A single frequency injection-seeded Tm:YAG laser with pulse energy of 2.38 mJ was employed in the system. By utilizing the speed measurement system, the line-of-sight speed of the rotating target was obtained, and the measurement error was 0.68 m/s. The injection-seeded Tm:YAG laser was promising to apply in coherent Doppler wind lidar.

Acknowledgements This research was supported by the Doctoral Fund of Ministry of Education of China (No. 20101101110015) and the National Natural Science Foundation of China (Grant No. 60908009).

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