Conductively cooled 1-kHz single-frequency Nd:YAG laser for remote sensing

Juntao Wang (王君涛), Ren Zhu (朱 韧), Jun Zhou (周 军), Huaguo Zang (臧华国), Xiaolei Zhu (朱小磊)*, and Weibiao Chen (陈卫标)

Shanghai Key Laboratory of All Solid-State Laser and Applied Techniques, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

Corresponding author: xlzhu@siom.ac.cn

Received February 28, 2011; accepted April 4, 2011; posted online June 21, 2011

A conductively cooled, laser diode (LD) end-pumped, injection-seeded single-frequency Nd:YAG laser is designed and implemented. The laser is capable of producing an 8-mJ Q-switched pulse with a 11-ns pulse width at 1 064 nm and at a pulse repetition rate of 1 000 Hz. At the maximum output energy of 8 mJ, the frequency jitter is less than 3.5 MHz (root mean square (RMS)) over two minutes, and the linewidth is around 54.2 MHz. The M^2 of the laser beam is approximately 1.30 in both horizontal and vertical directions. The optimized ramp-fire technique is applied to build reliable single longitudinal mode oscillating.

OCIS codes: 140.3520, 140.3540, 140.3570.

doi: 10.3788/COL201109.081405.

The use of reliable lidar systems in airborne and space-based missions is considered to be an effective approach in the measurement of earth surface mapping, horizontal vector wind profiling[1,2], carbon dioxide (CO_2) profiling, and ozone (O_3) profiling, among others. A number of plans of developing airborne and space-based lidar systems for earth and planetary measurements[3−5] have been fielded or are currently being constructed, and in most of these lidar systems, a robust single frequency laser transmitter is basically imposed[6]. In the project of atmospheric laser doppler instrument (ALDIN), which is currently being developed in the European Space Agency (ESA), a space-based single frequency Nd:YAG master oscillator/power amplifier (MOPA) laser system with high pulse energy will be used to directly measure wind profiles on a global scale. In the ALDIN airborne demonstrator (A2D), the laser oscillator provided an output of 10 mJ at the pulse repetition rate of 100 Hz at 1 064-nm wavelength. After amplification, a single pulse energy of 200 mJ and a pulse duration (full-width at half-maximum (FWHM)) of 35 ns were obtained at 50 Hz[7]. When the laser is operating at the maximum output level, the frequency stability of 1.3 MHz (root mean square (RMS)) could be obtained over 14 s, and the mean value of the linewidth was 14.8 MHz. In 2007, Hovis *et al.* reported a conductively cooled single-frequency laser transmitter with high repetition rate of 200 Hz[6]. The output of the diode-pumped single-frequency ring oscillator was over 17 mJ per pulse with an M^2 of about 1.1. After a single pass through the amplifier, the energy of the amplified pulse was over 75 mJ per pulse, the M^2 was about 1.2, and the pulse duration was around 17 ns.

In 2007, we reported a water-cooled laser diode (LD) side-pumped solid-state single longitudinal mode (SLM) laser for direct detection lidar applications[8]. The laser was capable of outputting 14 mJ per pulse at wavelength of 532 nm and had been successfully used as a transmitter in mobile Doppler lidar system. In order to meet the requirements of space-based lidar applications, we presented in 2010 a design of conductively cooled injection-seeded single-frequency 1 064-nm laser oscillator, which could operate at a repetition rate of 250 Hz[9]. It provided single pulse energy of 10 mJ with pulse width (FWHM) of 13 ns.

The signal-to-noise rate (SNR) of the lidar system is proportional to the square root of the pulse repetition rate of the laser transmitter under the condition of certain single pulse energy. Thus, higher pulse repetition rate enables longer detection range and higher detection accuracy. Therefore, it is essential to increase the pulse repetition rate and the single pulse energy of the laser transmitter. In this letter, we present a stable injection-seeded single frequency laser that can operate at the repetition rate of 1 kHz. This will be very helpful to lidar systems. To the best of our knowledge, this is the first report on a conductively cooled single frequency laser operating at a repetition rate of 1 000 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 1 064-nm wavelength is a continuous wave (CW) nonplanar ring oscillator (NPRO) Nd:YAG laser manufacturedly by ourselves. This seeder had the capability of outputting CW laser with a

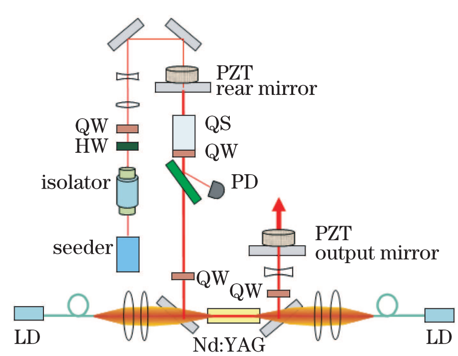

Fig. 1. Schematic of LD dual-end-pumped injection seeded Nd:YAG laser. PD: photo diode; QS: Q-switch.

linewidth of several kilohertz at the output power of 500 mW, and the beam qualities of M^2 in the horizontal and vertical directions were both less than 1.1. Two isolators with an extinction ratio greater than 60 dB were inserted between the seeder and the oscillator. Half wave (HW) plate and quarter wave (QW) plate were then introduced after the isolators to derive the suitable polarization state, as required by the ramp-fire technique[10]. The rear mirror was planar with a transmission of 5% at 1 064 nm. The output mirror was also planar with a transmission of 60% at 1 064 nm. The cavity length was about 410 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 the spatial hole burnign effect effect[11,12].

The pump sources, two QCW 150-W fiber-coupled 808 nm LDs with core diameters of 600 μm and numerical apertures (NAs) of 0.22, were focused into the gain rod from the two ends. When these two LDs operated at 1 000 Hz, the laser crystal would generate much more heat, and this would result in larger temperature gradient in the axis of the rod. In order to produce 1-kHz single frequency laser, the gain material was still chosen to be a composite YAG/Nd:YAG/YAG crystal rod with a diameter of 4 mm, but with lower dopant concentration than that used in Ref. [9]. In this letter, the dopant concentration of 0.3 at.-% was chosen, and accordingly longer length of the doped area of 30 mm. The length of each undoped YAG rod bonded at two ends was 5 mm. The composite gain material was used to reduce the focal length. In addition, a negative lens was inserted in the cavity to compensate for the thermal lens.

The crystal was held in a heat sink cooled by thermoelectric cooler (TEC). The hot side of the TEC was cooled by the interface plate attached to a heat sink in the experimental setup. Heat transition to the radiatively cooled interface plate was rather straightforward. A brace held these two heat sinks for the crystal and TEC. This structure proved to be stable in the experiment. The temperature of the heat sink of the laser crystal was bonded at 22 °C, and the accuracy was less than 0.1 °C, whereas it is 0.2 °C in Ref. [9].

Both the rear and output mirrors of the cavity were mounted onto two piezo actuators (PZTs). A modified ramp-fire technique, as described in our previous work[8], was applied to achieve reliable single longitudinal mode oscillating. In every pumping period, one PZT was rapidly ramped by periodic high voltage, and the Q-switch was fired when the cavity was in resonance with the seeder laser wavelength. Another PZT served as a feedback controller to stabilize the resonance peak at a fixed point of the ramp voltage, that is, at a fixed point of time in every period.

The stable single-frequency operation was obtained at the repetition rate of 1 000 Hz. The FWHM pulse duration was around 11 ns. The pulse temporal profile, as shown in Fig. 2, was detected by a 500-MHz bandwidth photodiode and recorded by a Tektronix TDS3054 oscilloscope (500 MHz, 5 GS/s).

In order to measure the spectral width and frequency stability of the laser pulse, the optical heterodyne technique was adopted. Another 1 064-nm Nd:YAG NPRO

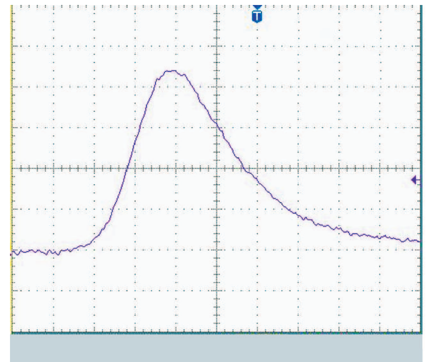

Fig. 2. Single temporal pulse profile. The FWHM pulse duration is 11 ns.

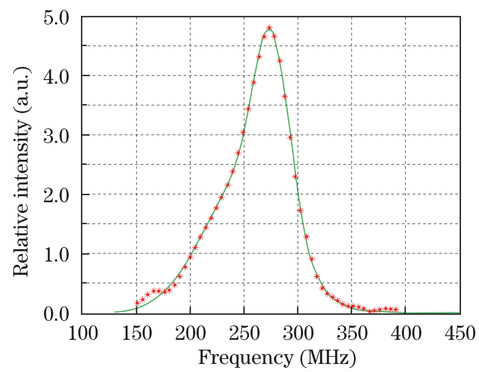

Fig. 3. Spectrum of a pulse. The center frequency is 273.1 MHz, and the linewidth is 57.5 MHz.

single frequency CW laser (Mephisto OEM200), manufactured by Innolight GmbH, was used as an offset local oscillator for the heterodyne mixing. This laser produced 200 mW with a linewidth of less than 1 kHz. The frequency shift per minute is less than 1 MHz, and its long-term frequency stability is <45 MHz/3 h. Therefore, the short-term jitter of the beat frequency can be used to represent the frequency stability of the pulsed laser. A photodiode with a 500-MHz bandwidth and a 600-MHz oscilloscope (LeCroy WaveRunner 62Xi 10 GS/s) was used to sample and save the data. This CW laser was set to have a frequency difference of about 300 MHz with the pulsed laser. The resulting digitized beat signal was transferred to a computer for processing. A fast Fourier transform (FFT) algorithm using the Hanning window type produced the spectral intensity of the seeded laser pulse. Intensity spectrum around 300 MHz was abstracted and used to represent the linewidth of the pulsed laser because of the very narrow linewidth of this seeder. Figure 3 shows the spectrum of one outputting laser pulse, and its linewidth is 57.5 MHz (FWHM). Figure 4 shows the linewidth over two minutes, and the mean value of 54.2 MHz was calculated. The shift of beat frequency is 3.5 MHz (RMS) over two minutes, and the mean frequency is 279.1 MHz, which is illustrated in Fig. 5. Because of the limit of the recording speed, only seven beats were saved per second; nevertheless, it was regular. Hence, 840 beats respond to two minutes. In this letter, all the measurements were taken under the maximum output energy of 8 mJ.

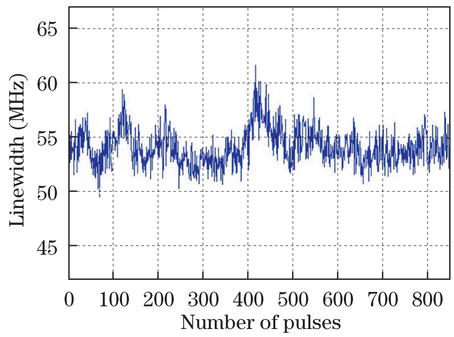

Fig. 4. Linewidth stability over two minutes. The mean value is 54.2 MHz, and the RMS value is 1.7 MHz.

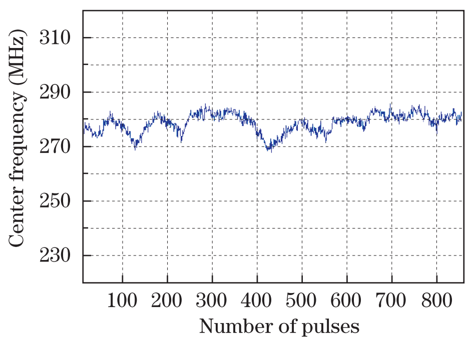

Fig. 5. Frequency stability over two minutes. The mean value is 279.1 MHz, and the RMS is 3.5 MHz.

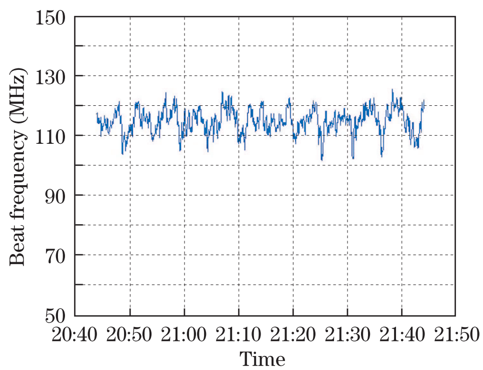

Fig. 6. Frequency stability of our NPRO laser over one hour. The mean value is 115.5 MHz, and the RMS is 3.5 MHz.

The absolute frequency stability over two minutes of 3.5 MHz (RMS) was not good enough, mainly due to the frequency stability of the seeder that we have manufactured. Its long-term frequency jitter was obtained by heterodyne technique with the Innolight NPRO CW laser, shown in Fig. 6. The frequency stability of 3.5 MHz (RMS) was calculated over one hour. We chose the duration of two minutes for one segment, and the short-term stability of these 30 segments is shown in Fig. 7. In this graph, approximately 85% of the RMS value were larger than 2.0 MHz, thus the frequency stability of the seeder laser was the main contributor to the pulsed laser. Therefore, the relative frequency stability is a better choice to describe precisely the frequency stability of the injection-seeded single-frequency laser, which is obtained by heterodyning the pulsed laser and

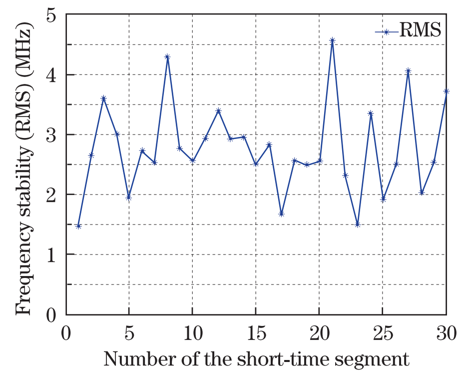

Fig. 7. The statistics of frequency stability (RMS) for every segment.

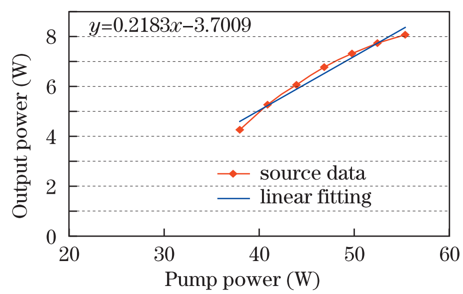

Fig. 8. Slope efficiency of the single-frequency Nd:YAG laser.

frequency-shifted seeder laser, as shown in Ref. [7], excluding the effect of the seeder laser.

As this injection-seeded laser was designed as the master oscillator of a high power MOPA system, considerable care was taken to ensure that the laser can provide high energy pulses. The maximum single pulse energy of 8 mJ was achieved when the pump duration was 260 μs at a repetition rate of 1 000 Hz (duty cycle of 26%). The corresponding optical-optical efficiency is 14.6%. The slope efficiency is 21.8%, as shown in Fig. 8. Additionally, the pump power used in this letter was detected after the pump coupling system. Higher slope efficiency and optical-optical efficiency could be achieved if the pump head is optimized. the beam quality of M^2 was measured by a Spiricon M^2-200 laser beam analyzer. When the laser output power is 8 W, the measured M^2 values are 1.30 (horizontal direction) and 1.31 (vertical direction).

In conclusion, a LD-pumped, conductively cooled, injection-seeded single frequency Nd:YAG laser is presented. Pulse energy of 8 mJ is achieved at 1 000-Hz repetition rate. Pulse duration is approximately 11 ns. The frequency jitter is less than 3.5 MHz (RMS) over two minutes, and the mean value of linewidth is 54.2 MHz. Beam qualities M^2 are 1.30 (horizontal direction) and 1.31 (vertical direction). This conductive cooling design can be adopted in space-based application.

This work was supported by the Shanghai Science and Technology Commission (No. 08DZ2230400) and State Administration of Science, Technology and Industry for National Defence (No. 0905671-CA0).

References

1. O. Reitebuch, C. Lemmerz, E. Nagel, U. Paffrath, Y. Durand, M. Endemann, F. Fabre, and M. Chaloupy, J. Atmos. Oceanic Technol. **26,** 2501 (2009).
2. F. Shen, H. Cha, J. Dong, D. Kim, D. Sun, and S. Kwon, Chin. Opt. Lett. **7,** 593 (2009).
3. M. T. Dehring, P. Tchoryk, Jr., and J. Wang, Proc. SPIE **6220,** 62200P (2006).
4. M. Pitts, C. Hostetler, J. Hair, R. Ferrare, and J. Yee, Proc. SPIE **5660,** 280 (2004).
5. J. Wang, V. Leyva, and F. E Hovis, Proc. SPIE **6681,** 668107 (2007).
6. F. E. Hovis, J. Edelman, T. Schum, J. Rudd, and K Andes, Proc. SPIE **6871,** 68710E (2008).
7. T. Schroeder, C. Lemmerz, O. Reitebuch, M. Wirth, C. Wuehrer, and R. Treichel, Appl. Phys. B **87,** 437 (2007).
8. J. Zhou, H. Zang, D. Liu, X. Zhu, J. Liu, and W. Chen, in *Proceedings of 24th International Laser Radar Conference* S01P_27 (2008).
9. J. Wang, J. Zhou, H. Zang, X. Zhu, and W. Chen, Chin. Opt. Lett. **8,** 670 (2010).
10. S. W. Henderson, E. H. Yuen, and E. S. Fry, Opt. Lett. **11,** 715 (1986).
11. S. W. Henderson, "Single frequency operation of Nd:YAG laser", PhD. Thesis (Texas A&M University, 1986).
12. V. Evtuhov and A. E. Siegman, Appl. Opt. **4,** 142 (1965).