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# Conductively-cooled, high-energy, single-frequency diode pumped slab laser for space applications

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**Abstract** A laser-diode-pumped high efficiency, high pulse energy and single-frequency oscillator and amplifier for potential space environment applications have been developed and demonstrated using conductively-cooled heat removal. A diode-pumped injection seeded single-frequency oscillator was achieved by using the resonance-detection technique in Q-Switching operation, and Nd: YAG zigzag slabs based on "pump on bounce" are used in power amplifier stage for high-efficiency pulse energy extraction. Output pulse energy of 800 mJ with 11 ns pulse duration is obtained at a repetition rate of 100 Hz, with a near 3× diffraction-limit beam and an optical-to-optical efficiency of 18%. The experimental result shows that the laser has compact structure, high efficiency, reliability, conductive cooling and can be used for space environments.

## 1 Introduction

High average power and high pulse energy all-solid-state lasers have potential applications in air-based and space-based environment due to their compact architecture, high efficiency, reliability and ease of engineering. The wavelength of 1 μm can be used for aerosol measurement and its nonlinear frequency conversion can be used for non-coherent direct detection Doppler lidar, vapor differential absorption lidar (532 nm), high-spectral-resolution lidar (355 nm), and ozone differential absorption lidar (266 nm), so the research based on 1 micron conductively-cooled solid-state lasers is the basis for development of air-based and space-based lasers. Conductively-cooled slab master oscillator and power amplifier with pulse energy of more than 1 J at a repetition rate of 32 Hz [1] were demonstrated, and a pulse energy of 1 J fundamental frequency with pulse width of 22 ns at 50 Hz for wind lidar applications and nonlinear 355 nm UV laser for direct detection wind lidar were reported by F. Hovis et al. [2–5]. Pulse energy exceeding 125 mJ at 1064 nm, which provided 36 mJ/pulse at 355 nm at 200 Hz for the Tropospheric Wind Lidar Technology Experiment (TWiLiTE), was also reported [6]. Laser prototype for the ALADIN (Atmospheric Laser Doppler Instrument) airborne demonstrator was introduced by Schroeder [7]. The 1064 nm laser provided a pulse energy of 200 mJ and a FWHM pulse duration of 35 ns at 50 Hz pulse repetition rate. After frequency tripling, up to 60 mJ of pulse energy at 355 nm wavelength was achieved, and the pulse duration reduced to 25 ns. To date, also many achievements were made above, the pulse width was relatively wide and the efficiency was low and the pulse energy did not exceed 200 mJ when operating at more than 100 Hz. It is well known that for the air-based and space-based lasers, a higher efficiency means decreasing the required power and waste heat removal that the satellite must accommodate and the energy resources on the satellite is limited. Higher repetition rate and high pulse energy, narrow pulse width can provide faster data acquisition and an adequate higher signal-to-noise ratio. Conductively-cooled high repetition rate, high efficiency and high pulse energy with high beam quality laser output were the trends of the lasers used for air-based and space-based environments.

In this letter we reported a conductively-cooled, single-frequency Q-switched Nd: YAG laser employing an oscillator-amplifier, featuring high efficiency, high pulse energy and narrow pulse width and high degree of polarization. The oscillator was a diode-pumped injection seeded single-

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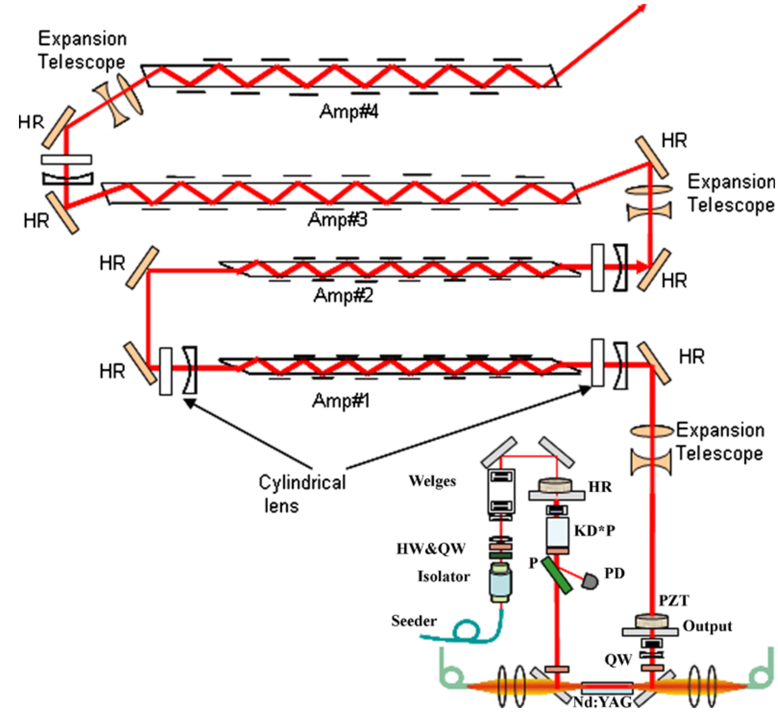



**Fig. 1** Schematic of single-frequency oscillator and amplifier

frequency laser achieved by using the resonance-detection technique in Q-Switching operation. Four zigzag Nd: YAG slabs were adopted in amplifier stage for minimizing thermal distortion and stress-induced birefringences which were used in many high-power solid-state laser designs [8–10]. The laser provides an output pulse energy of 800 mJ with pulse duration of 11 ns and near $3\times$ diffraction-limited beam at a repetition of 100 Hz with optical–optical efficiency over 18%. Finally, the degree of polarization was also measured and near 98%, this will improve the nonlinear conversion efficiency. This laser set new records for high efficiency, Q-switched pulse energy and for average power from laser diode-pumped lasers.

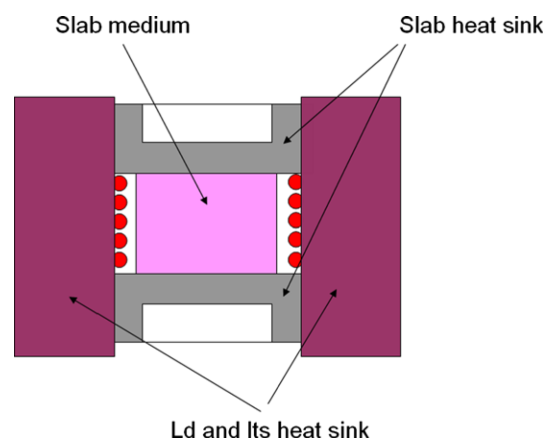



**Fig. 2** The pump and cooling architecture of the slab amplifier

## 2 Experimental setup

The conductively-cooled single-frequency oscillator and amplifier system is shown in Fig. 1. The oscillator is fiber-coupled LD dual-end-pumping and injection seeded Nd: YAG laser. The single-frequency seeder laser for the injection system at 1064 nm wavelength is a continuous wave (CW) non-planar ring oscillator (NPRO) Nd: YAG laser. The pulse oscillator is seeded through the high reflector end of the laser cavity and an optical isolator was placed for preventing feedback destabilization of the single-frequency seed laser. The rear mirror and output mirror of the cavity are mounted on two piezo actuators (PZT), respectively. A modified ramp-fire technique, which has been described in previous works [11, 12], is applied to achieve reliable single longitudinal mode oscillation. During every pump period, one of the PZT is rapidly ramped by periodic high voltage, and the Q-switch is fired when the cavity is in resonance with the seeder laser wavelength. Another PZT acts as a feedback controller, and makes the resonance signal in phase with the high voltage. The diode-pumped head uses two fiber-coupled 150 W CW output 808 nm laser diodes to longitudinally pump a $\varnothing 4$ mm $\times$ 10 mm long Nd: YAG crystal rod from two ends. Both the rod and diodes are conductively-cooled through heat pipes. In order to realize a high beam quality, high extraction efficiency and conductive cooling, a slab shaped Nd: YAG active material with zigzag path propagation and pump on bounce approach are perfect our choice in the amplifier region [13]. The cooling architecture of the slabs used in the amplifier stage is shown in Fig. 2, entirely conductively, is based on pumping from two opposite sides in the Total Internal Reflection plane and cooling in the perpendicular plane. To evaluate the performance of the MOPA system, a numerical model based on the Frantz–Nodvik model [14] was used including the effect of zigzag path to design the slab geometry and assign the pump energy. The preamplifiers were the same dual Nd: YAG zigzag slabs cut with Brewster angle and the post amplifiers were cut with 40° angle and 45°, respectively and near normal incident. All the Nd: YAG slabs with $Nd^{3+}$ concentration of 1 at. % are coated with simple AR at 808 nm on the TIR (total internal reflection) surface. The slab crystals are pumped by laser-diode arrays with a pulse duration of 150 us and 2% duty factor. The peak power for pumping the preamplifiers (Amp#1 and Amp#2) and post amplifiers (Amp#3 and Amp#4) were 14 kW and 24 kW, respectively. The laser diodes are directly coupled to the active gain medium in order to increase the coupling efficiency and the couple efficiency was more than 99%.

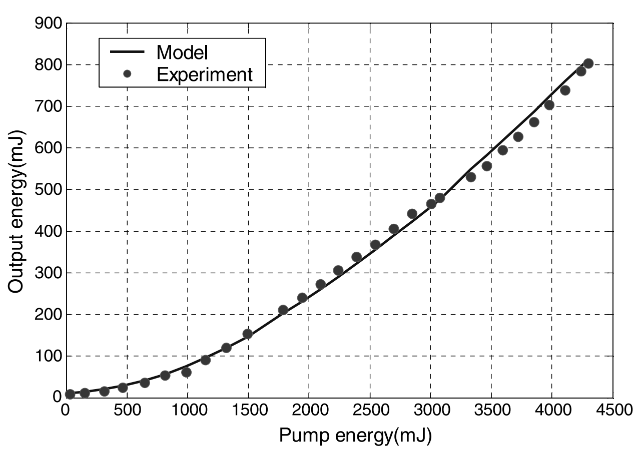



**Fig. 3** The output pulse energy as a function of the pump energy at a repetition of 100 Hz

## 3 Experiment result and discussion

Figure 3 shows the model predicted output energy based on the above mentioned Frantz–Nodvik approach and the measured pulse energy as a function of LD optical pump energy at a repetition rate of 100 Hz. Two lines fit very well, the output pulse energy increases with the pump energy first exponentially and then linearly, along with the input pulse energy increasing, and the amplifier is sufficiently extracted and saturated. The maximum output pulse energy of 800 mJ was extracted from the power amplifier with input pulse energy of 10 mJ from the oscillator when the total LD pump energy was 4.3 J, corresponding to an optical-to-optical efficiency of 18%.

The oscilloscope trace of the pulse duration from the power amplifier and that from the oscillator for comparison were shown in Fig. 4. The output pulse duration was shortened from 11.9 ns (FWHM) to 11.3 ns (FWHM) owing to saturation effect during amplifier section, corresponding to a peak power of 70 MW. The shape of the pulse becomes less smooth; the reason is that the flat surface of the cylindrical lens reflects the amplified laser back into the oscillator and disturbs the longitudinal modes, two isolators were used for isolating between the oscillator and amplifier or a tilt cylindrical lens of small angle about the optical axis to correct the pulse shape.

To evaluate the spatial properties for the laser beam from the amplifier, the beam quality measurement was made using Spiricon LBA-300PC system to determine the beam diameters for the output pulse energy of 800 mJ; the measurements of the beam intensity distribution in near field and the $M^2$ value of the beam quality are shown in Fig. 5, the zigzag axis (in the horizontal direction) had an $M^2$ of 3.53 and the non-zigzag axis (in the vertical direction) had an $M^2$ of 4.88. Since the input beam quality is an $M^2$ of 1.1 in both axes, this implies that the output beam quality from the amplifiers is near 3× diffraction-limited. The intensity distribution of the output beam becomes irregular and non-Gaussian. Two

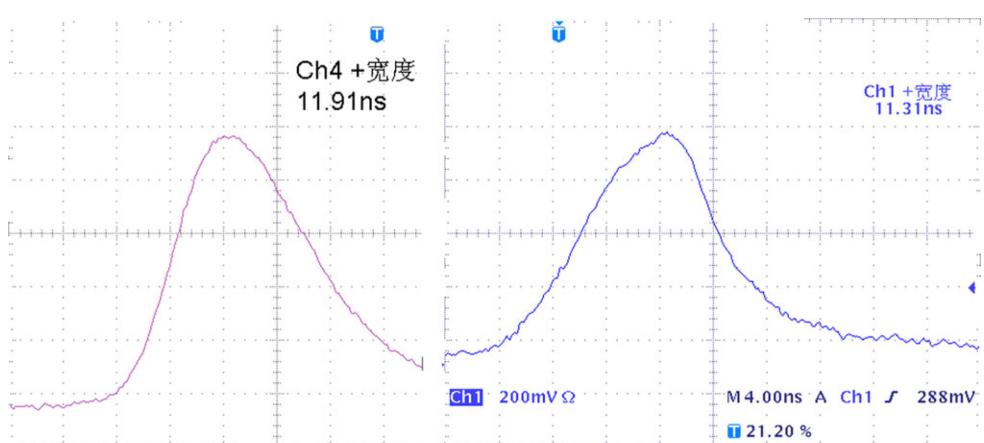
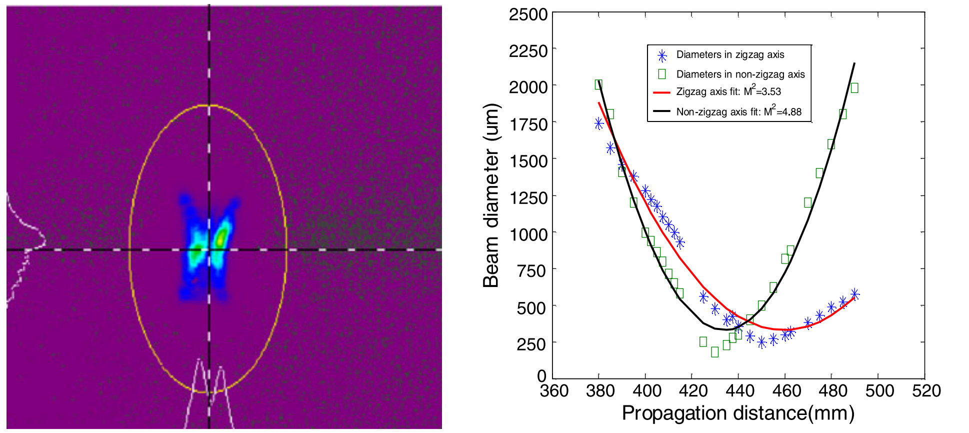



**Fig. 4** The pulse shape measurement from power amplifier compared with that from the oscillator

**Fig. 5** 100 Hz, 800 mJ per pulse beam quality measurement




Beam intensity in the near field    Beam diameter in horizontal and vertical direction

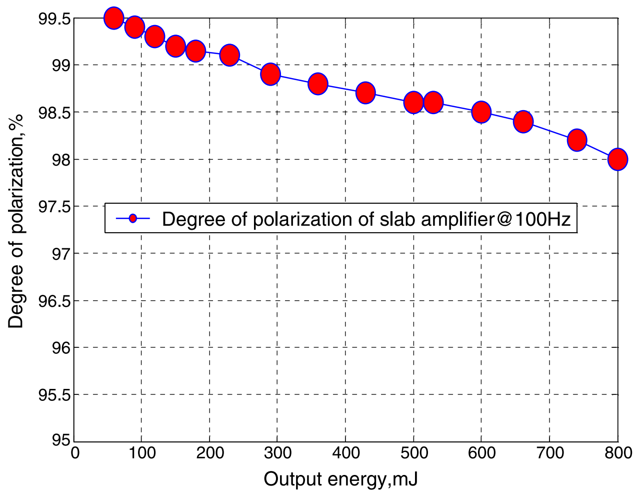



**Fig. 6** The degree of polarization ratio versus the output pulse energy

lobs of the beam are divided in zigzag direction because of the higher order aberration effects; also the thermal effect to the first order can be cancelled with zigzag optical propagation in theory, and higher order effects exist and cannot be corrected with spherical or cylindrical lenses due to the nonuniform pumping and cooling.

Finally, the degree of polarization was also measured using a Glan prism distinguishing the polarized beam $p$ from $s$, the relation between the degree of polarization and output pulse energy is shown in Fig. 6. When an output pulse energy of 800 mJ is achieved, the degree of polarization is about 98%. A high degree of polarization of the pulse laser can achieve high-efficiency nonlinear frequency conversion.

## 4 Conclusion

In this paper, the development of a conductively-cooled, diode-pumped, single-frequency oscillator and amplifier for space environment application was discussed. Higher than 800 mJ Q-switched per pulse with the beam quality of near $3\times$ diffraction-limited and pulse duration of 11 ns had been achieved at a repetition rate of 100 Hz; the overall optical-to-optical conversion efficiency was near 18%. The pump laser will be utilized for the generation of nonlinear frequency conversion.



## References

1. L.E. Holder, C. Kennedy, L. Long, G. Dubé, IEEE J. Quantum Electron. **28**, 986 (1992)
2. N.S. Prasad, U.N. Singh, F.E. Hovis, in *Earth Science Technology Conference, ESTC-06*, College Park, MD, 27–29 June 2006
3. F.E. Hovis, C. Culpepper, T. Schum, G. Witt, Proc. SPIE **5653**, 198 (2005)
4. N. Prasad, U. Singh, F. Hovis, D. Armstrong, Proc. SPIE **6214**, 263 (2004)
5. F. Hovis, J. Wang, Proc. SPIE **6555** (2007)
6. F.E. Hovis, J. Edelman, T. Schum, J. Rudd, K. Andes, Proc. SPIE **6871**, 68710E (2008)
7. T. Schroeder, C. Lemmerz, O. Reitebuch, M. Wirth, C. Wuehrer, R. Treichel, Appl. Phys. B **87**, 3 (2007)
8. D. Mudge, P.J. Veitch, J. Munch, D. Ottaway, M.W. Hamilton, IEEE J. Sel. Top. Quantum Electron. **3**, 19 (1997)
9. R.J. Shine, Jr., A.J. Alfrey, R.L. Byer, Opt. Lett. **20**, 459 (1995)
10. R.J.S. Pierre, G.W. Holleman, M. Valley, H. Injeyan, J.G. Berg, G.M. Harpole, R.C. Hilyard, M. Mitchell, M.E. Weber, J. Zamel, T. Engler, D. Hall, R. Tinti, J. Machan, IEEE J. Sel. Top. Quantum Electron. **3**, 64 (1997)
11. J. Zhou, H.G. Zang, T. Yu, J.Z. Bi, X.L. Zhu, W.B. Chen, Chinese Phys. Lett. **24** (2007)
12. S.W. Henderson, E.H. Yuen, E.S. Fry, Opt. Lett. **11**, 11 (1986)
13. F.E. Hovis, N. Martin, R. Burnham, Proc. SPIE **5798**, 101 (2005)
14. L.M. Frantz, J.S. Nodvik, J. Appl. Phys. **34**, 2346 (1963)