Dissipative soliton and synchronously dual-wavelength mode-locking Yb:YSO lasers

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Abstract: We experimentally demonstrate the dissipative soliton mode-locking operation of a Yb:YSO laser by using an all-normal dispersion cavity. Strongly chirped pulses are obtained with pulse duration of 9.3 ps at a repetition rate of 113.4 MHz. The central wavelength is 1082 nm with 3.1 nm FWHM bandwidth. A dual-wavelength synchronously mode-locking operation at central wavelengths of 1059.2 nm and 1082.2 nm is also reported. Stable mode-locked pulses are achieved with pulse duration of 10 ps and total average output power of 164 mW. Periodic ultrashort beat pulses with pulse duration of 169 fs at an ultrahigh repetition rate of 1.4 THz can be distinctly observed from the measured autocorrelation trace. To our knowledge, this is the first demonstration of dual-wavelength synchronously mode-locking operation from a Yb:YSO laser.

OCIS codes: (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers; (140.3615) Lasers, ytterbium: (140.3480) Lasers, diode-pumped.

References and links

1. A. Fernandez, T. Fuji, A. Poppe, A. Fürbach, F. Krausz, and A. Apolonski, "Chirped-pulse oscillators: a route to high-power femtosecond pulses without external amplification," Opt. Lett. **29**(12), 1366–1368 (2004).
2. S. Naumov, A. Fernandez, R. Graf, P. Dombi, F. Krausz, and A. Apolonski, "Approaching the microjoule frontier with femtosecond laser oscillators," New J. Phys. **7**, 216 (2005).
3. M. Siegel, N. Pfullmann, G. Palmer, S. Rausch, T. Binhammer, M. Kovacev, and U. Morgner, "Microjoule pulse energy from a chirped-pulse Ti:sapphire oscillator with cavity dumping," Opt. Lett. **34**(6), 740–742 (2009).
4. V. L. Kalashnikov and A. Apolonski, "Chirped-pulse oscillators: A unified standpoint," Phys. Rev. A **79**(4), 043829 (2009).
5. E. Sorokin, N. Tolstik, V. L. Kalashnikov, and I. T. Sorokina, "Chaotic chirped-pulse oscillators," Opt. Express **21**(24), 29567–29577 (2013).
6. L. M. Zhao, D. Y. Tang, and J. Wu, "Gain-guided soliton in a positive group-dispersion fiber laser," Opt. Lett. **31**(12), 1788–1790 (2006).
7. A. Chong, J. Buckley, W. Renninger, and F. Wise, "All-normal-dispersion femtosecond fiber laser," Opt. Express **14**(21), 10095–10100 (2006).
8. L. M. Zhao, D. Y. Tang, T. H. Cheng, H. Y. Tam, and C. Lu, "Generation of multiple gain-guided solitons in a fiber laser," Opt. Lett. **32**(11), 1581–1583 (2007).
9. A. Chong, W. H. Renninger, and F. W. Wise, "All-normal-dispersion femtosecond fiber laser with pulse energy above 20 nJ," Opt. Lett. **32**(16), 2408–2410 (2007).
10. W. D. Tan, D. Y. Tang, C. W. Xu, J. Zhang, X. D. Xu, D. Z. Li, and J. Xu, "Evidence of dissipative solitons in Yb^{3+}:$CaYAlO_4$," Opt. Express **19**(19), 18495–18500 (2011).
11. W. Tian, J. Zhu, Z. Wang, J. Wang, and Z. Wei, "Dissipative soliton operation in a diode pumped ultrafast Yb:$GdYSiO_5$ oscillator," Chin. Opt. Lett. **12**(3), 031401–031403 (2014).
12. W. D. Tan, D. Y. Tang, J. Zhang, D. Y. Shen, X. D. Xu, and J. Xu, "Dissipative soliton operation of an Yb^{3+}: Sc_2SiO_5 laser in the vicinity of zero group velocity dispersion," Opt. Photon. Lett. **5**(1), 1250001 (2012).
13. H. Ahmad, F. D. Muhammad, C. H. Pua, and K. Thambiratnam, "Dual-wavelength fiber lasers for the optical generation of microwave and terahertz radiation," IEEE J. Sel. Top. Quantum Electron. **20**(5), 1 (2014).

#223656 - $15.00 USD Received 23 Sep 2014; revised 29 Nov 2014; accepted 30 Nov 2014; published 30 Mar 2015

14. C. Xiong, Z. Chen, and W. J. Wadsworth, "Dual-wavelength-pumped supercontinuum generation in an all-fiber device," J. Lightwave Technol. **27**(11), 1638 (2009).
15. W. Z. Zhuang, M. T. Chang, K. W. Su, K. F. Huang, and Y. F. Chen, "High-power terahertz optical pulse generation with a dual-wavelength harmonically mode-locked Yb: YAG laser," Laser Phys. **23**(7), 075803 (2013).
16. J. M. Evans, D. E. Spence, D. Burns, and W. Sibbett, "Dual-wavelength self-mode-locked Ti:sapphire laser," Opt. Lett. **18**(13), 1074 (1993).
17. Z. Zhang and T. Yagi, "Dual-wavelength synchronous operation of a mode-locked Ti:sapphire laser based on self-spectrum splitting," Opt. Lett. **18**(24), 2126 (1993).
18. Z. Wei, Y. Kobayashi, Z. Zhang, and K. Torizuka, "Generation of two-color femtosecond pulses by self-synchronizing Ti:sapphire and Cr:forsterite lasers," Opt. Lett. **26**(22), 1806–1808 (2001).
19. G. Q. Xie, D. Y. Tang, H. Luo, H. J. Zhang, H. H. Yu, J. Y. Wang, X. T. Tao, M. H. Jiang, and L. J. Qian, "Dual-wavelength synchronously mode-locked Nd:CNGG laser," Opt. Lett. **33**(16), 1872–1874 (2008).
20. J. Hou, X. W. Fu, J. L. He, Y. Yang, B. T. Zhang, Z. W. Wang, K. J. Yang, Z. T. Jia, R. H. Wang, X. M. Liu, C. M. Dong, and X. T. Tao, "Dual-wavelength passively mode-locked Nd: LGGG laser with SESAM," IEEE Photon. Technol. Lett. **26**(1), 40–42 (2014).
21. J. L. Xu, S. Y. Guo, J. L. He, B. Y. Zhang, Y. Yang, H. Yang, and S. D. Liu, "Dual-wavelength asynchronous and synchronous modelocking operation by a Nd:CLTGG disordered crystal," Appl. Phys. B **107**(1), 53–58 (2012).
22. Z. Cong, D. Tang, W. De Tan, J. Zhang, C. Xu, D. Luo, X. Xu, D. Li, J. Xu, X. Zhang, and Q. Wang, "Dual-wavelength passively mode-locked Nd:$LuYSiO_5$ laser with SESAM," Opt. Express **19**(5), 3984–3989 (2011).
23. Y. J. Huang, Y. S. Tzeng, C. Y. Tang, S. Y. Chiang, H. C. Liang, and Y. F. Chen, "Efficient high-power terahertz optical pulse generation in a dual-wavelength synchronously mode-locked laser with dual gain media," Opt. Lett. **39**, 1477 (2014).
24. A. Agnesi, F. Pirzio, G. Reali, A. Arcangeli, M. Tonelli, Z. A. Agnesi, F. Pirzio, G. Reali, A. Arcangeli, M. Tonelli, Z. Jia, and X. Tao, "Multi-wavelength Nd:GAGG picosecond laser," Opt. Mater. **32**(9), 1130–1133 (2010).
25. Q. Yang, Y. G. Wang, D. H. Liu, J. Liu, L. H. Zheng, L. B. Su, and J. Xu, "Dual-wavelength mode-locked Yb:$LuYSiO_5$ laser with a double-walled carbon nanotube saturable absorber," Laser Phys. Lett. **9**(2), 135–140 (2012).
26. H. Yoshioka, S. Nakamura, T. Ogawa, and S. Wada, "Dual-wavelength mode-locked Yb:YAG ceramic laser in single cavity," Opt. Express **18**(2), 1479–1486 (2010).
27. D. Pudo, L. R. Chen, D. Giannone, L. Zhang, and I. Bennion, "Actively mode-locked tunable dual-wavelength erbium-doped fiber laser," IEEE Photon. Technol. Lett. **14**(2), 143–145 (2002).
28. R. M. Sova, C. S. Kim, and J. U. Kang, "Tunable dual-wavelength all-PM fiber ring laser," IEEE Photon. Technol. Lett. **14**(3), 287–289 (2002).
29. S. Yang, Z. Li, S. Yuan, X. Dong, G. Kai, and Q. Zhao, "Tunable dual-wavelength actively mode-locked fiber laser with an FP semiconductor modulator," IEEE Photon. Technol. Lett. **14**(11), 1494–1496 (2002).
30. Y. D. Gong, M. Tang, P. Shum, C. Lu, J. Wu, and K. Xu, "Dual-wavelength 10-GHz actively mode-locked erbium fiber laser incorporating highly nonlinear fibers," IEEE Photon. Technol. Lett. **17**(12), 2547–2549 (2005).
31. H. Zhang, D. Y. Tang, L. M. Zhao, and X. Wu, "Multiwavelength passively mode locked fiber laser: all normal dispersion," arXiv preprint arXiv: **0904**. 2066, (2009).
32. X. Zhu, C. Wang, S. Liu, D. Hu, J. Wang, and C. Zhu, "Switchable dual-wavelength and passively mode-locked all-normal-dispersion Yb-doped fiber lasers," IEEE Photon. Technol. Lett. **23**(14), 956–958 (2011).
33. Z. Luo, Y. Huang, J. Wang, H. Cheng, Z. Cai, and C. Ye, "Multiwavelength dissipative-soliton generation in Yb-fiber laser using graphene-deposited fiber-taper" IEEE Photon. Technol. Lett. **24**(17), 1539–1542 (2012).
34. H. Lin, C. Guo, S. Ruan, J. Yang, D. Ouyang, Y. Wu, and L. Wen, "Tunable and switchable dual-wavelength dissipative soliton operation of a weak-birefringence all-normal-dispersion Yb-Doped Fiber Laser," IEEE Photonics J. **5**(5), 1501807 (2013).
35. L. Zheng, L. Su, and J. Xu, "Growth and characterization of ytterbium doped silicate crystals for ultra-fast laser applications," Modern Aspects of Bulk Crystal and Thin Film Preparation Dr. Nikolai Kolesnikov (Ed.) (2012).
36. M. Jacquemet, C. Jacquemet, N. Janel, F. Druon, F. Balembois, P. Georges, J. Petit, B. Viana, D. Vivien, and B. Ferrand, "Efficient laser action of Yb:LSO and Yb:YSO oxyorthosilicates crystals under high-power diode-pumping," Appl. Phys. B **80**(2), 171–176 (2005).
37. F. Thibault, D. Pelenc, F. Druon, Y. Zaouter, M. Jacquemet, and P. Georges, "Efficient diode-pumped Yb^{3+}:Y_2SiO_5 and Yb^{3+}:Lu_2SiO_5 high-power femtosecond laser operation," Opt. Lett. **31**(10), 1555–1557 (2006).
38. A. S. Weling, B. B. Hu, N. M. Froberg, and D. H. Auston, "Generation of tunable narrow-band THz radiation from large aperture photoconducting antennas," Appl. Phys. Lett. **64**(2), 137 (1994).

1. Introduction

Dissipative solitons (DS) mode-locked lasers, which are generally occurred in net positive intra-cavity dispersion or all normal dispersion regions, have attracted much attention in recent years due to the large capacity in pulse energy and difficulty in soliton splitting.

Characterized by strongly chirped pulse and shaped spectrum with steep edge, the DS mode-locking operations have been demonstrated in various lasers such as chirped pulse oscillators [1–5] and all normal dispersion Yb or Er doped fiber lasers [6–9]. Recently, Tan et al. reported the evidence of DS in an Yb:$CaYAlO_4$ (Yb:CYA) laser for the first time [10], the result has implied that the DS operation can exist in the positive cavity dispersion mode-locking regime of the Yb doped solid state lasers. However, there are only several Yb-doped solid state bulk lasers have realized the DS operation [11, 12].

In addition, dual-wavelength synchronous ultrashort pulse source has versatile applications including microwave and terahertz radiation generation, ultrahigh repetition rate pulses and supercontinuum generation, ultrafast pump-probe technique [13–15]. To date, both conventional soliton dual-wavelength and DS dual-wavelength synchronously mode-locking in a single cavity have been implemented in a variety of lasers by different means. For example, conventional soliton dual-wavelength mode-locking operation is generally realized in Ti:sapphire laser [16–18], rare-earth doped solid state lasers such as Nd-doped [19–24] or Yb doped [25, 26] solid state lasers and fiber lasers [27–30]. Moreover, DS dual-wavelength mode-locking was mainly focused on all normal dispersion fiber lasers [31–34].

The Yb^{3+} doped oxyorthosilicate Y_2SiO_5 (Yb:YSO) crystal is an attractive laser material as the other Yb doped oxyorthosilicates because its admirable laser properties [35]. Firstly, the ground state energy splitting of Yb^{3+} ion in Yb:YSO crystal is up to 984 cm^{-1} which leads to a quasi-four level operation and then a low pump threshold. Secondly, the Yb:YSO crystal exhibits a fluorescence lifetime as large as 1.74 ms and excellent thermo-optical properties implying a potential to generate pulses with high energy. Last but not least, a broad emission spectra of 48 nm with four strong emission bands around 1008, 1040, 1056 and 1081 nm supports the generation of ultrashort pulses with several hundred femtosecond pulse duration. Excellent laser performances on both continue wave (CW) and femtosecond pulse generation have been demonstrated in recently years. The 7.3 W CW power corresponding to a slope efficiency of 67% directly from a diode pumped Yb:YSO lasers was obtained in 2005 [36]. In 2006, a femtosecond mode-locked Yb:YSO laser with 2.6W average output power and 198 fs pulse duration was reported [37]. Moreover, the fact of four emission peaks indicts that it is possible for a Yb:YSO laser to operate in simultaneously dual-wavelength or multi-wavelength mode-locking regime.

In this paper, we firstly report a diode pumped DS mode-locking Yb:YSO laser with 9.3 ps pulse duration at 1082 nm, then further demonstrate a dual-wavelength synchronously mode-locked operation at 1059.2 nm and 1082.2 nm with 10 ps pulse duration at 113.4 MHz repetition rate. Periodic ultrashort beat pulses with pulse duration of 169 fs at an ultrahigh repetition rate of 1.4 THz can be obviously observed from the measured autocorrelation trace. To the best of our knowledge, this is the first demonstration of a dual-wavelength synchronously mode-locking Yb:YSO laser..

2. Experimental setup

Figure 1 is a schematic diagram of the experimental setup. A commercial fiber-coupled diode laser emitting at 976 nm with a maximum output power of 25 W was used as the pump laser. The core diameter of the fiber is 105 μm and the numerical aperture (NA) is 0.22. We employed an imaging system with a magnification of 0.8 to couple the pump laser from the fiber into a 3 mm long, 5 at.% doped Yb:YSO crystal with antireflection-coating which was wrapped with indium foil and mounted tightly on a water-cooled copper heat sink block for effective heat dissipation. The copper block was cooled by 10 °C flowing water during the experiment.

A standard Z-folded cavity was employed in the experiment. Both M1 and M2 were dichroic mirrors with 75 mm radius of curvature (ROC) coated with high reflection in the range of 1020-1100 nm and high transmission at 970-980 nm. To achieve mode-locking in positive dispersion region, a Gires-Tournois Interferometer (GTI) mirror with group velocity dispersion (GVD) of + 1000 fs^2 per bounce around the 1080 nm was used. The GTI also introduces −800 fs^2 GVD per bounce around 1055 nm range. A plane mirror with 0.4% transmission at 1020-1100 nm was selected to be the output coupler (OC) for improving the intracavity power density. To initiate the mode-locking, a curved folding mirror M3 with ROC of 300 mm was used to focus the laser beam on a semiconductor saturable absorber mirror (SESAM, BATOP GmbH), which was designed for 1.2% modulation depth at 1064 nm, 60 μJ/cm^2 saturation fluence, and a relaxation time of less than 500 fs. The SESAM induces almost 800 fs^2 GVD in the range of 1060 ~1080 nm. In addition, the Yb:YSO crystal also contributes normal dispersion, while the GVD of other mirrors can be ignored. So an all-normal-dispersion Yb doped solid state laser around 1080 nm was designed. The total cavity length was about 1.32 m corresponding to a repetition rate of 113.4 MHz.

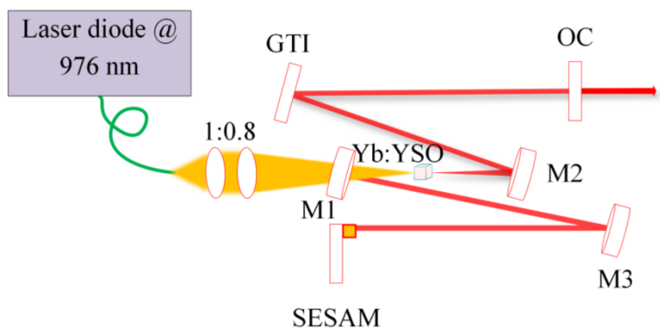

Fig. 1. Experimental setup of DS mode-locking as well as conventional soliton and DS dual-wavelength mode-locking operations.

3. Results and discussion

We firstly optimized the CW operation under a pump power of 13 W. Then by finely-tuning the position and angle of the SESAM, stable mode-locking operation was easily obtained at the central wavelength of 1082 nm. Figure 2 depicts the output power property of the DS mode-locked laser (Black solid squares). Higher pump power than 14 W was not applied in order to avoid damage either on the SESAM or on the crystal. When operated in pure DS mode-locking, the maximum output power was 144 mW and mode-locking operation would turn to be unstable when pump power down to 12.5 W. Compared to our previous work [11] reporting 558 mW output power with the similar material in the similar configuration, but higher output coupling and lower SESAM losses, here we obtained lower output power not only due to the low transmittance (0.4%) of the OC and the large non-saturable loss (0.8%) of the SESAM, but also because of the small absorbed pump power which was only 5 W at 14 W incident pump power as shown inserted in Fig. 2.

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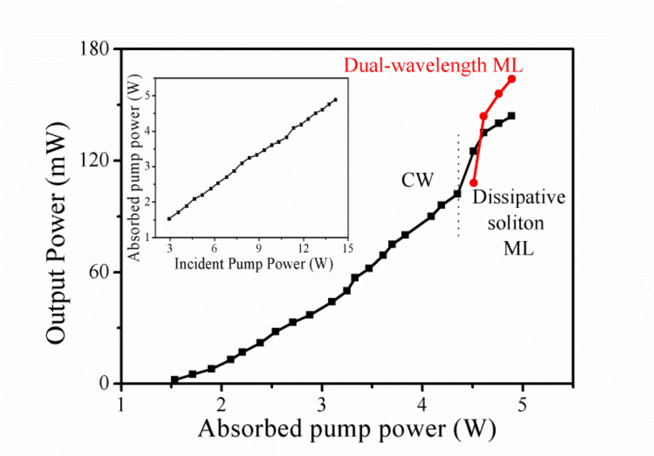

Fig. 2. The output power characteristics of the DS mode-locking and dual-wavelength mode-locking operations. Insert: Absorbed pump power of the Yb:YSO crystal at different incident pump powers.

An optical spectrum analyzer (YOKOGAWA, AQ6370C) and a commercial intensity autocorrelator (FR-103MN, Femtochrome Research, Inc.) were used to investigate the spectrum and autocorrelation trace. The optical spectrum had a full width at half maximum (FWHM) bandwidth of 3.1 nm with typical dissipative soliton characteristics, which is shown in Fig. 3(a). Fourier transformation of this spectrum shows that it supports a Fourier limit of 270 fs. Figure 3(b) describes the evolution of mode-locking spectra with increasing pump power. As evident from Fig. 3(b), a slight broadening of the optical spectrum could be found as the pump power increasing, which is in accordance with the situation in [7].

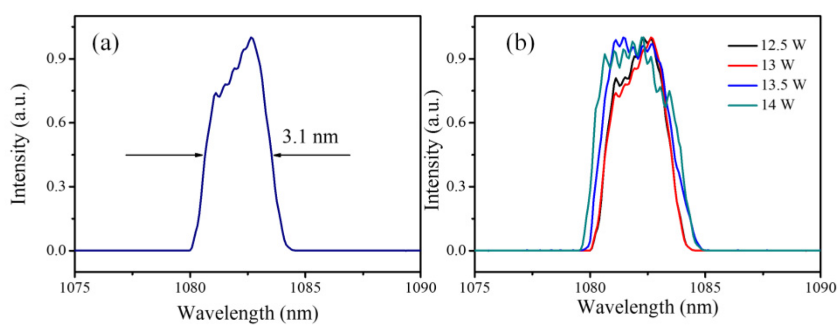

Fig. 3. (a)The optical spectrum of the DS mode-locked laser measured under 13 W incident pump power. (b)The Optical spectra of the DS mode-locked pulses under different incident pump powers.

The intensity autocorrelation trace sketched in Fig. 4 had a FWHM bandwidth of 14.3 ps, corresponding to the pulse duration of 9.3 ps if a $sech^2$-pulse shape was assumed. The pulse duration of 9.3 ps was almost 34.4 times of the Fourier transform pulse duration of the spectrum. Therefore, a typical DS pulse with strong frequency chirp feature was verified.

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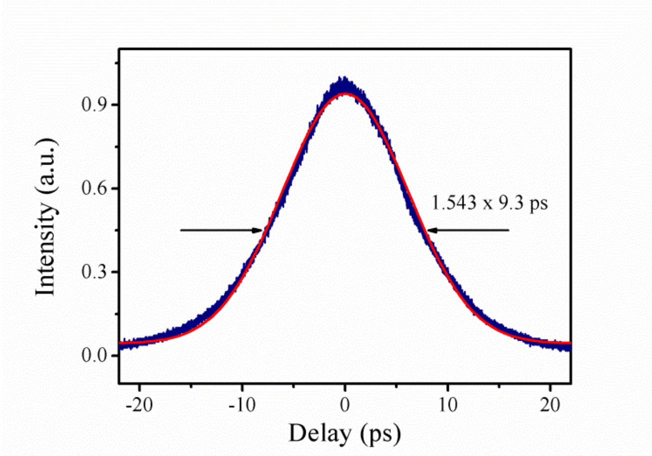

Fig. 4. The intensity autocorrelation trace of the DS mode-locked pulse. The experimental data and the sech^2-fitting curve are described by the blue curve and the red curve, respectively.

Because of the larger emission cross section at 1056 nm than that of at 1081 nm, we found that it is easy to generate CW component around 1060 nm when we adjusted the end mirrors (SESAM or OC). And a tending to mode-locking at both 1060 nm and 1080 nm was observed. Encouraged by the observed phenomenon, we further carefully tuned the positions both of the crystal and the SESAM, meanwhile adjusted the end mirrors. Dual-color synchronous mode-locking at 1059.2 nm and 1082.2 nm was obtained. The output property of the mode-locking operation is also given in Fig. 2 (Red solid dots). The maximum output power was 164 mW, which is a little larger than that of the DS operation.

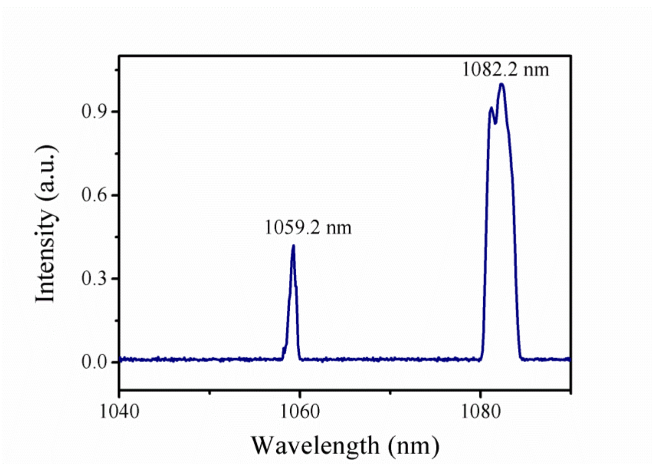

Fig. 5. The optical spectral of dual-wavelength synchronously mode-locked laser.

Figure 5 expresses the spectrum of the synchronously mode-locked pulses. It can be seen that the two color mode-locking pulses were centered at 1059.2 nm and 1082.2 nm, respectively. The center frequency difference between the two wavelengths is 6.1 THz and the intensity ratio between the dual-color pulses was about 1:2. The corresponding intensity autocorrelation traces were revealed in Fig. 6(a) and Fig. 6(b) with delay time spanning of 50 ps and 6 ps, respectively. The autocorrelation trace illuminated in Fig. 6(a) has a FWHM of 15.4 ps, thus the actual pulse duration should be 10 ps if a sech^2-shape pulse is assumed. Resulted from the optical beat between two carrier frequencies of the dual-wavelength synchronous pulses, periodical ultrafast pulses with pulse duratin of 169 fs, if a cosine shape

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pulse is assumed, are distinctly observed in the autocorrelation trace. The time interval between each beat pulses is 710 fs, corresponding to a repetition rate of 1.4 THz.

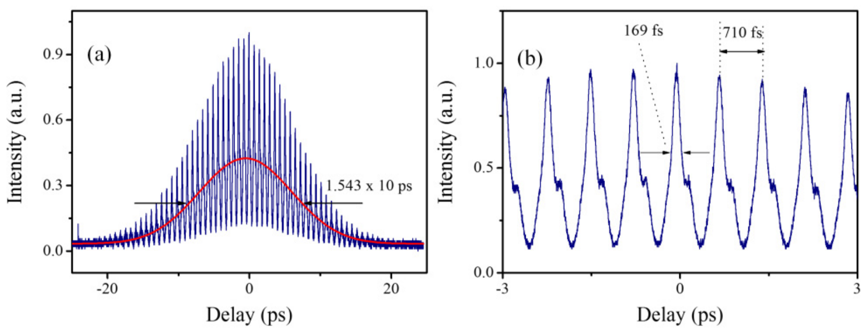

Fig. 6. The intensity autocorrelation traces of the dual-wavelength synchronously mode-locking laser with delay time of 50 ps (a) and 6 ps (b), respectively. The experimental data and $sech^2$-shape fitting curve are described by the blue curve and red curve, respectively.

Using a RF spectrum analyzer (Agilent E4407B), we measured the RF power spectrum shown in Fig. 7. A distinct 55.5 dBc fundamental beat note at 113.396 MHz was recorded in a frequency span of 200 kHz with a resolution bandwidth (RBW) of 1 kHz as in Fig. 7(a). Figure 7(b) gives the several harmonic frequency signals in a frequency span of 1 GHz under the RBW of 100 kHz. Though, two mode-locking pulses at different wavelengths were appearing, the RF spectrum indicates that the dual-color pulses were synchronously propagating in the cavity. It was also clearly incarnated by the typical mode-locked pulse train depicted in Fig. 8, which is measured with a high-speed detector and a 200-MHz-bandwidth oscilloscope. It can be seen that only one mode-locked pulse is observed in one cavity period, which is further confirmed that the two mode-locked pulses at different wavelengths were synchronized and temporally overlapped to a certain extent.

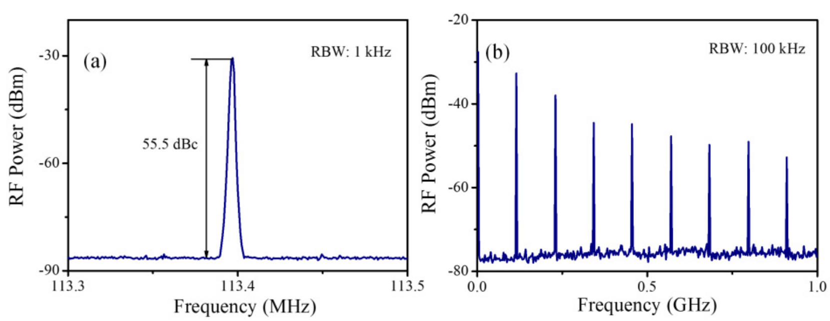

Fig. 7. The RF power spectrum of the dual-wavelength synchronously mode-locked laser in the frequency span of 200 kHz (a) and 1 GHz (b), respectively.

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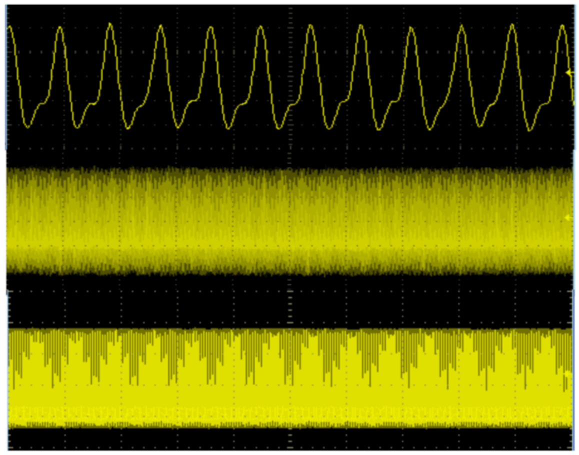

Fig. 8. The oscilloscope traces of the dual-wavelength synchronously mode-locked pulse train in the time scales of 10 ns/div, 2μs/div and 1 ms/div, respectively.

To explore the characteristics of the mode-locking pulses at 1059 nm and 1082 nm, we separated the dual-color pulses with a prism and measured the spectra and intensity autocorrelation traces, respectively. For mode-locking pulse at 1082 nm, the spectra and intensity autocorrelation trace were just similar to those of the pure DS mode-locking operation at 1082 nm. Figure 9(a) and 9(c) shows the corresponding spectra and intensity autocorrelation traces of the mode-locking pulse at 1059 nm and 1082 nm, respectively. The FWMHs of the optical spectra at 1059 nm and 1082 nm are 2.1 nm and 3.1 nm which corresponding to the Fourier limit of 324 fs and 270 fs. The different between the dual color mode-locking spectra is mainly due to the different total cavity round-trip GDDs between these two emission bands, which resulting in different types of mode-locking operations which traditional ps mode-locking at 1059 nm while DS mode-locking at 1082 nm. The corresponding intensity autocorrelation traces sketched in Fig. 9(b) and 9(d) had FWHM bandwidths of 19.3 ps and 14.9 ps. If sech^2-pulse shape was assumed, the pulse durations are 12.5 ps and 9.7 ps, respectively.

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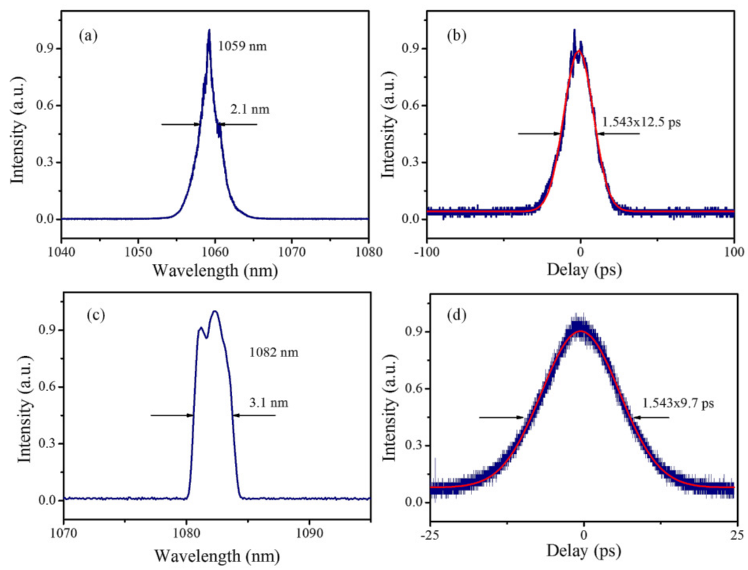

Fig. 9. The spectra (a), (c) and corresponding intensity autocorrelation traces (b), (d) of the mode-locking pulses at 1059.2nm and 1082.2 nm. The experimental data and the $sech^2$-shape fitting curves are described by the blue curve and the red curve, respectively.

To explain why the dual-wavelength synchronously mode-locking operation happened in our experiment, we assume that it is due to the alliance between the large gain cross sections at the two wavelength bands (1056 nm and 1081 nm) and an appropriate SESAM. Just as the situation in [19], the dual-color pulses turned out to be synchronous were mainly driven by the modulation of the SESAM. It is worth noticed that the repetition rate of beat pulses is not equal to 6.1 THz, the center frequency difference between the two wavelengths, but to be a fractional number of the frequency difference. And the shape of beat pulses is not completely cosine-like, which we contribute to the strong chirp features of the dual-color pulses and that the dual-color pulses are not completely overlapped in the time domain. According to the discussion in [38], the beat frequency does depend on not only the center frequency difference but also the time delay between the two pulses as well as the linear frequency chirp rate.

4. Conclusion

In conclusion, we have presented a dissipative soliton mode-locked Yb:YSO laser by using an all-normal-dispersion cavity. Strongly chirped pulses have been obtained with pulse duration of 9.3 ps at a repetition rate of 113.4 MHz. The central wavelength was 1082 nm with 3.1 nm FWHM bandwidth and the maximum output power was 144 mW. Furthermore, we have demonstrated what we believe the first dual-wavelength synchronously mode-locking operation at 1059.2 nm and 1082.2 nm from a Yb:YSO laser. . It is proved that the two color pulses were synchronized and partially temporally overlapped in the cavity. The two synchronous pulses generated beat pulses train with 169 fs pulse width and a repetitive rate of 1.4 THz. We believe that it is a potential laser source to generate ultrashort THz-wave pulses.

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