Passively Q-Switched Nd,Cr:YAG Laser Simultaneous Dual-Wavelength Operation at 946 nm and 1.3 μm *

Bin Lin(林斌)[1], Qiu-Lin Zhang(张秋琳) [1], Dong-Xiang Zhang(张东香) [1], Bao-Hua Feng(冯宝华)[1**], Jing-Liang He(何京良)[2], Jing-Yuan Zhang(张景园)[3]

[1]*Key Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190*
[2]*State Key Lab of Crystal Materials, Shandong University, Jinan 25010*
[3]*Department of Physics, Georgia Southern University, Statesboro 30460, USA*

(Received 16 March 2016)

A diode-end-pumped Q-switched high-efficiency Nd,Cr:YAG laser with simultaneous dual-wavelength emission at 946 nm and 1.3 μm is demonstrated. The maximum output power of 1.93 W with simultaneous dual-wavelength operation is achieved at an absorbed pump power of 13.32 W and an absorbed slope efficiency of 15.15%. The maximum optical–optical efficiency is 14.49% with pulse widths of 16.38 ns at 946 nm and 26.65 ns at 1.3 μm. A maximum total repetition rate of 43.25 kHz is obtained.

PACS: 42.55.Xi, 42.55.Px, 42.55.Rz DOI: 10.1088/0256-307X/33/7/074203

The rapid developments in diode-pumped all-solid-state lasers in recent years have contributed to the improvement of diode lasers.[1–4] Simplicity, effectiveness and compactness are the advantages for the all-solid-state lasers. Dual-wavelength lasers have attracted much attention over the past few years. They have many applications such as in medical instruments, precision laser spectroscopy, optical communications, remote sensing. The dual-wavelength lasers have been reported frequently in recent years, by using various host materials such as Nd:LuVO4, Nd:GdVO4, Nd:YVO4, Nd:YAG. Continuous wave dual-wavelength operation has been reported in many works.[5–13] Dual-wavelength Q-switched operation has also been demonstrated.[14–20]

Yttrium aluminum garnet (YAG) crystals have excellent optical and mechanical properties, good thermal properties and high storage energy for their long upper-state lifetime. YAG is an ideal host material for dual-wavelength laser operation. Nd,Cr:YAG has the advantage that combines the saturable absorber and the gain medium in one crystal.[21,22] The Cr^{4+}-ions serve as the emitters for the wavelength from 900 nm to 1200 nm which can be used at 946 nm Q-switched lasers in the scheme. It is beneficial for the compact laser system. The Nd^{3+} active ion has three main emitting lines at 946 nm, 1.06 μm and 1.3 μm. Multi-wavelength operations can be achieved by different device schemes. The emission cross sections of 946 nm and 1.3 μm in Nd,Cr:YAG are similar to each other. The stimulated-emission cross sections are $5.1 \times 10^{-20}\,\mathrm{cm}^2$ at 946 nm and $45.8 \times 10^{-20}\,\mathrm{cm}^2$ at 1064 nm, $8.7 \times 10^{-20}\,\mathrm{cm}^2$ at 1319 nm and $9.2 \times 10^{-20}\,\mathrm{cm}^2$ at 1338 nm.[23] It is clear that the emission cross sections of 946 nm and 1.3 μm lines in Nd,Cr:YAG are similar to each other. They are available for laser operation. Zhang *et al.* achieved a dual-wavelength Q-switched Nd:YAG laser operation at 946 nm and 1.06 μm in 2006.[19] A multi-wavelength Q-switched Nd:YAG laser has been reported by Hou *et al.* with three wavelengths at 1.06 μm, 1.319 μm and 1.338 μm.[15] To the best of our knowledge, our present work is the first demonstration of a diode-pumped passively Q-switched Nd,Cr:YAG laser operating at 946 nm and 1.3 μm, simultaneously.

The experimental schematic diagram of the Q-switched multi-wavelength laser operation is shown in Fig. 1. The pump source is a fiber-coupled CW diode laser (Unique Mode) emitting at 808 nm. The diameter of the fiber core is 400 μm with a numerical aperture of 0.22. The pump laser, which is introduced to the laser crystal at the ratio of 2:1 with a beam diameter of 200 μm by two coupling lenses, giving a coupling efficiency of 90%, is collimated and focused into the crystal with a diameter of 200 μm. A 946 nm self-Q-switched two-mirror linear cavity is designed with a length of 12 mm (between M1 and M2). The input mirror M1 is a concave mirror with a curvature radius of 200 mm. The actual transmission at both surfaces is 93.57% at 808 nm and 67.99% at 1064 nm. The concave surface of M1 is coated with high-reflection (HR) at 946 nm and 1.3 μm ($R > 99\%$). The left surface of plane mirror M2 is coated with transmission of 12% at 946 nm and the right surface with high transmission (HT) at 946 nm. Both sides are coated with HT at 1064 nm ($T > 99\%$) and the transmission of 1.3 μm is 90%. The cavity, with Q-switched emission at 1.3 μm, is obtained between two mirrors (between M1 and M3)

*Supported by the National Basic Research Program of China under Grant No 2013CB632704.
**Corresponding author. Email: bhfeng@aphy.iphy.ac.cn
© 2016 Chinese Physical Society and IOP Publishing Ltd

with a length of 32 mm. The output mirror M3 is a concave mirror with a curvature radius of 50 mm. The M3 is served as an output coupler of 1.3 μm. The concave surface of M3 is coated with 1.3 μm with its transmission of 7.5% and the plane surface is HT at 1.3 μm. Both surfaces of M3 are coated with HT at 946 and 1064 nm ($T > 99\%$). In this way, the 1064 nm wavelength would be suppressed in two cavities of M1–M2 and M1–M3.

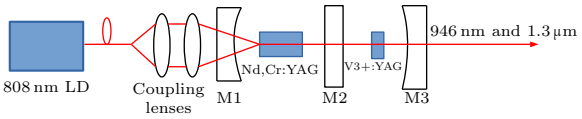

Fig. 1. Schematic diagram of the Q-switched dual-wavelength Nd,Cr:YAG setup.

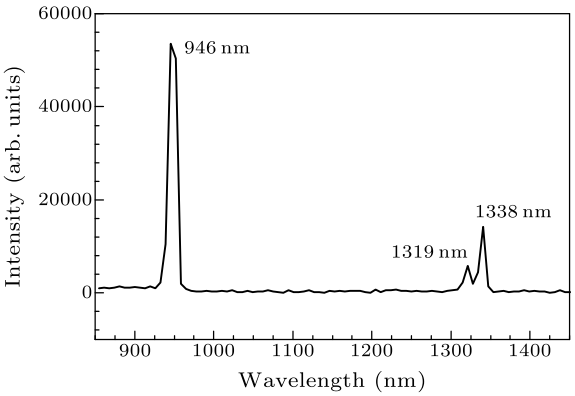

Fig. 2. The Q-switched emission spectrum of Nd,Cr:YAG crystal under 808 nm excitation.

The Nd,Cr:YAG crystal as the laser host material and passive Q-switcher at 946 nm used in our experiment is sized with $\phi 5.5 \times 3$ mm with concentration of 0.8 at.% for Nd^{3+} and 0.06 at.% for Cr^{4+}, and the initial transmission of 946 nm is about 94.5%. Both surfaces of the crystal are HT coated at 800–1350 nm. The Nd,Cr:YAG crystal is wrapped with indium foil and mounted in a water-cooled copper heat sink, and the water temperature is maintained at 10℃ during the experiment. The heat deposition could be dissipated effectively by this method. The saturable absorber V^{3+}:YAG crystal served as the Q-switcher at 1.3 μm with a dimensions of 3 mm × 3 mm × 3.65 mm and both the end-surfaces are coated for HT at 800–1350 nm with its initial transmission of 90% at around 1.3 μm. The Q-switcher is placed near the output coupler M3. The average output power of 946 nm at 1.3 μm is measured simultaneously by an optical power meter (Model 1917-R, Newport). The output power is measured at a distance of 60 cm away from the M3 output mirrors to remove the influence of the residual pump light. The temporal profile and repetition rate of the output laser pulse are recorded by an oscilloscope (Tektronix TDS 3052C, 500 MHz bandwidth, 5.0 Gs/s) and a fast photo detector with a rising time of 70 ps (DET 08C/M, Thorlabs). The spectrum is measured with a near-infrared spectrometer (Ocean Optics).

Figure 2 shows the emission spectrum of the Q-switched Nd,Cr:YAG laser under the absorbed pump power of 13.32 W at the wavelengths 946 nm and 1.3 μm. The strongest laser line at 1064 nm, which has the largest cross-section, is successfully suppressed by selective reflection in the cavity.

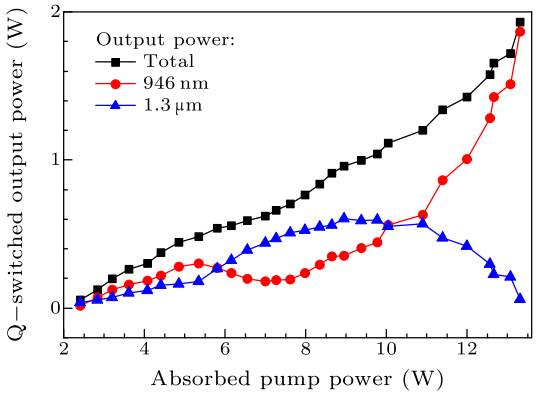

Fig. 3. The relationship of Q-switched output power at 946 nm and 1.3 μm, respectively.

Figure 3 presents the relationship of simultaneous multi-wavelength Q-switched output power. The thresholds of two wavelengths are almost the same and the absorbed pump power is about 2.4 W. From the figure we could safely infer that the total output power of the laser increases almost linearly with the absorbed pump power. During the oscillation, there is a fierce competition between two lasers. When the absorbed pump power is more than 11.4 W, the 1.3 μm laser dropped quickly. A simple method to measure the thermal lens proposed by Song *et al.* is used in our experiment.[24] When the absorbed pump power is more than 10.9 W, the cavity of the 1.3 μm laser becomes unstable while that of the 946 nm laser is still stable due to the thermal lens effect. As a result, the output power of the 1.3 μm laser decreases sharply while the 946 nm laser is not affected. ABCD matrix is introduced to analyze the variation of the laser mode radius in the cavity. The calculation shows that the mode radius of 1.3 μm laser in Nd,Cr:YAG is 103 μm and 134 μm in V:YAG, which is matched with the radius of pumping beam at low pump power at the beginning. The mode radius of the 946 nm laser is 119 μm in Nd,Cr:YAG but decreases with the gradually shorter focal length of the thermal lens. As the pump power increases, the result of calculation shows that the radius of the 1.3 μm laser increases while that of the 946 nm laser decreases in Nd,Cr:YAG. At the maximum absorbed pump power, the mode radius of 1.3 μm increases to 107 μm in Nd,Cr:YAG and 105 μm in V:YAG, and that of 946 nm laser is 84 μm.

There is a fierce competition between two lasers. The laser mode radius matched with the pumping beam radius could gain more energy from the pump power. That is why the output power of two lasers fluctuated. A maximum total Q-switched output power of 1.93 W and a maximum optical–optical conversion efficiency of 14.49% are obtained under the absorbed pump power of 13.32 W. The slope efficiency of absorbed total output power is 15.15%.

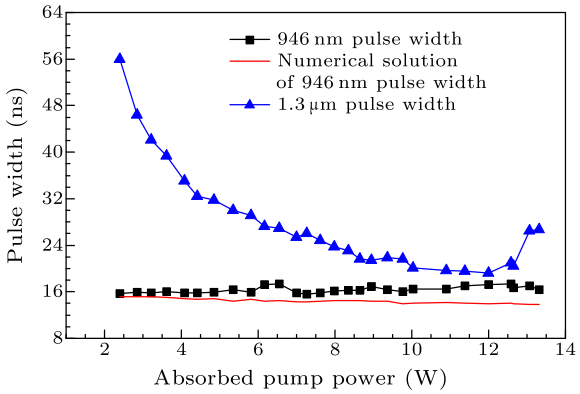

Fig. 4. Pulse widths of 946 nm and 1.3 μm versus the absorbed pump power.

Figure 4 presents the variation of pulse width of the Q-switched dual-wavelength laser on the absorbed pump power. A digital oscilloscope is used in recording the pulse shape of the Q-switched laser. The pulse width of 1.3 μm laser is monotonously decreased with increasing the absorbed pump power. The pulse width broadens for the decrease of output power of the 1.3 μm laser during the fierce competition with the 946 nm laser. This might give an insight into the decreasing output at high pump power. It could be observed that the pulse width of 946 nm has not varied much during the oscillation in accordance with Refs. [25,26]. The pulse width of the 946 nm laser fluctuated around 16 ns through the whole experiment. For the quasi-three-level operation, the pulse width of Q-switched Nd,Cr:YAG laser at 946 nm correlated with three factors: maximum inversion population density n_i, threshold inversion population density n_t, and minimum inversion population density n_f. They change slightly with increasing the absorbed pump power and this work has been demonstrated by Li *et al.* in 2008.[27] In this manuscript, the Runge–Kutta method is used in numerical solution of the rate equations. The pulse widths change from 15.18 ns to 13.85 ns. It fluctuates during the laser oscillation but decreases slightly. The pulse width is shorter than what we measured. However, it maintains around 14.5 ns. The pulse width of 1.3 μm Q-switched laser decreases with increasing the absorbed pump power as shown in Fig. 4. It could be attributed to the characteristic of the saturable absorber V:YAG, which takes less time to change its transmission when the output power of Nd,Cr:YAG is higher. The pulse width becomes wider when the output power of 1.3 μm laser decreases. The variation tendency of pulse width of 1.3 μm is similar to the result of Refs. [28,29].

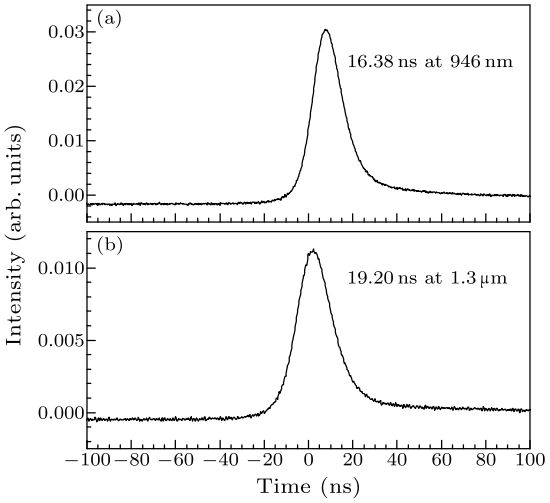

Fig. 5. The pulse widths of 946 nm (a) at the absorbed pump power of 13.32 W and 1.3 μm (b) at the absorbed pump power of 12 W lasers.

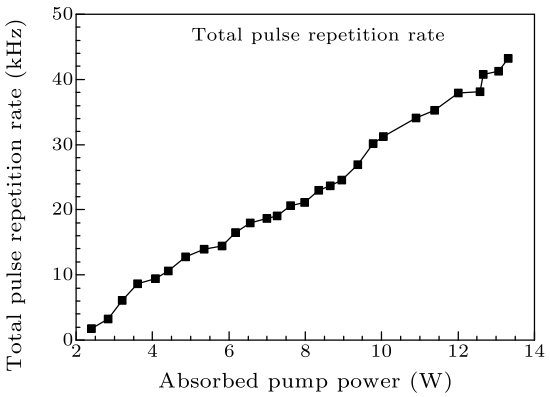

Fig. 6. Pulse repetition rate versus the absorbed pump power.

Figure 5 shows the pulse widths of dual-wavelength under different absorbed pump powers. At the maximum absorbed pump power of 13.32 W the pulse width of 946 nm is 16.38 ns (Fig. 5 (a)). The minimum pulse width of 1.3 μm is 19.20 ns (Fig. 5 (b)) could be obtained at the absorbed pump power at 12 W. In our experiment, it is also found that the repetition rate of the Q-switched laser depends on the pumping power. Figure 6 shows the relationship between two lasers pulse repetition rate and the increasing absorbed pump power. A maximum pulse repetition rate of 43.25 kHz is obtained with an absorbed pump power of 13.32 W. Pulse repetition rate varies with the enhancement of the input absorbed pump power. The relationship of repetition rate between two lasers could be accountable for heat deposition and the competi-

tion between 946 nm and 1.3 μm lasers.

Figure 7 illustrates the short-term instability of the Q-switched output power, and the data is measured in half an hour when the absorbed pump power is 12 W. The output power is recorded every two minutes. The instability of the output power is calculated to be 1.47% by using the following formula of standard deviation[30]

$$\frac{\Delta P}{\overline{P}} = \frac{1}{\overline{P}}\sqrt{\frac{\sum_{i=1}^{n}(P_i - \overline{P})^2}{n-1}} = 1.47\%, \qquad (1)$$

where P_i refers to the output power, n is the number of the measure times, $\overline{P}$ and ΔP are the average and the variation of the output power, respectively. The result demonstrates that the laser is fairly stable even if the cavity is pumped under the intensity of absorbed pump power of 12 W.

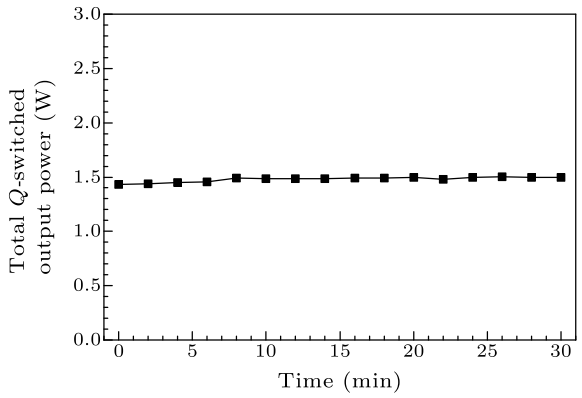

Fig. 7. Q-switched output power short term instability at the absorbed pump power 12 W.

In conclusion, a passively Q-switched dual-wavelength operation at 946 nm and 1.3 μm laser has been successfully demonstrated under the 808 nm pump system. With an absorbed pump power of 13.32 W, the maximum total output power is 1.93 W, which corresponds to an optical–optical conversion efficiency of 14.49% and an absorbed slope efficiency of 15.15%. Pulse width of the 946 nm laser changes slightly with the pumping power around 16 ns. The 1.3 μm Q-switched laser is operated with V^{3+}:YAG as the saturable absorber and the minimal pulse width is 19.20 ns under the absorbed pump power of 12 W. The repetition rate also increases with the pump power and the maximum repetition rate is 43.25 kHz at an absorbed pumping power of 13.32 W. The instability of the Q-switched output is measured to be 1.47%, demonstrating an excellent stability of the laser.

References

[1] Xuan H W, Zhao Z G, Igarashi H, Ito S, Kakizaki K and Kobayashi Y 2015 *Opt. Express* **23** 10564
[2] Lo H Y, Alonso J, Kienzler D, Keitch B C, de Clercq L E, Negnevitsky V and Home J P 2014 *Appl. Phys.* B **114** 17
[3] Zhang J 2014 *Optik* **125** 7061
[4] Pogoda A P, Smetanin S N, Ershkov M N, Khakhalin I S, Lebedev V F and Boreysho A S 2015 *Russ. J. Phys. Chem.* B+ **9** 521
[5] Lünstedt K, Pavel N, Petermann K and Huber G 2006 *Appl. Phys.* B **86** 65
[6] Hsu C C, Wu S S, Chou C C and Wei M D 2011 *Laser Phys.* **21** 1871
[7] Chen Y F 2000 *Appl. Phys.* B **70** 475
[8] Salamu G, Osiac E, Dascalu C, Pavel N and Dascalu T 2012 *Laser Phys.* **22** 866
[9] Xu L J, Zhang X H, Tan Y, Zhang F D and Jin G Y 2011 *Laser Phys.* **21** 1054
[10] Zhang H N, Chen X H, Wang Q P and Li P 2013 *Chin. Phys. Lett.* **30** 104202
[11] Zhang L, Zhang C Y, Wei Z Y, Zhang Z G, Strohmaier S and Eichler H J 2006 *Chin. Phys. Lett.* **23** 2088
[12] Geng Y F, Tan X L, Li X J and Yao J Q 2010 *Chin. Phys.* B **19** 104202
[13] Lin B, Xiao K, Zhang Q L, Zhang D X, Feng B H, Li Q N and He J L 2016 *Appl. Opt.* **55** 1844
[14] Jin G Y, Wu C T, Chen X Y, Yu Y J and Wang C 2013 *Chin. Phys. Lett.* **30** 034209
[15] Hou Y E, Fan Y X, He J L and Wang H T 2006 *Opt. Commun.* **265** 301
[16] Cheng H P H, Tidemand-Lichtenberg P, Jensen O B, Andersen P E, Petersen P M and Pedersen C 2010 *Opt. Express* **18** 23987
[17] Abdul Ghani B and Hammadi M 2013 *Optik* **124** 622
[18] Sato A, Okubo S, Asai K, Ishii S and Mizutani K 2014 *Appl. Phys.* B **117** 621
[19] Zhang L, Wei Z Y, Feng B H, Li D H and Zhang Z G 2006 *Opt. Commun.* **264** 51
[20] Sato A, Okubo S, Asai K, Ishii S, Mizutani K and Sugimoto N 2015 *Appl. Opt.* **54** 3032
[21] Jiang M, Zhang Q L, Qiu K S, Zhang D X and Feng B H 2012 *Opt. Commun.* **285** 3684
[22] Wang S M, Li Q N, Du S F, Zhang Q L, Shi Y X, Xing H, Zhang D X, Feng B H, Zhang Z G and Zhang S W 2007 *Opt. Commun.* **277** 130
[23] Singh S, Smith R G and van Uitert L G 1974 *Phys. Rev.* B **10** 2566
[24] Song F, Zhang C B, Ding X, Xu J J, Zhang G Y, Leigh M and Peyghambarian N 2002 *Appl. Phys. Lett.* **81** 2145
[25] Qi Y F, Lou Q H, Liu Y P, Zhang Y H, Ma H X, Dong J X and Wei Y R 2006 *J. Opt.* A **8** 550
[26] Kong J, Zhang Z Z, Tang D Y, Xie G Q, Chan C C and Shen Y H 2008 *Laser Phys.* **18** 1508
[27] Li Q, Feng B, Zhang D, Du S, Shi Y, Zhang Z and Zhang S 2008 *Appl. Phys.* B **93** 421
[28] Xiao K, Lin B, Zhang Q L, Zhang D X, Feng B H, He J L, Zhang H J and Wang J Y 2015 *Appl. Opt.* **54** 7071
[29] Grabtchikov A S, Kuzmin A N, Lisinetskii V A, Orlovich V A, Demidovich A A, Yumashev K V, Kuleshov N V, Eichler H J and Danailov M B 2001 *Opt. Mater.* **16** 349
[30] Liu H, Gong M, Wushouer X and Gao S 2010 *Laser Phys. Lett.* **7** 124