Compact and high-energy diode-side-pumped Q-switched Nd:YAG slab laser system for space application

Hailong Yang (杨海龙)*, Junqing Meng (孟俊清), Xiuhua Ma (马秀华), and Weibiao Chen (陈卫标)

Key Laboratory of Space Laser Communication and Detection Technology, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

**Corresponding author: longhaizhidian@163.com*

Received September 1, 2014; accepted October 24, 2014; posted online November 28, 2014

We develop a compact and high-energy Nd:YAG slab laser system consisting of an oscillator and an amplifier for space applications. The oscillator is a diode-side-pumped electro-optically Q-switched slab laser with a cross-Porro resonator. The KD*P Pockels cell with a low driving voltage of 950 V is used to polarization output coupling. The amplifier is a Nd:YAG zigzag slab pumped at bounces. The maximum output pulse energy of 341 mJ with 13 ns pulse duration is obtained from the system at the repetition rate of 20 Hz and the beam quality factors are $M_x^2=3.1$ and $M_y^2=3.5$. The beam pointing stabilities of the laser system are 3.05 μrad in the X-direction and 3.99 μrad in the Y-direction, respectively.

OCIS codes: 140.3460, 140.3540.
doi: 10.3788/COL201412.121406.

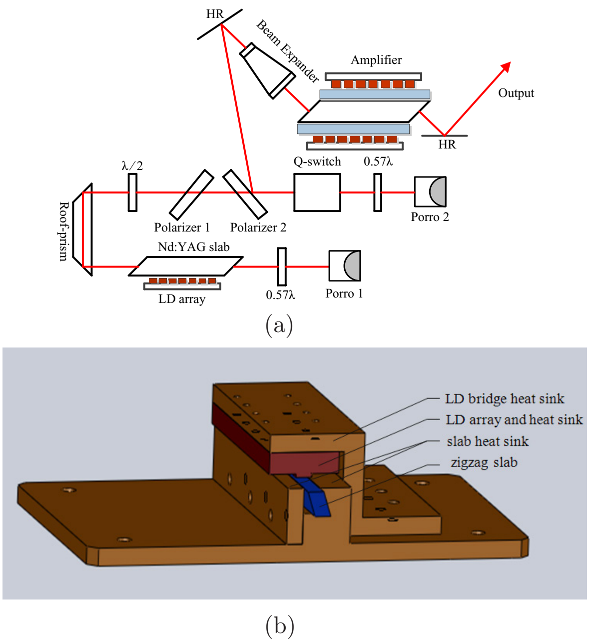
Recently, lasers have been widely used in space applications, such as spaceborne lidars, communication, and space debris cleaning[1–3]. Diode-pumped slab lasers have gained extensive attention of high output energy, high beam quality, high reliability, and long working life to operating in space[4–9]. However, it is difficult to maintain the optical alignment with the traditional flat or curved mirrors in space-based laser systems with vibration and shock. A cross-Porro prism resonator could provide high misalignment tolerance of the resonator and improve the laser system's reliability. The Porro prism could reflect the beam parallel to the incident ray ignoring any tilt of the prism. In 1980, Fuelop *et al.*[10] reported that a sensitivity to misalignment of Porro prism was 30 times lower than that of flat or curved mirrors. Therefore, it could induce different phase shift in a linearly polarized beam with different azimuth angles of the Porro prism[11]. Now many laser systems with this resonator have been applied for space application and successfully completed the tasks, such as Mars Global Surveyor (MOLA II, a laser altimeter, which was the same as MOLA)[4], Clementine (a laser altimeter)[12], and Cloud-Aerosol Lidar and Infrared Pathfinder Spaceborne Observations[5].

In addition, most space lasers are Q-switched lasers. They are often electro-optically (E-O) Q-switched by nonlinear crystals such as $LiNbO_3$ and KD*P. As for E-O Q-switch, it requires kilovolt electrical pulses with tens of nanoseconds rising times to driving Q-switch, which could increase a risk of failure of the system, especially operating in space. In order to reduce risks from such a high-voltage switch, many researchers have designed a passively Q-switch technology by using Cr:YAG crystal as a saturable absorber. There are some successful applications for space using, such as Near Earth Asteroid Rendezvous[6] and Lunar Orbiter Laser Altimeter[7]. But they all have a common disadvantage that by using saturable absorbers it is not easy to get high pulse energy output.

In this letter, we demonstrate a compact and high-energy diode-side-pumped two stage Nd:YAG slab space laser system with an E-O Q-switch (KD*P) master oscillator and a slab amplifier. The system successfully obtained a low Q-switch driving voltage to polarization output coupling. The output pulse energy of 73.8 mJ was obtained from the oscillator and was amplified to 341 mJ after the second stage at the repetition rate of 20 Hz, and the pulse widths were 15 and 13 ns, respectively. The optical-to-optical conversion efficiency of the master oscillator was 12.6% and that of second stage was 17%, respectively. The laser beam quality factors were measured as $M_x^2=2.3$, $M_y^2=2.6$ of the master oscillator and $M_x^2=3.1$, $M_y^2=3.5$ of the second stage. The system's beam pointing stabilities of the X- and Y-directions were 3.05 and 3.99 μrad, respectively.

The laser system was designed as a MOPA system. Figure 1(a) shows the schematic of the laser system with an oscillator and an amplifier. The master oscillator was designed as a U-shaped cavity in order to compact the laser system, which consisted of a zigzag Nd:YAG slab, two polarizers, E-O Q-switch, $\lambda/2$ and 0.57λ wave plates, two Porro prisms, and a roof prism. In the oscillator, a cross-Porro resonator was designed to adapt to harsh environments in space application.

The configuration of the pumping and cooling of the laser head is shown in Fig. 1(b). A Nd:YAG Brewster-cut slab with 1 at.% doping was cut with 5×5 (mm) cross section and 110 mm length with 14 bounces. Both of the zigzag faces were coated with 0° AR film for both 808 and 1064 nm to improve pumping efficiency and prevent the parasitic oscillating. The slab was pumped at one zigzag face and was bonded to the heat



(a)

(b)

Fig. 1. (a) Optical schematic of the laser system and (b) laser head of the oscillator.

sink with the vertical faces. Six diode array stacks with seven bars each operating at a repetition rate of 20 Hz were used as pump source, and each bar in a 200 μs pulse emitted a pulse energy of 13 mJ at the operating current of 80 A. The working medium of the amplifier was a Nd:YAG slab of 6×8×121.3 (mm) with 50° angle ends. The slab of the amplifier provided a 16-bounce zigzag path through the medium and was double-side-pumped on bounces by waveguide coupled 14 diode array stacks. Each stack provided a pulse energy of 85.3 mJ operating at 80 A operating current in a 200 μs pulse.

As we designed, the gain arm and the feedback arm of the resonator were the same. The resonator was polarization out-coupled by using suitable driving voltage of the Q-switch to optimum the output energy. Because of the Brewster end faces of the slab in the oscillator, only the s-polarized beam could pass through the slab, which was vertical to the polarization of polarizers 1 and 2. So a $\lambda/2$ wave plate was inserted between the slab and polarizers to change the s-polarization beam top-polarization. After the beam passing through the 0.57λ wave plate and then being reflected through 0.57λ wave plate again by Porro 2, the polarization of the reflected beam could be changed into s-polarization, and the beam could be totally reflected by polarizer 2. That was the low Q state of the resonator. As is known, the polarization of the beam passing through E-O Q-switch would be changed with different driving voltages. Based on the above design, a KD*P Q-switch with an appropriate driving voltage was employed between polarizer 2 and 0.57λ wave plate, and the resonator would be at the high Q state. The effective output coupling reflectivity of polarizer 2 as a function of the Pockels cell voltage was measured (Fig. 2). For operating in space, the laser system must be used in a vacuum, which increases the risk of failure from a high-voltage switch. In order to reduce the photon flux in the cavity and ensure the reliability of the laser system in vacuum for long time working, the voltage applied to KD*P was chosen as 950 V, corresponding to the effective reflectivity of 82%. That was far lower than the typical 1/4λ voltage of KD*P (3–4 kV). In this way, the driving circuit of Q-switch could be simplified and the laser system's reliability could be enhanced.

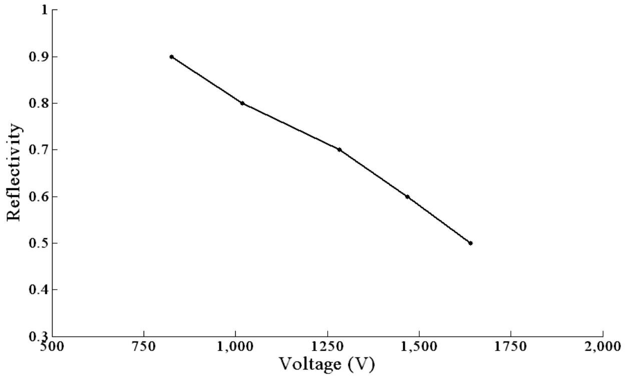
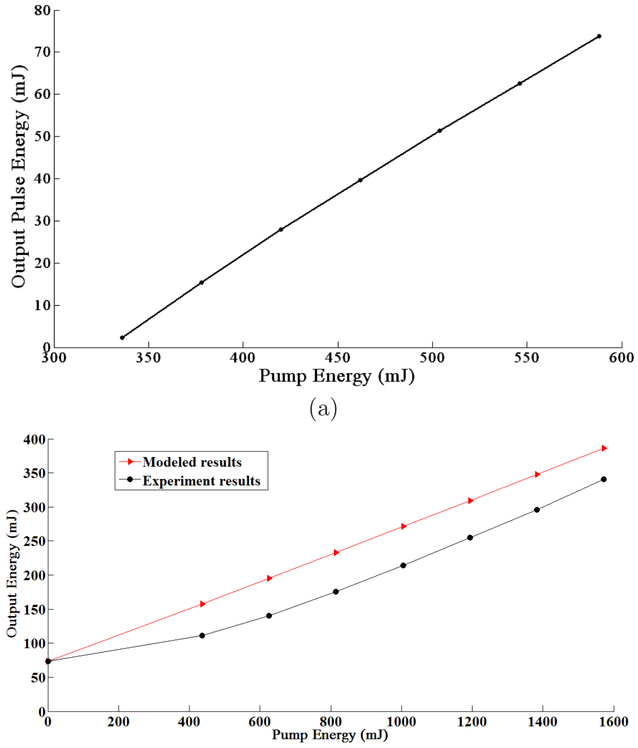


Fig. 2. Reflectivity for various Pockels cell voltages.

Figure 3(a) shows the measured pulse energy of the master oscillator as a function of pump energy at a



(a)

(b)

Fig. 3. Output pulse energy as a function of pump energy: (a) oscillator in Q-switch mode and (b) modeled and experiment results of the amplifier.

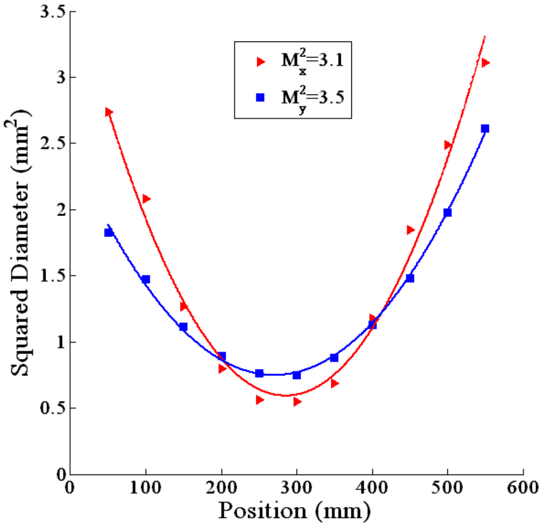


Fig. 4. Beam quality of the laser at the maximum output energy.

repetition rate of 20 Hz. The maximum output energy of 73.8 mJ with 15 ns pulse width was achieved at the pump energy of 588 mJ. The optical-to-optical conversion efficiency was 12.6%. The measured beam quality factors of the master oscillator operating at the highest output energy were $M_x^2=2.3$ and $M_y^2=2.6$, respectively.

The approach from Ref. [13] was used to model the amplifier performance. The output energy of the slab amplifier E_{out} is given by

$$E_{\text{out}} = E_{\text{sat}} A\cos(\theta) f(2-f) \times \ln\left\{1+\left[\exp\left(\frac{E_{\text{in}}}{AF_{\text{sat}}\cos(\theta)f(2-f)}\right)-1\right]\exp\left[\frac{E_{\text{stored}}}{AE_{\text{sat}}\cos(\theta)}\right]\right\}, \tag{1}$$

where E_{sat} is the four-level saturation fluence, A is the cross-section area of the input beam, θ is the zigzag transmission angle, f is the fill fraction of a slab, E_{in} is the input energy, and E_{stored} is the available energy stored in the upper lasing level.

Figure 3(b) shows the measured energy compared with the calculated results of the amplifier as a function of pump energy with a pulse energy of 73.8 mJ input.

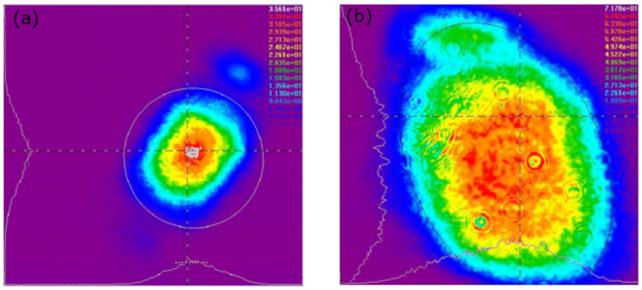


Fig. 5. Spatial distribution of the laser beam in near field: (a) oscillator and (b) amplifier.

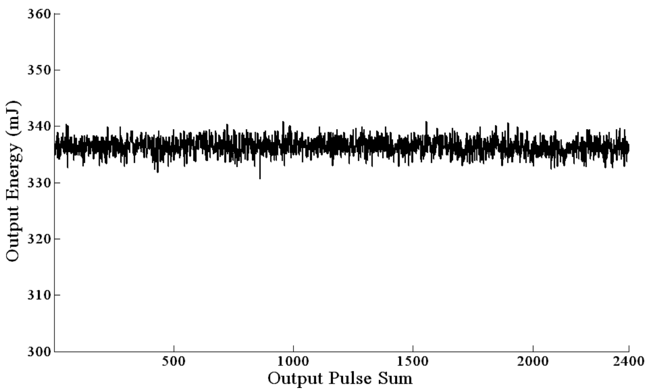
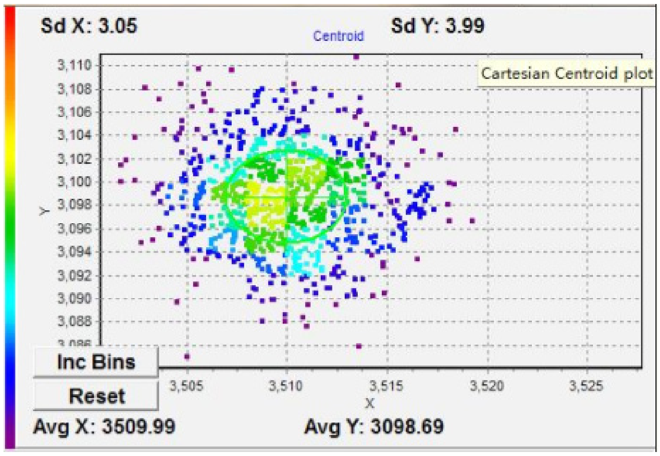


Fig. 6. Output energy of 2400 pulses.

We obtained the maximum output energy of 341 mJ with 13 ns pulse width and the optical-to-optical conversion efficiency was 17%. At the maximum output energy, the measured beam quality factors were $M_x^2=3.1$ and $M_y^2=3.5$ (Fig. 4). The spatial distribution of the beam from the amplifier compared with the one from the oscillator is shown in Fig. 5. The spot sizes were 3×3.5 (mm) from the oscillator and 5.9×7.8 (mm) from the amplifier. The beam spatial distributions were relatively uniform for both the oscillator and amplifier, and the amplifier almost maintained the original shape of the beam from the oscillator. As for our space application, the divergence angle of the laser system should be sub-μrad. From the beam quality and the spot size of the laser system, the divergence angles in the X- and Y-directions were calculated as 0.71 and 0.61 μrad, respectively. It could meet our application requirement.

As for space applications, one of the most important requirements is the stability of the laser system for working life. The cross-Porro resonator designed in this letter could improve the stability of output energy and beam pointing of the laser system. Energy meter was applied to monitor the energy of 2400 output pulses continuously (Fig. 6). The output energies were 336±5 mJ. Figure 7 shows the spatial wandering


Sd X: 3.05

Sd Y: 3.99

Avg X: 3509.99

Avg Y: 3098.69

Fig. 7. 2D movement of far-field spot.

of Cartesian centroid plots of the laser system in the far field. The stabilities of beam points in the X- and Y-directions were measured as 3.05 and 3.99 μrad, respectively.

In conclusion, we report a compact and high-energy Nd:YAG slab laser system with a cross-Porro resonator for space applications. A low driving voltage of KD*P Q-switch is employed to polarization output coupling. The laser system successfully generates 341 mJ pulse energy with pulse width of 13 ns at the repetition rate of 20 Hz. The beam quality of the system is measured as $M_x^2 = 3.1$ and $M_y^2 = 3.5$. Such a laser system with an excellent stability of output energy and beam pointing meets its requirements for use in space.

References

1. Y. Tang, H. Li, Y. Wang, Z. Hao, and D. Xiao, Proc. SPIE **8906,** 890615 (2013).
2. A. A. Kazemi and A. Panahi, Proc. SPIE **8368,** 83680H (2012).
3. A. M. Rubenchik, A. C. Erlandson, and D. Liedahl, AIP Conf. Proc. **1464,** 448 (2012).
4. R. S. Afzal, Appl. Opt. **33,** 3184 (1994).
5. F. E. Hovis, Proc. SPIE **6100,** 61001X (2006).
6. T. D. Cole, M. Boies, and A. El-Dinary, Proc. SPIE **2748,** 122 (1996).
7. G. B. Shaw, M. A. Stephen, E. Troupaki, A. A. Vasilyev, and A. W. Yu, Proc. SPIE **7193,** 719306 (2009).
8. T. Lu, J. Wang, M. Huang, D. Liu, and X. Zhu, Chin. Opt. Lett. **10,** 081403 (2012).
9. S. Li, X. Ma, H. Li, F. Li, X. Zhu, and W. Chen, Chin. Opt. Lett. **11,** 071402 (2013).
10. B. A. See, K. Fuelop, and R. Seymour, "An assessment of the crossed Porro prism resonator," Technical Memorandum ERL-0162-TM, Electronics Research Lab, Adelaide (1980).
11. M. K. Chun and E. A. Teppo, Appl. Opt. **15,** 1942 (1976).
12. M. E. Kushina, M. G. Grote, C. E. Wiswall, D. A. Halland, and J. B. Russek, Proc. SPIE **2379,** 137 (1995).
13. J. M. Eggleston, L. M. Frantz, and H. Injeyan, IEEE J. Quant. Electron. **25,** 1855 (1989).