Highly efficient single longitudinal mode-pulsed green laser

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A novel design for a highly efficient 1-kHz single-frequency green laser is proposed. An efficient single-frequency laser pulse output at 532-nm wavelength may be obtained by combining the injection seeding with intracavity frequency doubling in a compact U-shaped cavity formed by two plano dichroic mirrors in an end-pumping arrangement. The laser is capable of producing green pulses with a total energy of 6.3 mJ at a pulse repetition rate of 1 kHz. The pulse width is about 10 ns and the optical–optical efficiency from the 808-nm pump source to the 532-nm green output is around 12.7%.

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The Doppler wind lidar is considered to be an effective method of measuring wind profiles and aerosols[1−6]. A stable single-frequency (single longitudinal mode) pulsed laser with high energy and good beam quality is of critical importance in a Doppler wind lidar. The injection seeding is the most popular method of achieving single longitudinal mode oscillation. Single-frequency lasers of 532 and 355 nm that are converted from a single-frequency 1 064-nm neodymium-doped yttrium aluminum garnet (Nd:YAG) laser by second harmonic generation (SHG) and third harmonic generation are the most common laser transmitters for direct-detection Doppler wind lidar. Single-frequency green laser pulses may be obtained from a master oscillation power amplification system[7−10]. One of the well-known work is the conductively cooled single-frequency laser transmitter developed by Hovis *et al.*[9] for the tropospheric wind lidar technology experiment. The fundamental output energy from the single-frequency oscillator is 17 mJ/pulse at a repetition rate of 200 Hz and the energy of the single-frequency pulse may be increased to 75 mJ using a single-pass amplifier[7]. The development of a compact single-frequency green laser with high conversion efficiency is desirable for mobile and airborne Doppler wind lidar applications. To the best of our knowledge, a compact intracavity frequency-doubling single-frequency laser operating at a repetition rate of 1 kHz with output of several watts at a wavelength of 532 nm has not been reported.

In this letter, injection seeding was combined with intracavity frequency-doubling techniques in a dual-end-pumping conductively cooled single-frequency Nd:YAG laser to produce a 532-nm laser pulse with narrow linewidth and high efficiency. The proposed method is capable of producing a Q-switched 532-nm laser with a total pulse energy of 6.3 mJ (two beams of 4.8 and 1.5 mJ) at a repetition rate of 1 kHz. The green laser is believed to be useful as a laser transmitter in a direct-detection Doppler wind lidar for determining 1-m/s wind errors within 10 km and in a high-spectral resolution lidar for measuring optical aerosol properties, aerosol backscattering coefficients, and extinction coefficients.

Figure 1 shows a schematic of the 1-kHz single-frequency green laser. A nonplanar ring oscillator Nd:YAG laser served as the seeder laser. This laser can produce a continuous wave (CW) laser with a linewidth of several kHz at an output power of 500 mW. Two isolators in series with extinctions ratio greater than 60 dB followed the seeder. A half-wave plate (HWP) and a quarter-wave plate (QWP) were introduced after the isolator (ISO) to derive a suitable polarization state, as required by the ramp-fire technique[11]. A rear mirror M1 was planar with a transmission of 5% at 1 064 nm. Another cavity mirror M2 was also planar and had high reflectivity (HR) at 1 064 nm. The electro-optic Q-switch (QS) was composed of a KD*P Pockels cell, a QWP, and a polarizer (P). Two QWPs were set at both ends of the rod to eliminate any space hole-burning effect[12,13]. Both cavity mirrors were mounted onto two piezo actuators (PZTs).

Two fiber-coupled 150 W CW laser diodes (LDs) with core diameters of 600 μm and numerical apertures of 0.22 operating in pulsed mode were used as pump sources.

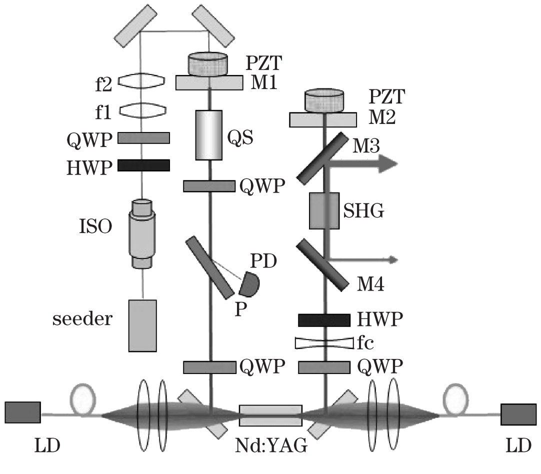

Fig. 1. Schematic of the LD dual-end-pumped injection-seeded intracavity frequency-doubling Nd:YAG laser.

The pump beams were focused into the gain rod from the two end faces. The gain material was a composite YAG/Nd:YAG/YAG crystal rod with a diameter of 4 mm and a length of 40 mm. The dopant concentration in the central 30 mm was 0.3 at.-%. The gain crystal was held in a heat sink cooled by a thermo electric cooler. The optical length of the cavity was 580 mm. A negative lens was inserted in the cavity to compensate for thermal lens effects in the rod due to the high pump power input.

A modified ramp-fire technique, as described in a previous study[10,14], was applied to achieve a single reliable longitudinal mode oscillation in the cavity. In every pumping period, one PZT was rapidly ramped by a periodic high voltage and the QS 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, the laser output at a fixed point at a time in every pump period.

The intracavity frequency-doubling module consisted of four elements: the HWP, the SHG crystal, as well as the planar dichroic mirrors M3 and M4. HWP ensured a suitable polarization direction for type I phase-matching lithium triborate (LBO) SHG crystals with a length of 12 mm. The dichroic mirror reflected the green laser out from the resonator.

Stable single-frequency pulsed 532-nm laser operation may be obtained at a repetition rate of 1 kHz. P1 and P2 denote the green lasers reflected by M3 and M4, respectively. When the input pump energy is 49.7 mJ, the output pulse energy of P1 is scaled up to 4.8 mJ and the pulse energy of P2 is 1.5 mJ. The corresponding pulse temporal profile was detected by a 500-MHz bandwidth photodiode and recorded by a Tektronix TDS3054 oscilloscope (500 MHz, 5 GS/s), as shown in Fig. 2. The pulse duration (full-width at half-maximum) of P1 is about 10 ns (red trace) while that of P2 (blue trace) is about 9 ns. The 4-ns temporal delay between P1 and P2 is attributed to variations in optical length arrangements from the LBO crystal to the two detecting photodiodes.

The smooth temporal profile of the pulse reveals that the green laser lases in single longitudinal mode for an injection seeding laser system. In the experiments, a Fabry–Perot etalon was also used to confirm the predication of a single-frequency green laser pulse obtained from the compact laser. The optical length of the etalon is 175 mm and its theoretical finesse is 61. Figure 3 shows the recorded interference fringes of the laser beam from P1 and illustrates that only a single longitudinal mode is detected. Thus, the narrow linewidth of the 532 nm laser pulse may be obtained directly from the injection seeding laser using the intracavity frequency-doubling method. In a previous study[15], the laser pulse linewidth at 1 064 nm was around 54.2 MHz in the absence of a LBO, and the frequency jitter was less than 3.5 MHz (root mean square (rmt)) for 2 min.

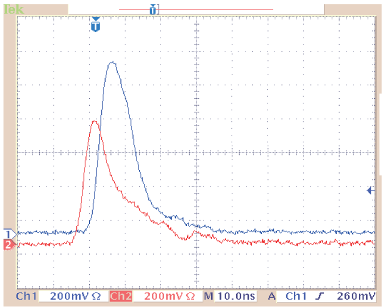

Fig. 2. (Color online) Temporal pulse profile at maximum output.

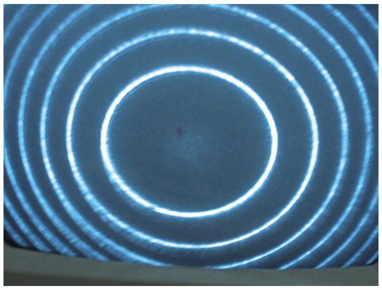

Fig. 3. Interference fringes.

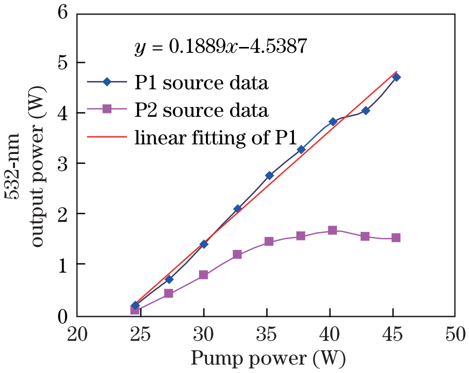

Fig. 4. Laser output power at 532 nm as a function of pump power input.

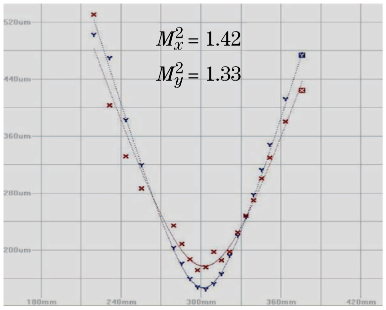

Fig. 5. Beam diameters with respect to position after focusing lens for determining beam quality.

Figure 4 shows the output power of the 532-nm single-frequency laser as a function of the pump power. The slope efficiency of beam P1 is 18.9% and the optical–optical efficiency from 808 to 532 nm is 9.6% at maximum output. Considering the total output power of beams P1 and P2, the optical–optical efficiency of the laser is about 12.7%. The M^2 of P1 was measured by a Spiricon M^2-200 laser beam analyzer. The M^2 values are about 1.42 and 1.33 in the horizontal and vertical directions, respectively, at maximum output, as shown in Fig. 5. The minimum cross sections of the laser beam in two directions are located at almost the same position and the measured astigmatism is about 0.10.

In this experimental arrangement, green beams of P1 and P2 are both obtained by a single pass of the LBO crystal. In our experiments, we tried to combine the forward and backward green laser together to obtain high SHG conversion efficiency. First, the HR M2 was replaced by an outputting coupler mirror with a transmission of 60% at 1 064 nm. Mirror M3 was then replaced by another dichroic mirror set to 0° to form the green laser into a single beam. Unfortunately, the results of this configuration are unsatisfactory and the laser power output from M4 fluctuates severely. Fluctuation of the output power is observed even after removal of M3 because the cavity lengths vary during laser oscillation. A variation in the phase relationship may be observed between 1 064 and 532 nm at every pulse period when the QS of the resonator is opened, resulting in green laser power fluctuations.

In conclusion, a highly efficient injection-seeded single-frequency 532-nm laser with a pulse repetition rate of 1 kHz is demonstrated. The total output power is scaled up to 6.3 W, corresponding to peak powers of 480 and 170 kW for the laser beams of P1 and P2, respectively. The green beam qualities M^2 are 1.42 and 1.33 in the horizontal and vertical directions, respectively. This novel design of an injection-seeded narrow linewidth green laser oscillator can be directly adopted in all types of lidar applications.

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