$KLu(WO_4)_2$ crystal as the Raman medium in a diode-pumped passively Q-switched Nd:YAG laser*

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A diode-pumped passively Q-switched Nd:YAG/$KLu(WO_4)_2$ (KLW) Raman laser is presented for the first time. As high as 1.89 W average output power is obtained at the pump power of 15.7 W with the pulse repetition frequency (PRF) of 27.2 kHz, and the corresponding diode-to-Stokes conversion efficiency is 12.0%. The highest pulse energy of 84.0 μJ is obtained. The obtained average output power and pulse energy are much higher than the previously reported results of diode-pumped passively Q-switched Raman lasers.

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Stimulated Raman scattering (SRS) in crystalline materials is one of the most efficient methods for generating new laser lines[1–3]. With the development of high-quality Raman crystals in recent years, the interest in solid-state Raman lasers has been rapidly increased[4–6].

$KLu(WO_4)_2$ (KLW) crystal is a promising Raman material for high Raman gain coefficient[7–10]. Data on spontaneous Raman scattering spectra reveal that the c-cut KLW crystal has high Raman gain at the vibration frequency of 907 cm^{-1}, and the b-cut KLW crystal has high Raman gain at the vibration frequencies of 757 cm^{-1}, 907 cm^{-1} and 88 cm^{-1}[7, 9–12]. In 2005, a passively Q-switched Yb:KLW self-Raman laser was reported[8]. Owing to the short length of the Raman medium, the conversion efficiency was only 5.7%. In 2010, the LD-pumped actively Q-switched intracavity Nd:YAG/KLW Raman lasers were studied[9,10]. With a 22 mm c-cut KLW crystal, a 2.5 W 1178 nm laser was obtained at a pulse repetition frequency (PRF) of 25 kHz, and the conversion efficiency was 20.1%. With a b-cut KLW crystal, 14 wavelengths were obtained, including the first to the ninth order Stokes wavelengths for the 88 cm^{-1} Raman shift, the 1064 nm fundamental wavelength and the other four wavelengths for the 757 cm^{-1} and 907 cm^{-1} Raman shifts. However, there is no report about the diode-pumped passively Q-switched intracavity KLW Raman laser to our knowledge.

In this paper, we present the characteristics of an LD-pumped Cr^{4+}:YAG passively Q-switched intracavity Nd:YAG/KLW Raman laser. At a pump power of 15.7 W, the Raman laser system delivers the average output power of 1.89 W with a PRF of 27.2 kHz. The corresponding diode-to-Stokes conversion efficiency is 12.0 %. The highest pulse energy of 84.0 μJ is obtained. The obtained average output power and pulse energy are much higher than the previously obtained results of diode-pumped passively Q-switched Raman lasers[13-18].

Fig.1 gives the configuration of the diode-pumped passively Q-switched Nd:YAG/KLW Raman laser. The rear mirror M1 is a concave mirror with the curvature radius of 300 mm. It is coated for high transmission (HT) at 808 nm (T > 96%) and high reflection (HR) at 1000-1200 nm (R > 99.8%). Three output couplers (OC1, OC2 and OC3) with different transmissions at 1178 nm (T = 8.4%, 16.1% and 25.2%) are used. All the output couplers are plane mirrors and coated for HR at 1064 nm (R > 99.9%). The overall laser cavity

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length is about 7.5 cm. A dichroic mirror is used for blocking the residual fundamental laser at 1064 nm.

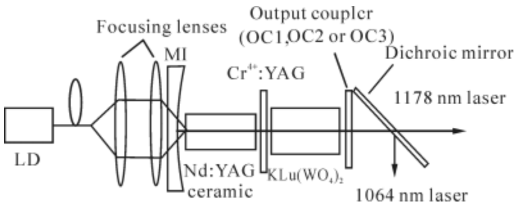


Fig.1 Experimental setup of the LD-pumped passively Q-switched Nd:YAG/KLW Raman laser

The pump source is a fiber-coupled laser diode with the output power of 25 W at 808 nm, a core diameter of 600 μm and a numerical aperture of 0.22. The laser gain medium is a 1.0 at.% Nd:YAG ceramic with the dimension of ϕ4 mm × 10 mm. The Raman active medium is a 6 mm × 6 mm × 22 mm c-cut KLW crystal. Both sides of the Nd:YAG ceramic and the KLW crystal are coated for antireflection (AR) at 1064 nm and 1178 nm (R<0.2%). The entrance face of the Nd:YAG ceramic is also coated for HT at 808 nm. The three Cr^{4+}:YAG crystals with different initial transmissions of 94%, 87% and 81% are coated for AR at 1000−1350 nm on both faces. The Nd:YAG ceramic and the KLW crystal are wrapped with indium foil and mounted in water-cooled copper heat sinks. The water temperature is maintained at 20°C.

The average output power is measured by a power meter (Molectron PM3) connected to Molectron EPM2000. The spectral information is monitored by a wide range optical spectrum analyzer (Yokogawa AQ6315A, 350–1750 nm). The temporal behavior of Raman pulse is recorded by a Tektronix digital phosphor oscilloscope (TDS 5052B, 5 G samples/s, 500 MHz bandwidth) with a fast pin photodiode.

Fig.2 depicts the optical spectrum of output from the passively Q-switched Nd:YAG/KLW Raman laser, which is recorded at a pump power of 15.7 W for OC3 at T_0=81% without the dichroic mirror. Corresponding to the fundamental laser at 1064 nm, the flrst-Stokes laser is at 1178 nm. The frequency shift between the first-Stokes and the fundamental laser is 907 cm^{-1}, which is in agreement with the Raman vibration frequency of the c-cut KLW crystal.

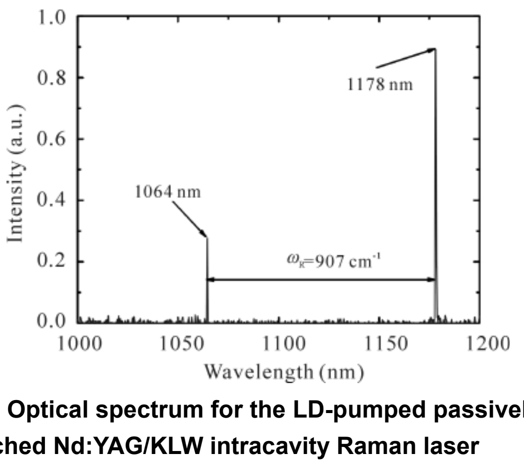
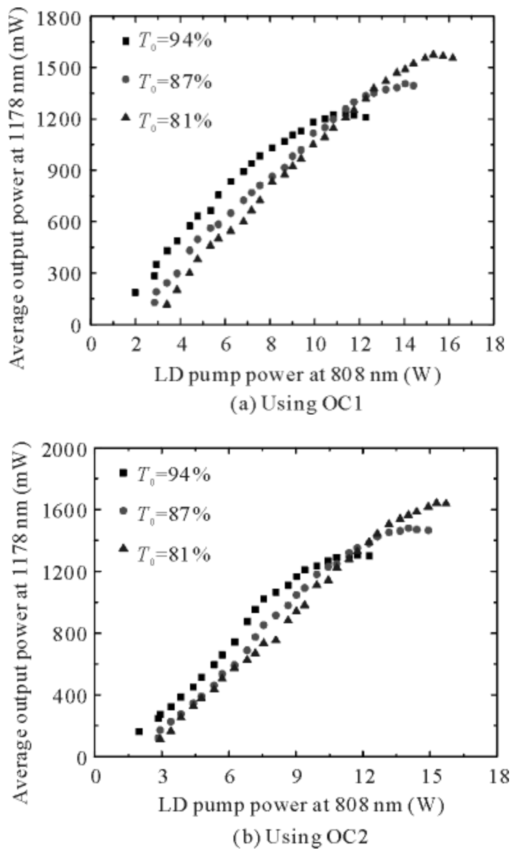
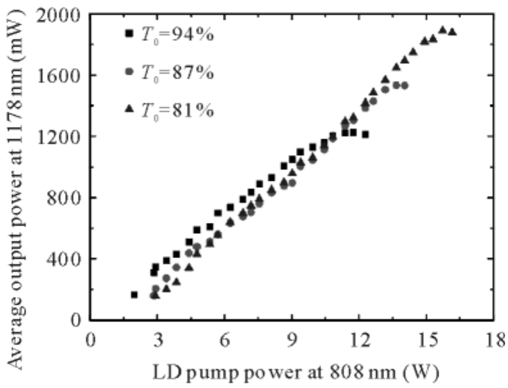


Fig.2 Optical spectrum for the LD-pumped passively Q-switched Nd:YAG/KLW intracavity Raman laser

The relation between the average output power at 1178 nm and the pump power is shown in Fig.3 while OC1, OC2 and OC3 are used, respectively. As seen from Fig.3, the first-Stokes power is increased with increasing pump power, and the threshold is decreased with increasing initial transmission of Cr^{4+}:YAG. The highest average output power is 1.89 W with a PRF of 27.2 kHz for OC3 at T_0=81%, which is obtained at the pump power of 15.7 W. The corresponding conversion efficiency from the diode laser to the 1178 nm laser is 12.0%. The highest pulse energy of 84.0 μJ is obtained for OC3 at T_0=81% with the pump power of 4.8 W. The obtained average output power and pulse energy are much higher than the previously reported results of LD-pumped passively Q-switched intracavity Raman lasers[13−18].

There are two main reasons for the high average power and the high pulse energy. One is the good mechanical and optical properties of KLW as Raman active medium. The other is that the thermal effect of Cr^{4+}:YAG crystals is reduced by a heat sink. At the beginning, we study the characteristics of Raman laser without cooling the Cr^{4+}:YAG crystals because they are too thin to be put in heat sinks like Nd:YAG and KLW. The laser has low efficiency, and the average output power is less than 1 W at T_0=81%. The thermal effect in





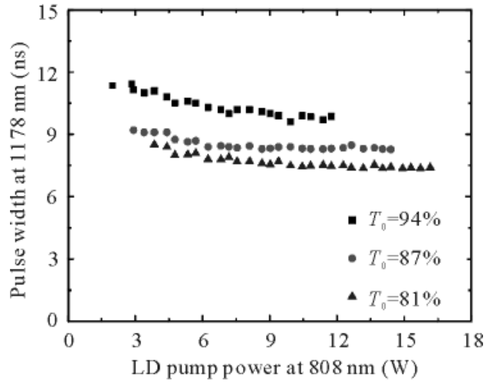
(c) Using OC3

Fig.3 Average output power at 1178 nm versus the pump power for Cr^{4+}:YAG with different initial transmissions when OC1, OC2 and OC3 are used, respectively

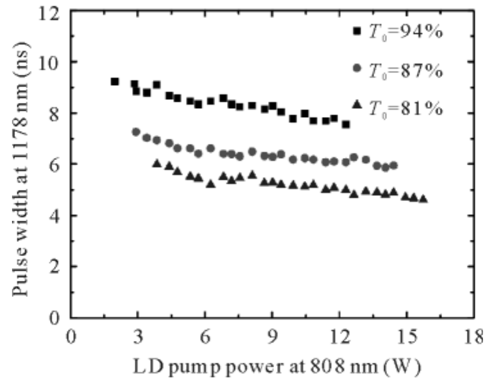
the Cr^{4+}:YAG crystals becomes serious with increasing pump power, which impacts the stabilization of the resonator and impedes the increase of the Raman laser output power. So in the following experiment, the Cr^{4+}:YAG crystal is stuck to the water-cooled copper heat sink with a hole, and the water temperature is maintained at 20°C. In this way, the Raman laser output power and conversion efficiency are significantly increased.

Fig.4 shows the pulse widths at 1178 nm with increasing pump power while OC1, OC2 and OC3 are used, respectively. Fig.5 shows pulse repetition rates at 1178 nm with increasing pump power while OC1, OC2 and OC3 are used, respectively. As shown in Figs.4 and 5, the pulse width is decreased slightly and the pulse repetition rate is increased with increasing pump power. With decreasing the initial transmission of Cr^{4+}:YAG, the pulse width becomes narrower, and the pulse repetition rate becomes smaller.

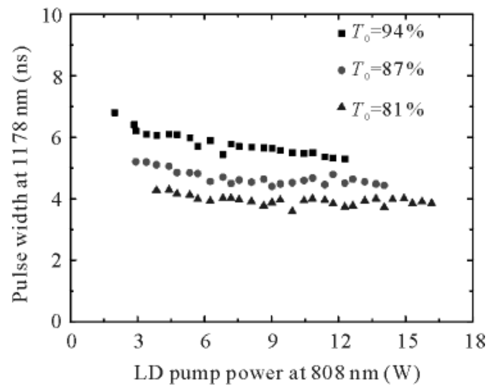
As shown in Fig.3, there are obvious saturation effects for the Raman laser output power, and there is an obvious relation between the saturation and the initial transmission T_0. The larger the initial transmission T_0 is, the easier the output power is saturated. As seen from Fig.5, at a given high



(a) Using OC1



(b) Using OC2

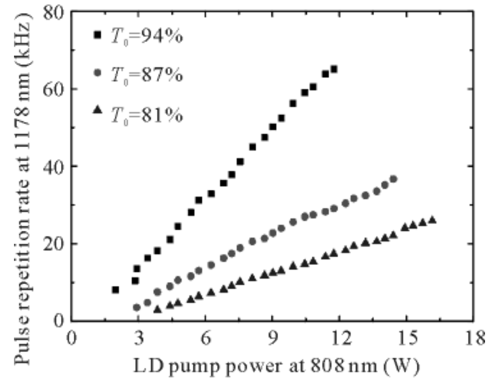


(c) Using OC3

Fig.4 Pulse width at 1178 nm versus the pump power for Cr^{4+}:YAG with different initial transmissions when OC1, OC2 and OC3 are used, respectively

pump power, the higher the initial transmission of the saturable absorber T_0 is, the higher the pulse repetition rate of the Raman laser is. And when the pulse repetition rate becomes higher, the laser goes through the Cr^{4+}:YAG crystal more frequently, the accumulated heat in the Cr^{4+}:YAG crystal becomes larger, the stabilization of the resonator becomes worse, and the output power at 1178 nm is easier to be saturated. So the Raman laser output power is easier to be saturated while the initial transmission of Cr^{4+}:YAG crystals is higher, which can be seen from Fig.3.

The typical time-domain spectrum at 1178 nm is shown in



(a) Using OC1

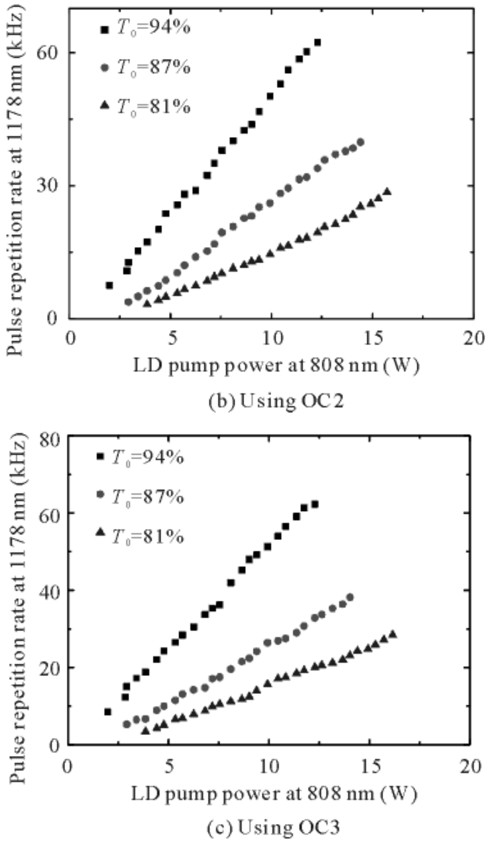


Fig.5 Pulse repetition rate at 1178 nm versus the pump power for Cr^{4+}:YAG with different initial transmissions when OC1, OC2 and OC3 are used, respectively

Fig.6, which is recorded at the pump power of 15.7 W for OC3 at T_0=81%. The pulse duration of the Raman lasers is about 4.1 ns.

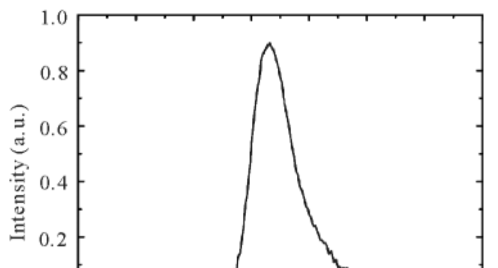


Fig.6 Typical oscilloscope trace for the Raman pulse at 1178 nm

In summary, the characteristics of the diode-pumped Cr^{4+}:YAG passively Q-switched Nd:YAG/KLW intracavity Raman laser are investigated for the first time. With the pump power of 15.7 W, the average output power as high as 1.89 W at 1178 nm is generated with a PRF of 27.2 kHz, and the corresponding diode-to-Stokes conversion efficiency is 12.0 %. The highest pulse energy of 84.0 μJ is achieved at a pump power of 4.8 W. The obtained pulse energy and average power are much higher than those of the previously reported diode-pumped passively Q-switched intracavity Raman lasers.

References

[1] H. M. Pask, Prog. Quantum Electron. **27**, 3 (2003).

[2] P. Èerný, H. Jelínková, P. G. Zverev and T. T. Basiev, Prog. Quantum Electron. **28**, 113 (2004).

[3] Yanfei Lü, Xihe Zhang, Shutao Li, Jing Xia, Weibo Cheng and Zheng Xiong, Opt. Lett. **35**, 2964 (2010).

[4] J. A. Piper and H. M. Pask, IEEE Sel. Top. Quantum Electron. **13**, 692 (2007).

[5] X. H. Chen, X. Y. Zhang, Q. P. Wang, P. Li, S. T. Li, Z. H. Cong, G. H. Jia and C. Y. Tu, Opt. Lett. **33**, 705 (2008).

[6] X. H. Chen, X. Y. Zhang, Q. P. Wang, P. Li, S. T. Li, Z. H. Cong, Z. J. Liu, S. Z. Fan and H. J. Zhang, Laser Phys. Lett. **6**, 363 (2009).

[7] A. A. Kaminskii, K. Ueda, H. E. Eichler, J. Findeisen, S. N. Bagayev, F. A. Kuznetsov, A. A. Pavlyuk, G. Boulon and F. Bourgeois, Jpn. J. Appl. Phys. **37**, L923 (1998).

[8] J. H. Liu, U. Griebner, V. Petrov, H. J. Zhang, J. X. Zhang and J. Y. Wang, Opt. Lett. **30**, 2427 (2005).

[9] Z. H. Cong, X. Y. Zhang, Q. P. Wang, X. H. Chen, S. Z. Fan, Z. J. Liu, H. J. Zhang, X. T. Tao, J. Y. Wang, H. Y. Zhao and S. T. Li, Laser Phys. Lett. **7**, 862 (2010).

[10] Z. H. Cong, X. Y. Zhang, Q. P. Wang, X. H. Chen, S. Z. Fan, Z. J. Liu, H. J. Zhang, X. T. Tao, J. Y. Wang, H. Y. Zhao and S. T. Li, Multi-Wavelength Operation of Intracavity Nd:YAG/$KLu(WO_4)_2$ Raman Laser, Photonics Global Conference (PGC), Singapore, 1 (2010).

[11] V. Petrov, M. C. Pujol, X. Mateos, O. Silvestre, S. Rivier, M. Aguilo, R. M. Sole, J. Liu, U. Griebner and F. Diaz, Laser & Photon. Rev. **1**, 179 (2007).

[12] J. Hanuza and L. Macalik, Apectrochimica Acta **43**, 361 (1987).

[13] Y. F. Chen, Opt. Lett. **29**, 1251 (2004).

[14] V. E. Kisel, A. E. Troshin, N. A. Tolstik, V. G. Shcherbitsky, N. V. Kuleshov, V. N. Matrosov, T. A. Matrosova and M. I. Kupchenko, Appl. Phys. B **80**, 471 (2005).

[15] J. Y. Wang, H. J. Zhang, Z. P. Wang, W. W. Ge, J. X. Zhang and M. H. Jiang, J. Cryst. Growth **292**, 377 (2006).

[16] T. T. Basiev, M. E. Doroshenko, L. I. Ivleva, I. S. Voronina, V. A. Konjushkin, V. V. Osiko and S. V. Vasilyev, Opt. Lett. **34**, 1102 (2009).

[17] T. Omatsu, A. Lee, H. M. Pask and J. Piper, Appl. Phys. B **97**, 799 (2009).

[18] T. T. Basiev, S. N. Smetanin, A. V. Fedin and A. S. Shurygin, Quantum Electron. **40**, 704 (2010).