Diode-pumped 88-fs Kerr-lens mode-locked Yb:$Y_3Ga_5O_{12}$ crystal laser

Jinwei Zhang,[1] Hainian Han,[1] Wenlong Tian,[2] Liang Lv,[2] Qing Wang,[1] and Zhiyi Wei[1,*]

[1] *Beijing National Laboratory for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*
[2] *School of Technical Physics, Xidian University, Xi'an 710126, China*
**zywei@iphy.ac.cn*

Abstract: We realized a stable Kerr-lens mode-locked operation in a diode-pumped Yb:$Y_3Ga_5O_{12}$ laser. Pulses as short as 88 fs at the center wavelength of 1042 nm were obtained at a repetition rate of 159.3 MHz. The maximum output power was 104 mW under the incident pump power of 3.9 W. By comparing the mode-locked characteristics under different output transmissions, we obtained pulses with the highest output power of 330 mW and a duration of 149 fs. To the best of our knowledge, this is the first demonstration of a Kerr-lens mode-locked Yb:$Y_3Ga_5O_{12}$ laser.

OCIS codes: (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers; (140.3615) Lasers, ytterbium

References and links

1. U. Keller, W. H. Knox, and H. Roskos, "Coupled-cavity resonant passive mode-locked Ti:sapphire laser," Opt. Lett. **15,** 1377–1379 (1990).
2. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, "Semiconductor saturable absorber mirrors (SESAMs) for femtosecond to nanosecond pulse generation in solid-state lasers," IEEE J. Sel. Top. Quantum Electron. **2,** 435–453 (1996).
3. Y. Zaouter, J. Didierjean, F. Balembois, G. Lucas Leclin, F. Druon, P. Georges, J. Petit, P. Goldner, and B. Viana, "47-fs diode-pumped Yb^{3+}:$CaGdAlO_4$ laser," Opt. Lett. **31,** 119–121 (2006).
4. A. Yoshida, A. Schmidt, V. Petrov, C. Fiebig, G. Erbert, J. Liu, H. Zhang, J. Wang, and U. Griebner, "Diode-pumped mode-locked Yb:YCOB laser generating 35 fs pulses," Opt. Lett. **36,** 4425–4427 (2011).
5. S. Rivier, X. Mateos, J. Liu, V. Petrov, U. Griebner, M. Zorn, M. Weyers, H. Zhang, J. Wang, and M. Jiang, "Passively mode-locked Yb:$LuVO_4$ oscillator," Opt. Express **14,** 11668–11671 (2006).
6. F. Druon, S. Chénais, P. Raybaut, F. Balembois, P. Georges, R. Gaumé, G. Aka, B. Viana, S. Mohr, and D. Kopf, "Diode-pumped Yb:$Sr_3Y(BO_3)_3$ femtosecond laser," Opt. Lett. **27,** 197–199 (2002).
7. C. Hönninger, F. Morier-Genoud, M. Moser, U. Keller, L. R. Brovelli, and C. Harder, "Efficient and tunable diode-pumped femtosecond Yb:glass lasers," Opt. Lett. **23,** 126–128 (1998).
8. S. Uemura and K. Torizuka, "Center-wavelength-shifted passively mode-locked diode-pumped ytterbium(Yb):yttrium aluminum garnet(YAG) laser," Jpn. J. Appl. Phys. **44,** L361–L363 (2005).
9. G. Paunescu, J. Hein, and R. Sauerbrey, "100-fs diode-pumped Yb:KGW mode-locked laser," Appl. Phys. B **79,** 555–558 (2004).
10. F. Friebel, F. Druon, J. Boudeile, D. N. Papadopoulos, M. Hanna, P. Georges, P. Camy, J. L. Doualan, A. Benayad, R. Moncorgé, C. Cassagne, and G. Boudebs, "Diode-pumped 99 fs Yb:CaF_2 oscillator," Opt. Lett. **34,** 1474–1476 (2009).
11. S. Rivier, V. Petrov, A. Gross, S. Vernay, V. Wesemann, D. Rytz, and U. Griebner, "Diffusion bonding of monoclinic Yb:$KY(WO_4)_2$/$KY(WO_4)_2$ and its continuous-wave and mode-locked laser performance," Appl. Phys. Express **1,** 112601 (2008).
12. V. E. Kisel, A. E. Troshin, V. G. Shcherbitsky, N. V. Kuleshov, V. N. Matrosov, T. A. Matrosova, M. I. Kupchenko, F. Brunner, R. Paschotta, F. Morier-Genoud, and U. Keller, "Femtosecond pulse generation with a diode-pumped Yb^{3+}:YVO_4 laser," Opt. Lett. **30,** 1150–1152 (2005).

#196772 - $15.00 USD Received 30 Aug 2013; revised 4 Nov 2013; accepted 12 Nov 2013; published 26 Nov 2013

13. A. Agnesi, A. Greborio, F. Pirzio, G. Reali, J. Aus der Au, and A. Guandalini, “40-fs Yb^{3+}:$CaGdAlO_4$ laser pumped by a single-mode 350-mW laser diode,” Opt. Express **20,** 10077–10082 (2012).
14. D. E. Spence, P. N. Kean, and W. Sibbett, “60-fsec pulse generation from a self-mode-locked Ti:sapphire laser,” Opt. Lett. **16,** 42–44 (1991).
15. M. T. Asaki, C. P. Huang, D. Garvey, J. Zhou, H. C. Kapteyn, and M. M. Murnane, “Generation of 11-fs pulses from a self-mode-locked Ti:sapphire laser,” Opt. Lett. **18,** 977–979 (1993).
16. R. Szipocs, K. Ferencz, C. Spielmann, and F. Krausz, “Chirped multilayer coatings for broad-band dispersion control in femtosecond lasers,” Opt. Lett. **19,** 201–203 (1994).
17. S. Uemura and K. Torizuka, “Sub-40-fs pulses from a diode-pumped Kerr-lens mode-locked Yb-doped yttrium aluminum garnet laser,” Jpn. J. Appl. Phys. **50,** 010201 (2011).
18. S. Uemura and K. Torizuka, “Kerr-lens mode-locked diode-pumped Yb:YAG laser with the transverse mode passively stabilized,” Appl. Phys. Express **1,** 012007 (2008).
19. H. Liu, J. Nees, and G. Mourou, “Diode-pumped Kerr-lens mode-locked Yb:$KY(WO_4)_2$ laser,” Opt. Lett. **26,** 1723–1725 (2001).
20. A. A. Lagatsky, A. R. Sarmani, C. T. A. Brown, W. Sibbett, V. E. Kisel, A. G. Selivanov, I. A. Denisov, A. E. Troshin, K. V. Yumashev, N. V. Kuleshov, V. N. Matrosov, T. A. Matrosova, and M. I. Kupchenko, “Yb^{3+}-doped YVO_4 crystal for efficient Kerr-lens mode locking in solid-state lasers,” Opt. Lett. **30,** 3234–3236 (2005).
21. M. Tokurakawa, A. Shirakawa, K. Ueda, H. Yagi, T. Yanagitani, and A. A. Kaminskii, “Diode-pumped sub-100 fs Kerr-lens mode-locked Yb^{3+}:Sc_2O_3 ceramic laser,” Opt. Lett. **32,** 3382–3384 (2007).
22. M. Tokurakawa, A. Shirakawa, K. Ueda, H. Yagi, M. Noriyuki, T. Yanagitani, and A. A. Kaminskii, “Diode-pumped ultrashort-pulse generation based on Yb^{3+}:Sc_2O_3 and Yb^{3+}:Y_2O_3 ceramic multi-gain-media oscillator,” Opt. Express **17,** 3353–3361 (2009).
23. A. Schmidt, V. Petrov, U. Griebner, R. Peters, K. Petermann, G. Huber, C. Fiebig, K. Paschke, and G. Erbert, “Diode-pumped mode-locked Yb:$LuScO_3$ single crystal laser with 74 fs pulse duration,” Opt. Lett. **35,** 511–513 (2010).
24. M. Tokurakawa, A. Shirakawa, K. Ueda, H. Yagi, S. Hosokawa, T. Yanagitani, and A. A. Kaminskii, “Diode-pumped 65 fs Kerr-lens mode-locked Yb^{3+}:Lu_2O_3 and nondoped Y_2O_3 combined ceramic laser,” Opt. Lett. **33,** 1380–1382 (2008).
25. O. Pronin, J. Brons, C. Grasse, V. Pervak, G. Boehm, M.-C. Amann, V. L. Kalashnikov, A. Apolonski, and F. Krausz, “High-power 200 fs Kerr-lens mode-locked Yb:YAG thin-disk oscillator,” Opt. Lett. **36,** 4746–4748 (2011).
26. J. E. Geusic, H. M. Marcos, and L. G. Van Uitert, “Laser oscillations in Nd-doped yttrium aluminum, yttrium gallium and gadolinium garnets,” Appl. Phys. Lett. **4,** 182–184 (1964).
27. F. Euler and J. A. Bruce, “Oxygen coordinates of compounds with garnet structure,” Acta Crystallogr. **19,** 971–974 (1965).
28. B. Henderson, H. G. Gallagher, T. P. J. Han, and M. A. Scott, “Optical spectroscopy and optimal crystal growth of some Cr^{4+}-doped garnets,” J. Phys.: Condens. Matter **12,** 1927–1938 (2000).
29. S. G. P. Strohmaier, H. J. Eichler, C. Czeranowsky, B. Ileri, K. Petermann, and G. Huber, “Diode pumped Nd:GSAG and Nd:YGG laser at 942 and 935 nm,” Opt. Commun. **275,** 170–172 (2007).
30. R. Adair, L. L. Chase, and S. A. Payne, “Nonlinear refractive index of optical crystals,” Phys. Rev. B **39,** 3337–3350 (1989).
31. P. A. Giesting and A. M. Hofmeister, “Thermal conductivity of disordered garnets from infrared spectroscopy,” Phys. Rev. B **65,** 144305 (2002).
32. E. Antic-Fidanccv, J. Hölsä, M. Lastusaari and A. Lupei, “Dopant-host relationships in rare-earth oxides and garnets doped with trivalent rare-earth ions,” Phys. Rev. B **64,** 195108 (2001).
33. I. A. Kamenskikh, N. Guerassimova, C. Dujardin, N. Garnier, G. Ledoux, C. Pedrini, M. Kirm, A. Petrosyan, and D. Spassky, “Charge transfer fluorescence and f-f luminescence in ytterbium compounds,” Opt. Mater. **24,** 267–274 (2003).
34. S. Heer, M. Wermuth, K. Krämer, and H. U. Güdel, “Sharp ^2E upconversion luminescence of Cr^{3+} in $Y_3Ga_5O_{12}$ codoped with Cr^{3+} and Yb^{3+},” Phys. Rev. B **65,** 125112 (2002).
35. A. Yoshikawa, M. Nikl, H. Ogino, J. H. Lee, and T. Fukuda, “Crystal growth of Yb^{3+}-doped oxide single crystals for scintillator application,” J. Cryst. Growth **250,** 94–99 (2003).
36. H. Yu, K. Wu, B. Yao, H. Zhang, Z. Wang, J. Wang, Y. Zhang, Z. Wei, Z. Zhang, X. Zhang, and M. Jiang, “Growth and characteristics of Yb-doped $Y_3Ga_5O_{12}$ laser crystal,” IEEE J. Quantum Electron. **46,** 1689–1695 (2010).
37. Y. Zhang, Z. Wei, B. Zhou, C. Xu, Y. Zou, D. Li, Z. Zhang, H. Zhang, J. Wang, H. Yu, K. Wu, B. Yao, and J. Wang, “Diode-pumped passively mode-locked Yb:$Y_3Ga_5O_{12}$ laser,” Opt. Lett. **34,** 3316–3318 (2009).
38. Y. Zhang, Z. Wei, Q. Wang, D. Li, Z. Zhang, H. Yu, H. Zhang, J. Wang, and L. Lv, “Diode-pumped efficient continuous-wave Yb:$Y_3Ga_5O_{12}$ laser at 1035 nm,” Opt. Lett. **36,** 472–474 (2011).

1. Introduction

In recent years Yb-doped laser materials are attracting more and more attentions for ultrafast lasers because of their numerous excellent characteristics, such as no excited state absorption, no cross relaxation, high quantum efficiency, long fluorescence lifetime, broad emission bands and ability of being directly pumped by diode lasers. Benefiting from the rapid development of the available Yb-doped laser materials and the high brightness diode lasers, remarkable progresses on diode-pumped mode-locked Yb-doped lasers were achieved. With a semiconductor saturable absorber mirror (SESAM) which is commonly used in solid-state mode-locked lasers [1, 2], stable femtosecond laser pulses have been generated with various Yb-doped laser materials [3–13]. Kerr-lens mode locking is another well-developed technique for the generation of ultrashort pulses [14–16]. Up to now, several kinds of Yb-doped laser materials have been studied and used to generate the sub-100 fs pulses by Kerr-lens mode locking [17–24]. Among all these laser materials, Yb:YAG has attracted the most attentions because of its remarkable advantages and capability of support sub-100 fs laser pulses [18]. As a special case, pulse duration as short as 35 fs was obtained by shifting the central wavelength from 1030 nm to 1060 nm when a prism pair was used to precisely compensate the intracavity group velocity dispersion (GVD) [17]. By employing a thin disk as gain medium, O. Pronin et al. even realized high-power Kerr-lens mode-locked (KLM) operation with the average power of 17 W and pulse duration of 200 fs [25]. Meanwhile, the attempt of exploring new Yb-doped gain medium for supporting even shorter pulse duration and higher power never stop, it still attracts extensive interesting for the pursue of directly diode-pumped ultrafast laser with promising gain materials in laser field.

Yb:$Y_3Ga_5O_{12}$ (YGG) is obtained with gallium replacing aluminum in the YAG crystal [26, 27]. As the isomorph of YAG crystal, YGG shows similar properties as YAG [28, 29], and supports a strong Kerr effect for its high linear refractive index of 1.91 and nonlinear refractive index of 5.2×10^{-16} cm^2/W at 1.06 μm [30]. Although the physical and optical properties have been studied in previous reports [31–35], Yb:YGG crystal was not recognized as an attractive material for ultrafast lasers until optical floating zone method was introduced to grow high-quality crystals [36]. As the first femtosecond operation, Y. Zhang et al. generated 245 fs pulses from a diode-pumped Yb:YGG laser by using Gires-Tournois interferometer (GTI) mirrors for dispersion compensation and a SESAM for passive mode locking [37]. Further experimental research demonstrated an efficient continuous-wave (CW) operation with an optical-to-optical efficiency of 39.5% and maximum slope efficiency of 84.5% [38], which revealed that even higher mode-locked power should be possible. In addition, in those works Yb:YGG shown a broad emission bandwidth of about 22 nm (FWHM) which was nearly four times wider than that of Yb:YAG [37] and had a great potential to support even shorter pulses and higher power. In this letter, we report the first demonstration, to our knowledge, of a directly diode-pumped KLM Yb:YGG laser with the pulse duration of 88 fs. This result is much shorter than our previous result which has the pulse duration of 245 fs with a SESAM [37]. Although several Yb-doped materials have been used to generate sub-100 fs or high-power pulses, Yb:YGG could become another excellent candidate which has great potential for high-power ultrashort solid-state laser with KLM mode.

2. Experimental setup

The experimental setup is described as Fig. 1. A 4.5-mm-long, antireflection-coated, and 5 at. %-doped Yb:YGG crystal was used as the gain medium. It was end-pumped by a high-brightness fiber-coupled diode laser at emission wavelength of 970 nm (Jenoptik, JOLD-7.5-BAFC-105). The pump beam from the fiber (50 μm core diameter and 0.22 NA) was focused into the crystal by an imaging system. In this situation, we calculated the confocal parameter

#196772 - $15.00 USD Received 30 Aug 2013; revised 4 Nov 2013; accepted 12 Nov 2013; published 26 Nov 2013

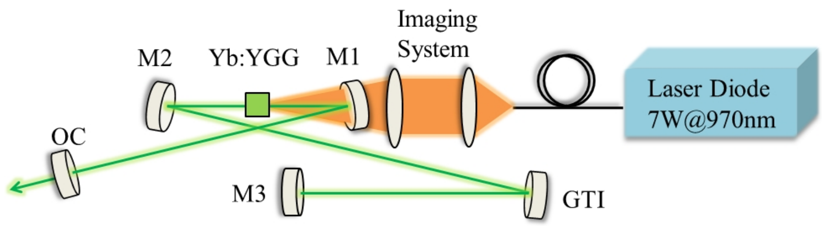

Fig. 1. Experimental setup of a KLM Yb:YGG laser.

of the pump as 0.31 mm, which was much shorter than the length of the crystal. This might result in the decrease of the laser efficiency, however, the small pump spot diameter (50 μm) was beneficial for the increase of the pump power density, the laser power density at the focus will also increase because of the small laser beam waist. High laser power density would be very important for Kerr-lens mode locking. A standard X-folded cavity was employed to compact the whole size. Both M1 and M2 were plane-concave dichroic mirrors with the curvature radiuses of 75 mm. They were coated with high transmission at 970 nm and high reflection at 1020-1100 nm. The tight focusing configuration is helpful to increase the intracavity power density and enhance the Kerr-lens effect. M3 was a plane mirror with a reflection of more than 99.9% in the 1020-1070 nm range. To compensate the normal dispersion resulted from the crystal and the air inside the cavity, a GTI mirror with the group velocity dispersion of -1000 fs^2 per bounce within the wavelength range from 1035 nm to 1055 nm was used. A plane mirror with the transmission of 0.3% was used as the output coupler (OC) to ensure the intracavity pulse energy high enough. The whole cavity length was approximately 941.6 mm corresponding to a repetition rate of 159.3 MHz. Based on the above design, we calculated the intracavity transverse mode and got the beam waist diameters of 45 μm$\times$38 μm (1/e^2 level).

3. Experimental results and discussion

At first we adjusted the laser cavity to generate the maximum output power under the CW operation, then by finely tuning the position of M2 mirror, we got the KLM operation after a small, fast translation of the end mirror of M3 when the incident pump power exceeded 3.2 W. Under the pump power of 3.2 W, the maximum average output power under CW operation was 38 mW. After the tuning of M2 mirror to a proper position for mode locking, the average power decreased to 20 mW. At this position, the laser was mode-locked and the average power increased to 36 mW. When we increased the pump power to 3.9 W, we could get a CW output power of 72 mW and the maximum mode-locked laser power of 104 mW. In this case we measured the autocorrelation trace, as shown in Fig. 2(a). The width (FWHM) of the autocorrelation trace was about 136 fs, corresponding to mode-locked pulse duration of 88 fs if a sech^2-pulse shape was assumed. Figure 2(b) shows the corresponding spectrum measured by a commercial available spectrum analyzer (YOKOGAWA, AQ6370C) with high resolution of 0.1 nm. The center wavelength is 1042 nm with the spectrum bandwidth (FWHM) of about 16.8 nm, corresponding to a time-bandwidth product of 0.41. It indicates that there is residual dispersion inside the cavity because of the uncompleted compensation by the GTI mirror. According to the laser specifications, we calculated the intracavity peak power of laser pulses as 8.5×10^5 W when the pump power was 3.2 W. With the nonlinear refractive index of 5.2×10^{-16} cm^2/W [28], the focus length of the equivalent lens was estimated as 1.54 mm. Considered the larger nonlinear refractive index of Yb:YGG crystal, the Yb:YGG laser would be easier to obtain Kerr-lens mode locking than Ti:sapphire laser.

#196772 - $15.00 USD Received 30 Aug 2013; revised 4 Nov 2013; accepted 12 Nov 2013; published 26 Nov 2013

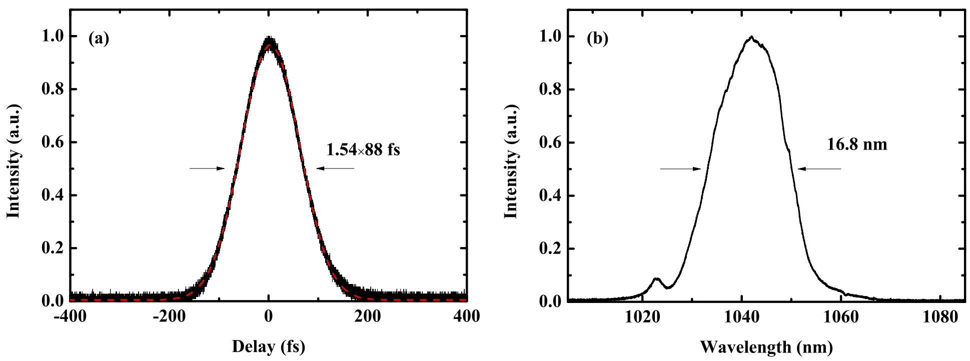

Fig. 2. (a) Intensity autocorrelation trace of the KLM laser pulses. The experimental data and the $sech^2$-fitting curve are shown by the solid curve and the dashed curve respectively. (b) Laser spectrum.

We measured the radio frequency (RF) spectrum of the laser with a RF spectrum analyzer (Agilent E4407B). The fundamental beat note at 159.3 MHz with a high extinction down to 73.9 dBc was recorded with a resolution bandwidth of 1 kHz, as shown in Fig. 3(a). Figure 3(b) is the wide-span measurement which shows the high harmonics of the fundamental beat note. The RF spectrum clearly proves that the oscillator is in a stable mode-locked operation. Once started, the KLM operation was stable for nearly two hours even though no care was taken to isolate the laser from the environment. The lost of the KLM operation was owing to the obvious perturbation from the surroundings. After a slight and fast translation of the end mirror M3, we could obtain the KLM operation again. Now the laser is constructed directly on the optical table without any housing, we believe that the KLM operation will be stable for a whole day with a good housing. Figure 4 shows the beam profiles in the CW and mode-locked operations with a commercial available CCD camera (WinCamD-UCD15). The M^2 factors in the mode-locked operation are 1.17 and 1.36 for tangential direction and sagittal direction, respectively. For the CW operation, these two parameters are 1.08 and 1.73.

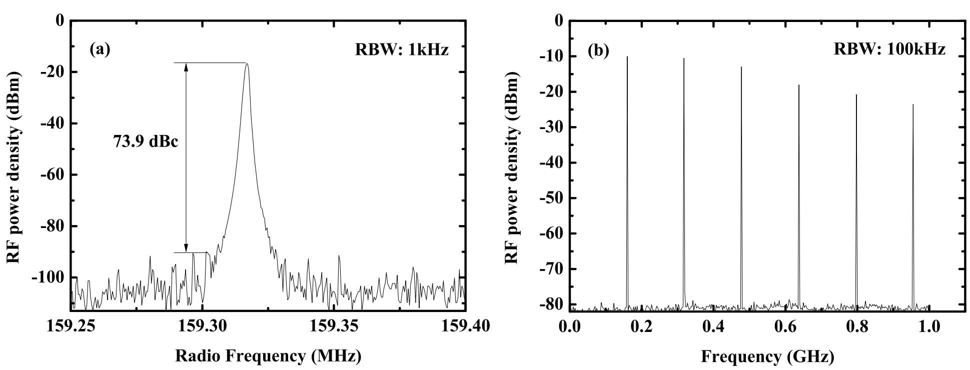

Fig. 3. Radio frequency spectrum of the mode-locked Yb:YGG laser. (a) RF spectrum at the fundamental beat note with the RBW of 1 kHz. (b) RF spectrum of 1 GHz wide-span range with the RBW of 100 kHz.

As we know, the Kerr-lens effect strongly depends on the laser intensity inside the medium. Therefore, apart from the pump power, the intracavity laser power also plays an important role

#196772 - $15.00 USD Received 30 Aug 2013; revised 4 Nov 2013; accepted 12 Nov 2013; published 26 Nov 2013

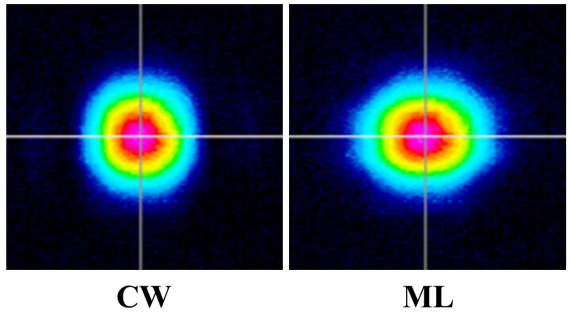

Fig. 4. Beam profiles in CW and mode-locked operations

for the stable KLM operation. To explore the characteristic, we readjusted and optimized the mode-locked performance for different output couplers with transmissions of 0.5%, 0.8% and 2% respectively. Stable KLM operations were also demonstrated experimentally with the pulse durations of 96 fs, 112 fs and 149 fs by $sech^2$-fitting. The corresponding maximum output powers were 133 mW, 171 mW and 330 mW under the pump powers of 4.1 W, 4.0 W and 4.0 W respectively. Figure 5 shows the spectra, pulse durations and laser powers under the four different transmissions, which indicates a blue shift of the central wavelength and an increase of the output power under higher transmission. According to this result, we inferred that the weaker self-phase modulation (SPM) led to a shorter wavelength, which meant the central wavelength of the mode-locked laser would be more close to the peak emission because of the lower intracavity power density. Moreover, we noticed that the bandwidth became narrower under higher transmission. That is reasonable, for the weak self-phase modulation (SPM) under high transmission would lead to a weak spectrum broadening, thus limiting the available pulse duration. This well agrees with the results in Fig. 5(b). Based on the results and analysis, we may further choose an optimized output coupler to support even higher mode-locked power, and finely compensate the SPM with suitable dispersion control to obtain the corresponding shorter pulse duration. With suitable optical components balancing the intracavity SPM, we could obtain even higher-power and shorter pulses.

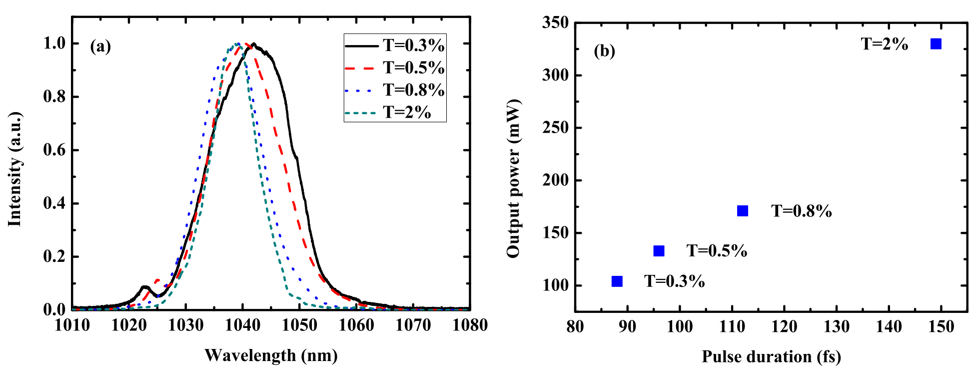

Fig. 5. (a) Spectrum of the Kerr-lens mode-locked operation under four different transmissions (T = 0.3%, 0.5%, 0.8% and 2%). (b) Summary of the results (output power versus pulse duration).

#196772 - $15.00 USD Received 30 Aug 2013; revised 4 Nov 2013; accepted 12 Nov 2013; published 26 Nov 2013

4. Conclusions

In conclusion, we have demonstrated the first diode-pumped KLM Yb:YGG laser to the best of our knowledge. Pulses with a duration of 88 fs and an output power of 104 mW were obtained at a repetition rate of 159.3 MHz. This is, to our knowledge, the shortest result obtained from Yb:YGG laser up to now. In addition, we further compared the KLM laser characteristics of output powers and pulse durations under different transmissions, pulses with average power of 330 mW and duration of 149 fs were obtained. It shows that Yb:YGG is an excellent material for ultrashort pulse generation. Currently, limited by the cut-off wavelength of the cavity mirrors (1020 nm) and the GTI mirror (1035-1055 nm), the center wavelength of 1042 nm of the present spectrum is not coincided with the gain peak of the emission spectrum(1025 nm), which means that the gain bandwidth has not been fully taken advantage of. In next step, we would choose mirrors with suitable coatings to solve this problem. Meanwhile, we could optimize the intracavity dispersion compensation and the transmission of the output coupler, we believe that higher power and shorter pulse duration should be possible.

Acknowledgments

We thank Prof. Huaijin Zhang for supplying us with the Yb:YGG crystal. We also thank Prof. Zhiguo Zhang, Liwen Xu and Dr. Yongdong Zhang for the helpful discussion. This work is partially supported by the National Key Basic Research Program of China (Grant No. 2013CB922402), the National Basic Research Program of China (973 Program Grant No. 2012CB821304) and the National Natural Sciences Foundation of China (Grant No. 11078022, 60808007).

#196772 - $15.00 USD Received 30 Aug 2013; revised 4 Nov 2013; accepted 12 Nov 2013; published 26 Nov 2013