Diode-pumped self-starting mode-locked femtosecond $Yb:YCa_4O(BO_3)_3$ laser

2014 Chinese Phys. B 23 054207

(http://iopscience.iop.org/1674-1056/23/5/054207)

Chin. Phys. B Vol. 23, No. 5 (2014) 054207

Diode-pumped self-starting mode-locked femtosecond $Yb:YCa_4O(BO_3)_3$ laser*

Gao Zi-Ye(高子叶)[a], Zhu Jiang-Feng(朱江峰)[a], Tian Wen-Long(田文龙)[a], Wang Jun-Li(王军利)[a], Wang Qing(王 庆)[b], Zhang Zhi-Guo(张治国)[b], Wei Zhi-Yi(魏志义)[b]†, Yu Hao-Hai(于浩海)[c], Zhang Huai-Jin(张怀金)[c], and Wang Ji-Yang(王继扬)[c]

[a] *School of Physics and Optoelectronic Engineering, Xidian University, Xi'an* 710071, *China*
[b] *Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing* 100190, *China*
[c] *State Key Laboratory of Crystal Material and Institute for Crystal Material, Shandong University, Jinan* 250100, *China*

(Received 30 November 2013; revised manuscript received 4 January 2014; published online 18 March 2014)

A self-starting mode-locked femtosecond laser is accomplished with an oxoborate self-frequency doubling crystal $Yb:YCa_4O(BO_3)_3$ (Yb:YCOB) as the gain medium and a semiconductor mirror as the saturable absorber. Pumped by a 976-nm fiber-coupled diode laser with 50-μm core diameter, stable mode-locked laser pulses up to 430 mW were obtained at a repetition rate of 83.61 MHz under 5-W pump power. The autocorrelation measurement shows that the pulse duration is as short as 150 fs by assuming the $sech^2$ pulse shape at a central wavelength of 1048 nm. This work has demonstrated a compact and reliable femtosecond laser source for prospective low-cost applications.

Keywords: diode pump, $Yb:YCa_4O(BO_3)_3$ crystal, femtosecond mode-locking

PACS: 42.55.Rz, 42.55.Xi, 42.60.Fc **DOI:** 10.1088/1674-1056/23/5/054207

1. Introduction

Ultrafast lasers with a directly diode-pumped scheme have attracted continuous interest due to their high energy conversion efficiency, compact size, and low cost. In the last decade, remarkable progress has been made with a series of new solid state hosts[1–3] as gain media. Among these hosts, the trivalent ytterbium ion (Yb^{3+}) has been recognized as one of the best dopants for efficient diode-pumped lasers because Yb^{3+}-doping materials have many advantages, such as broad emission bands and less quantum defects. Yb^{3+}-doped materials have been recognized as promising substitutes for all solid-state ultrafast lasers in the 1000-nm range with direct diode-pump instead of Ti:sapphire crystal. Extensive mode-locking has been reported on various of Yb^{3+}-materials, such as garnet Yb:YAG[4,5] and Yb:YGG,[6] vanadate $Yb:YVO_4$,[7] oxyorthosilicates Yb:GYSO,[8,9] tungstates Yb:KGW[10] and Yb:KYW,[11] fluorite Yb:YLF,[12] sesquioxide $Yb:Sc_2O_3$,[13] silicate Yb:SYS,[14] borates Yb:GdCOB[15] and Yb:BOYS,[16] etc.

Yb^{3+}-doped $YCa_4O(BO_3)_3$ (Yb:YCOB) is a non-centrosymmetric biaxial crystal. It exhibits a large ground state splitting of 1000 cm^{-1} of the ground state manifold ($^2F_{7/2}$), which is greater than other Yb-doped materials.[17–19] This is desirable for efficient room temperature laser operation. Yb:YCOB in thin disk laser design can produce output power as high as 100 W in the continuous-wave (CW) regime with a slope efficiency of 53%[20] and tunable range from 997 nm to 1092 nm.[21] All polarization configurations in Yb:YCOB have been thoroughly compared with longitudinal pumping in the cw regime, achieving in the best cases maximum output power of 7.3 W and a slope efficiency 83%.[22] The fluorescence lifetime was measured to be 2.20 ms,[21] which is one of the longest upper state lifetimes observed for Yb-doped oxide crystals.[17] The broad emission bandwidth supports the possible generation of ultrashort pulses. The first mode-locked Yb:YCOB laser delivered a modest pulse duration of 210 fs.[23] Recently, 42-fs pulses have been generated in a Yb:YCOB crystal,[24] with external compression pluses as short as 35 fs were reported at 1055 nm.[25] However, such short pulse duration relies on critical cavity alignment with the assistance of the Kerr-lens effect. As a result, the average output power is limited to tens of mW and its mode-locking is not reliably self-starting.

In this paper, a new experimental investigation is carried out based on the mode-locking of Yb:YCOB laser with a semiconductor saturable absorber mirror (SESAM). By precisely adjusting the cavity dispersion, pulses as short as 150 fs were produced with bandwidth of 9.6 nm at 1048 nm and the average output power was 430 mW with a slope efficiency of 21.3%.

2. Experimental arrangement

A high quality Yb:YCOB crystal was grown by the Czochralski method, with a Yb concentration of 20 at.%. The

*Project supported by the National Natural Science Foundation of China (Grant No. 61205130), the National Key Scientific Instruments Development Program of China (Grant No. 2012YQ120047), and the Fundamental Research Funds for the Central Universities of Ministry of Education of China (Grant No. K5051305008).

†Corresponding author. E-mail: zywei@aphy.iphy.ac.cn

uncoated Yb:YCOB crystal was cut along the X axis with thickness of 2 mm and an aperture of 3 mm $\times$ 3 mm. To reduce the thermal load occurring inside the crystal, the Yb:YCOB crystal was wrapped with an indium foil and then mounted tightly in a water-cooled copper heat sink. The water temperature was maintained at 14 °C. A 7-W high-brightness fiber-coupled diode laser emitting at 976 nm (Jenoptik, JOLD-7.5-BAFC-105) was used to end pump the laser medium. The pump-laser output from the fiber (with 50-μm core diameter and 0.22 NA) was coupled into the crystal by a coupling system with a magnification of 0.8. We first characterized the crystal in CW operation. Figure 1(a) shows the overall experimental setup. The crystal was positioned at Brewster angle in the middle of an astigmatism compensated cavity between two curved mirrors with 200-mm radius of curvature (ROC). M1 was a plane dichroic mirror with high transmission at 976 nm and high reflection at 1020–1200 nm. An output coupler (OC) with transmission of 2.5% in the range of 1020–1200 nm was used for coupling the laser. We obtained the highest CW output power of 2 W under the pump power of 5 W. With a SF6 prism inserted into the cavity, we implemented a tunable laser wavelength from 1007–1100 nm, indicating a tunable range of about 93 nm. The tuning curve is shown in Fig. 2. The tuning wavelength beyond 1100 nm is restricted by the spectrometer used in our experiment. The broad tuning range of the Yb:YCOB crystal gives it a potential to generate very short pulses with a duration comparable to the conventional prism pair-based Ti:sapphire oscillator.

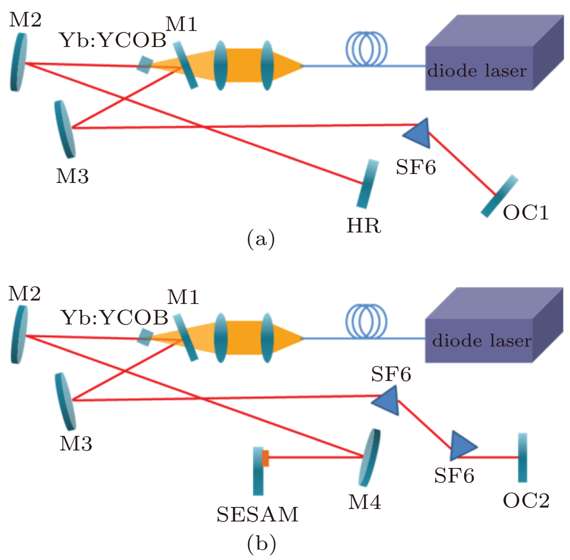

Fig. 1. (color online) Experimental setups used to study the (a) CW and (b) mode-locking operation of the Yb:YCOB laser. M1: dichroic mirror; M2, M3, M4: concave mirrors (M2, M3 with ROC of 200 mm; M4 with ROC of 300 mm); HR: high reflection mirror; OC1, OC2: plane output coupler with transmission $T = 2.5\%$ and $T = 0.8\%$, respectively; SESAM: semiconductor saturable absorber mirror.

The mode-locking experiment was carried out with a modified confocal cavity, as shown in Fig. 1(b). In one arm of the cavity, an additional folding was incorporated to increase the fluence on the SESAM by means of a ROC = 300 mm curved mirror. The relaxation time of the SESAM used in the experiment was less than 500 fs and the modulation depth was specified to be 0.5%. In the other arm of the cavity, a pair of SF6 prisms with a tip-to-tip distance of about 310 mm were used to compensate the normal dispersion resulted from the crystal inside the cavity. The OC with transmission of 0.8% in the range of 1020–1200 nm was used.

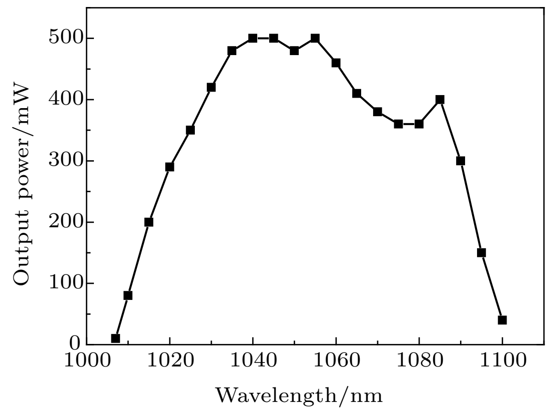

Fig. 2. Wavelength tuning curve of the Yb:YCOB laser with a 2.5% OC under the pump power of 2.5 W.

3. Results and discussion

The Yb:YCOB crystal was oriented along $E//Y$ polarization. With optimization of the cavity alignment and chirp compensation, stable mode-locking operation with single-mode output was self-starting when the incident pump power exceeded 2 W. The maximum output power was 430 mW under a pump power of 5 W. Figure 3 shows the stable CW mode-locked pulse train detected by a fast photodiode and recorded with a digital storage oscilloscope.

Using a commercial intensity autocorrelator (APE: pulseCheck USB), we measured the intensity autocorrelation trace that is shown in Fig. 4(a). Assuming a sech^2-pulse shape, the pulse duration is 150 fs. Its corresponding pulse spectrum in Fig. 4(b) has a full width at half maximum (FWHM) bandwidth of 9.6 nm. The time-bandwidth-product of 0.393 is close to the Fourier transform limitation (0.315), indicating less residual chirp within the mode-locking.

Figure 5 shows the corresponding radio frequency spectrum of the fundamental beat note at 83.61 MHz, which was recorded by a spectrum analyzer (Agilent: E4402B) with a resolution bandwidth (RBW) of 1 kHz measured for the shortest pulse operation. The high extinction down to 68 dBc and the absence of any spurious modulation prove a stable and clean CW mode-locked operation of the Yb:YCOB laser.

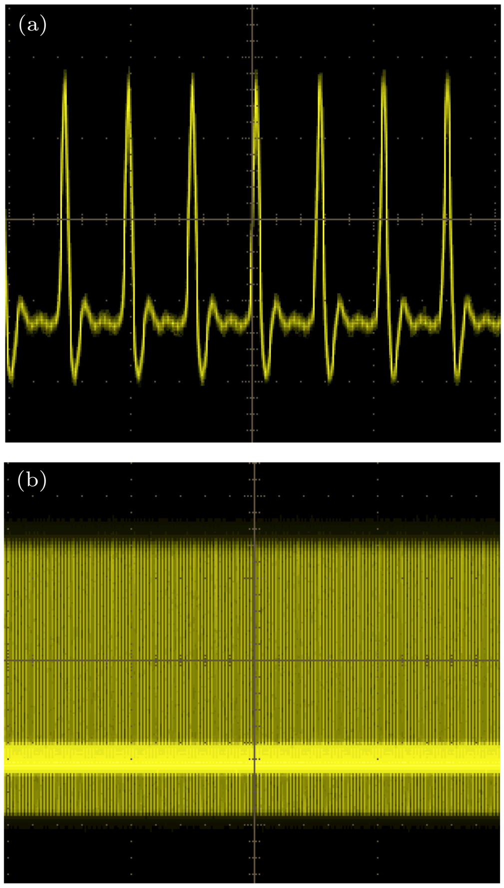

Fig. 3. (color online) Mode-locked pulse train at (a) 20 ns/div and (b) 200 ns/div.

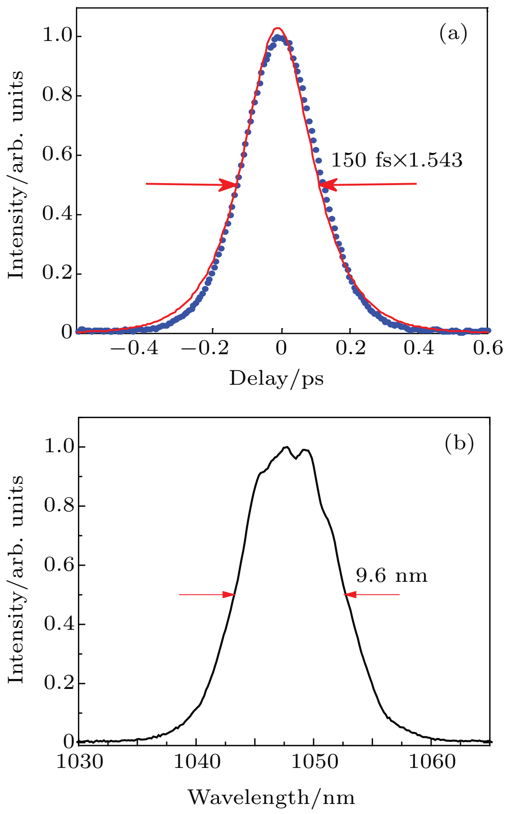

Fig. 4. (color online) (a) Autocorrelation trace of the mode-locked pulses (dotted-curve) with a sech^2 fitting (solid curve). (b) Spectrum of the mode-locked pulses.

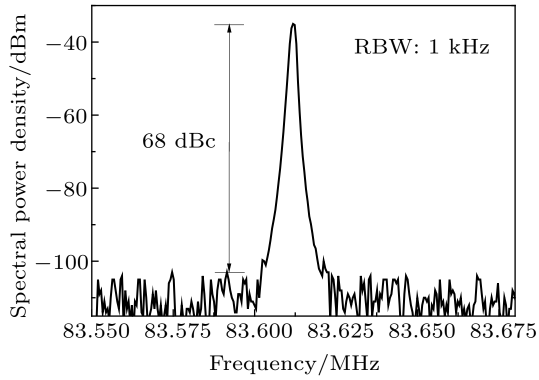

Fig. 5. Radio frequency spectrum of the mode-locked Yb:YCOB laser with RBW of 1 kHz.

4. Conclusion

We have achieved a stable self-starting mode-locking of the Yb:YCOB laser with a SESAM. The output pulse duration is as short as 150 fs at the central wavelength of 1048 nm and a spectral bandwidth of 9.6 nm. The average power is 430 mW under 5-W pump, with a slope efficiency of 21.3%. The broad wavelength tunability of Yb:YCOB crystal indicates that it is a promising gain medium for sub-100 fs pulse generation by further optimization of the cavity dispersion compensation. Furthermore, owing to the birefringent property of Yb:YCOB crystal, it is possible to generate green femtosecond pulses by means of self-frequency doubling.

Acknowledgment

We thank the helpful discussion with Profs. Zeng Xiao-Dong and Wang Zhao-Hua.

References

[1] Yang J M, Yang Q, Liu J, Wang Y G and Yuen H T 2013 *Chin. Phys. B* **22** 094210

[2] Qu Z S, Wang Y G, Liu J, Zheng L H, Su L B and Xu J 2012 *Chin. Phys. B* **21** 064211

[3] Xia P K, Yu H J, Yan P and Gong M L 2010 *Chin. Phys. B* **19** 044205

[4] Zhou B B, Wei Z Y, Li D H, Teng H and Bourdet G L 2009 *Appl. Opt.* **48** 5978

[5] Uemura S and Torizuka K 2011 *Jpn. J. Appl. Phys.* **50** 010201

[6] Zhang Y D, Wei Z Y, Zhou B B, Xu C W, Zou Y W, Li D H, Zhang Z G, Wang J Y, Yu H H, Wu K, Yao B and Wang J L 2009 *Opt. Lett.* **34** 3316

[7] Lagatsky A A, Sarmani A R, Brown C T A, Sibbett W, Kisel V E, Selivanov A G, Denisov I A, Troshin A E, Yumashev K V, Kuleshov N V, Matrosov V N, Matrosova T A and Kupchenko M I 2005 *Opt. Lett.* **30** 3234

[8] Zhou B B, Wei Z Y, Zhang Y D, Zhong X, Teng H, Zheng L H, Su L B and Xu J 2009 *Opt. Lett.* **34** 31

[9] Zhu J F, Tian W L, Wang J L, Wang Z H, Wei Z Y, Zheng L H, Su L B and Xu J 2012 *Opt. Lett.* **37** 5190

[10] Brunner F, Südmeyer T, Innerhofer E, Morier-Genoud F, Paschotta R, Kisel V E, Scherbitsky V G, Kuleshov N V, Gao J, Contag K, Giesen A and Keller U 2002 *Opt. Lett.* **27** 1162

[11] Brunner F, Spühler G J, Aus der A J, Krainer L, Morier-Genoud F, Paschotta R, Lichtenstein N, Weiss S, Harder C, Lagatsky A A, Abdolvand A, Kuleshov N V and Keller U 2000 *Opt. Lett.* **25** 1119

[12] Coluccelli N, Galzerano G, Bonelli L, Di Lieto A, Tonelli M and Laporta P 2008 *Opt. Express* **16** 2922
[13] Klopp P, Petrov V, Griebner U, Petermann K, Peters V and Erbert G 2004 *Opt. Lett.* **29** 391
[14] Druon F, Balembois F and Georges P 2004 *Opt. Express* **12** 5005
[15] Druon F, Balembois F, Georges P, Brun A, Courjaud A, Hönninger C, Salin F, Aron A, Mougel F, Aka G and Vivien D 2000 *Opt. Lett.* **25** 423
[16] Druon F, Chénais S, Raybaut P, Balembois F, Georges P, Gaumé R, Aka G, Viana B, Mohr S and Kopf D 2002 *Opt. Lett.* **27** 197
[17] Haumesser P H, Gaume R, Viana B and Vivien D 2002 *J. Opt. Soc. Am. B* **19** 2365
[18] Zhu Z, Li J, Alain B, Jia G, You Z, Lu X. Wu B and Tu C 2006 *Appl. Phys. B* **86** 71
[19] Zhu Z, Li J, Alain B, Jia G, You Z, Lu X, Wu B and Tu C 2006 *Appl. Phys. B* **86** 181
[20] Heckl O H, Kränkel C, Baer C R E, Saraceno C J, Südmeyer T, Petermann K, Huber G and Keller U 2010 *Opt. Express* **18** 19201
[21] Kränkel C, Peters R, Petermann K, Loiseau P, Aka G and Huber G 2009 *J. Opt. Soc. Am. B* **26** 1310
[22] Liu J, Han W, Zhang H, Wang J and Petrov V 2008 *Appl. Phys. B* **91** 329
[23] Valentine G J, Kemp A J, Birkin D J L, Burns D, Balembois F, Georges P, Bernas H, Aron A, Aka G, Sibbett W, Brun A, Dawson M D and Bente E 2000 *Electron. Lett.* **36** 1621
[24] Yoshida A, Schmidt A, Zhang H J, Wang J Y, Liu J H, Fiebig C, Paschke K, Erbert G, Petrov V and Griebner U 2010 *Opt. Express* **18** 24325
[25] Yoshida A, Schmidt A, Petrov V, Fiebig C, Erbert G, Liu J H, Zhang H J, Wang J Y and Griebner U 2011 *Opt. Lett.* **36** 4425