Conductively cooled 250-Hz single frequency Nd:YAG laser

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Received October 27, 2009

A conductively cooled, laser diode (LD) end-pumped, injection-seeded single frequency Nd:YAG laser is designed and implemented. The laser utilizes Nd:YAG rod as gain medium and compact dual-end-pumping arrangement using two fiber-coupled LDs with a maximum output of 150 W. The optimized ramp-fire technique is applied to build reliable single longitudinal mode oscillating. The laser is capable of producing a 10-mJ Q-switched pulse with 13-ns pulse width at 1064 nm at a pulse repetition rate of 250 Hz. The output beam qualities M^2 of approximately 1.19 and 1.22 in horizontal and vertical directions are detected, respectively.

OCIS codes: 140.3520, 140.3540, 140.3570.
doi: 10.3788/COL20100807.0670.

Lidars, especially airborne and spaceborne lidars, have played relevant roles in measurements of earth surface mapping, horizontal vector wind profiling[1,2], carbon dioxide (CO_2) profiling, ozone (O_3) profiling, etc. This led to plans of developing airborne and spaceborne lidars for earth and planetary measurements[3−5]. In most of these applications, a robust single frequency laser transmitter is necessary[6]. There have been many researches related to airborne and future spaceborne single frequency laser. Hovis *et al.* reported progress in developing single frequency transmitters for several National Aeronautics and Space Administration (NASA) airborne lidars[7]. One of the lasers operated at 200 Hz and provided 36 mJ per pulse at 355 nm for the Tropospheric Wind Lidar Technology Experiment (TWiLiTE). The laser module incorporated a robust single frequency 1064-nm ring oscillator amplified and frequency-converted to provide the desired 355-nm output. Another laser capable of producing 20 W at 200 Hz, the single frequency 1064-nm high spectral resolution lidar (HSRL)/ozone differential absorption lidar (DIAL) system, was also used. Nicklaus *et al.* discussed the frequency stability of the injection seeding laser[8]. The ramp-fire technique proved to be the most appropriate method in obtaining single longitudinal mode (SLM) lasers for airborne and spaceborne applications within vibrating environments. Schroeder *et al.* introduced the laser prototype for the Atmospheric Laser Doppler Instrument (ALADIN) airborne demonstrator[9]. The 1064-nm laser provided a pulse energy of 200 mJ and a full-width at half-maximum (FWHM) pulse duration of 35 ns at pulse repetition rate of 50 Hz. After frequency tripling, a maximum 60-mJ pulse energy at wavelength of 355 nm was achieved, and the pulse duration was reduced to 25 ns. All these single frequency laser transmitters for lidars adopted the master oscillator power amplifier (MOPA) system to achieve high energy and high stability. For a system that considers multiple laser parameters (i.e., output power, beam quality, and spectrum purity), the oscillator must be highly stable and with high quality.

In 2007, we reported a water-cooled laser diode (LD) side-pumped solid state SLM laser for direct detection lidar applications[10]. The laser was capable of outputting 14 mJ per pulse at wavelength of 532 nm. The laser was used as a transmitter in ground-based Doppler lidar. In order to meet the requirements of space-based lidar applications, we present a novel design of conductively cooled injection-seeded single frequency 1064-nm laser oscillator that can operate at repetition rate of 250 Hz in this letter. High efficiency has reduced the requirements of pump power and heat dissipation. To the best of our knowledge, this is the first report on a conductively cooled single frequency laser with a repetition of more than 200 Hz.

Figure 1 shows the schematic of the injection-seeded single frequency Nd:YAG laser with fiber-coupled LD dual-end-pumping structure. The single frequency seeder laser for the injection system at 1064-nm wavelength was a continuous wave (CW) nonplanar ring oscillator (NPRO) Nd:YAG laser (Mephisto OEM200, Innolight GmbH, Germany). This seeder had the ability of outputting CW laser with a linewidth of 1 kHz at the maximum output power of 200 mW, and the beam qualities of M^2 in horizontal and vertical directions were both less than 1.1. Two isolators (HP-04-I-1064, Electro-Optics Technology, Inc., USA) with an extinction ratio of greater than 60 dB were inserted

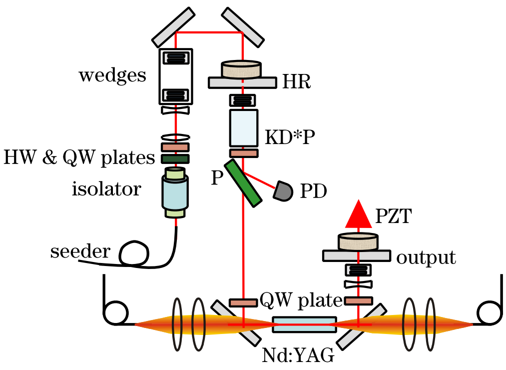

Fig. 1. Schematic of LD dual-end-pumped injection-seeded Nd:YAG laser. P: polarizer; PD: photo detector.

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between the seeder and oscillator. Then, half wave (HW) and quarter wave (QW) plates were introduced after the isolators to derive suitable polarization state, as required by the ramp-fire technique[11].

The rear mirror was planar with a transmission of 5% at 1064 nm. The output mirror was also planar with a transmission of 60% at 1064 nm. The cavity length was about 500 mm. The electric-optical Q-switch was composed of a KD*P electro-optic modulator, QW plate, and polarizer. Two QW plates were inserted at both ends of the laser rod to eliminate any space hole burning effect[12,13].

The gain material was a composite YAG/Nd:YAG/YAG crystal rod with a diameter of 4 mm. The length of the doped area was 10 mm and the Nd^{3+} dopant concentration was 0.5 at.%. The length of each undoped YAG rod bonded at two ends was 5 mm. We used this composite gain material to reduce the focal length. The pump sources, two fiber-coupled 150-W CW output 808-nm LDs with core diameters of 400 μm and numerical apertures (NAs) of 0.22 operating at pulsed mode, were focused into the gain rod from the two ends. Figure 2 shows the pumping beam distribution in the rod. Focal spot was set at 14.6 mm from the incident end. Beam waist was about 550 μm.

The crystal was held in a heat sink cooled by thermoelectric cooler (TEC) (Fig. 3). The hot side of the TEC was cooled by interface plate attached to a water cooled heat sink in the experimental setup. Heat transition to the radiatively cooled interface plate was rather straight-forward. A brace held these two heat sinks for crystal and TEC. This constructure proved to be stable in the experiment. Due to thermal effect in the rod, a negative lens was inserted in the cavity to compensate for the thermal lens.

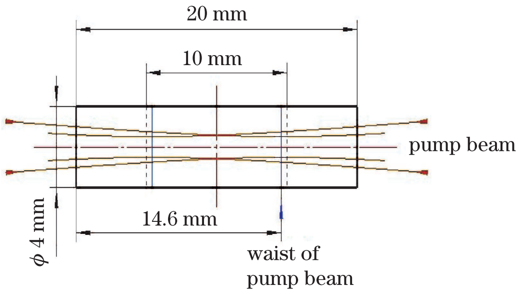

Fig. 2. Symmetric pumping of the laser crystal.

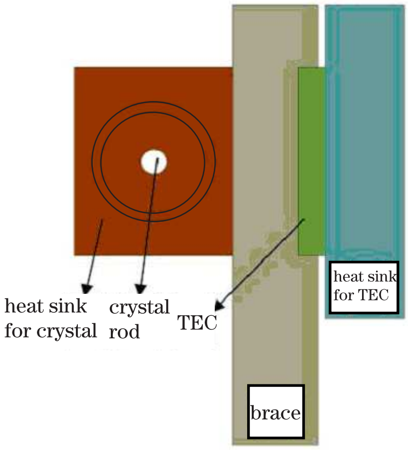

Fig. 3. Schematic of conductive cooling of crystal.

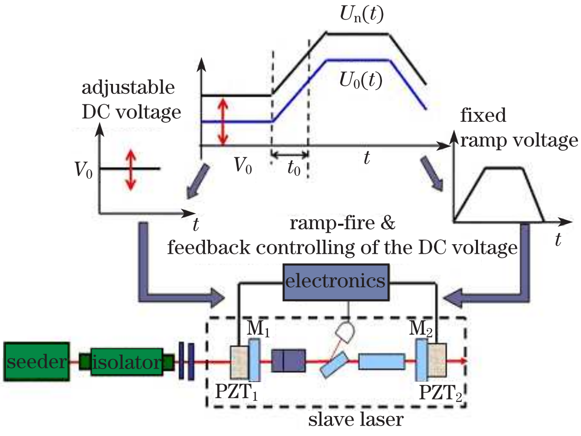

Fig. 4. Cavity controlling approach based on RF technique (a linear cavity is used to take the place of the U shape cavity used in the experiment). DC: direct current; M_1, M_2: mirrors.

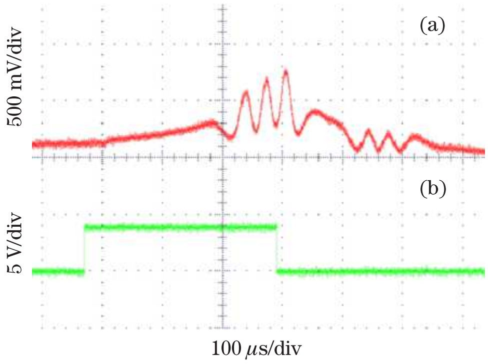

Fig. 5. (a) Resonance signal and (b) pump signal.

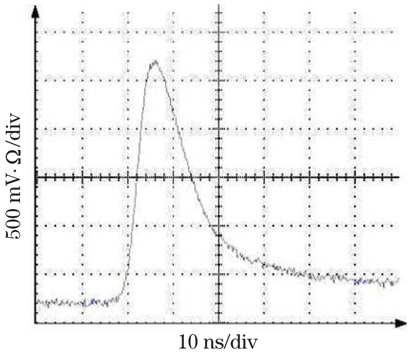

Fig. 6. Temporal pulse profile.

Both the rear and output mirror of the cavity were mounted onto two piezo actuators (PZTs). A modified ramp-fire technique, as described in our previous work[10], was applied to achieve reliable single longitudinal mode oscillating. The cavity controlling approach process is shown in Fig. 4. At each pumping period, one of the PZTs was rapidly ramped by periodic high voltage, and the Q-switch was fired when the cavity was in resonance with the seeder laser wavelength. Figure 5(a) shows the resonance signal. Another PZT served as feedback controller to allow the resonance signal to function appropriately with a high voltage.

The stable single frequency operation was obtained at

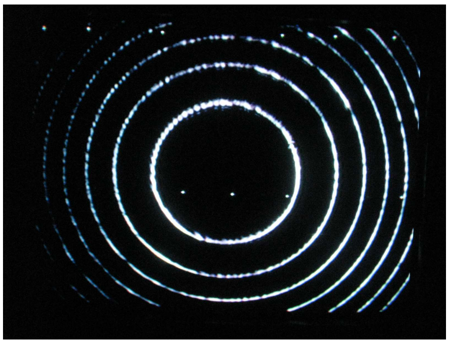

Fig. 7. Interference fringes of single-frequency laser with a Fabry-Perot etalon.

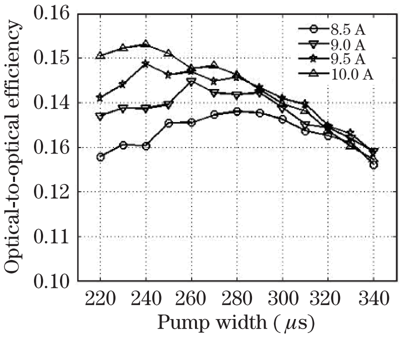

Fig. 8. Optical-to-optical efficiency as a function of pump width at different pump currents.

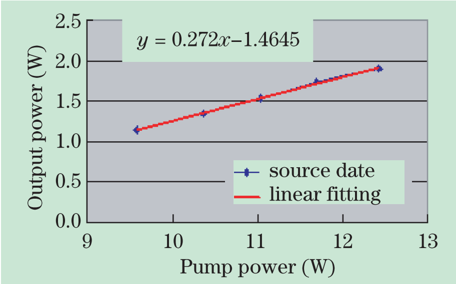

Fig. 9. Slope efficiency at 240 μs.

repetition rate of 250 Hz. The FWHM pulse duration was around 13 ns. The pulse temporal profile (Fig. 6) was sampled using a fast response photodiode and a Tektronix TDS3054 oscilloscope with a bandwidth of 500 MHz. Figure 7 shows the corresponding interference fringes produced with a 7-cm Fabry-Perot etalon.

As this injection-seeded laser was designed as the master oscillator of a high power MOPA system, considerable care was taken to ensure that this laser can output high energy pulses. Thus, we adopted a pump pulse duration that was longer than 200 μs. The maximum single pulse energy of 10 mJ was achieved when the pump duration was 320 μs at a repetition rate of 250 Hz (duty cycle of 8%). However, the maximum optical-to-optical efficiency η_{oo} occurred when the 240-μs pump pulse duration was adopted. The single pulse energy was 8 mJ. Figure 8 shows the optical-to-optical efficiency variation as a function of the pump pulse duration. Additionally, the pump power used in this letter was detected after pump coupling system.

Figure 9 shows the single frequency output performance at different pump powers when the pump duration is 240 μs. A slope efficiency of 27.2% is realized. We believe that this relatively low efficiency is mainly induced by the low absorption efficiency as only 90% of pump power is absorbed by the crystal. Higher output power could be achieved if the pump head is optimized.

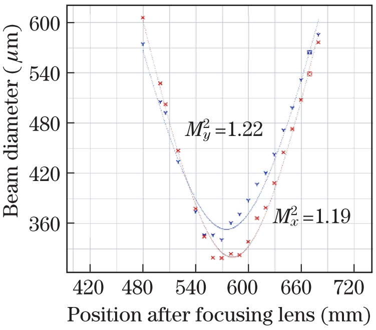

Fig. 10. Beam diameter versus position after focusing lens for determining beam quality.

The beam quality of M^2 was measured by a Spiricon M^2-200 laser beam analyzer. When the laser output is 2 W, the measured M^2 values are 1.19 (horizontal direction) and 1.22 (vertical direction). The detected results are shown in Fig. 10.

In conclusion, a LD pumped, conductively cooled, injection seeded single frequency Nd:YAG laser is presented. Pulse energy of 10 mJ is achieved at 250-Hz repetition rate. Pulse duration is approximately 13 ns. Beam qualities M^2 are 1.19 (horizontal direction) and 1.22 (vertical direction). This conductive cooling design can be adopted in space-based application.

This work was supported by the Shanghai Science and Technology Commission under Grant No. 08DZ2230400.

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