Appl. Phys. B (2015) 121:1–6
DOI 10.1007/s00340-015-6189-7

**Applied Physics B**
**Lasers and Optics**

# Tunable triple-wavelength mode-locked ytterbium fiber laser with birefringence filter

**Zhiguo Lv[1] · Hao Teng[2] · Rui Wang[2] · Lina Wang[2] · Junli Wang[1] · Zhiyi Wei[2]**

Received: 26 April 2015 / Accepted: 21 July 2015 / Published online: 20 August 2015

**Abstract** A mode-locked ytterbium fiber laser based on all normal dispersion (ANDi) technique and nonlinear polarization rotation (NPR) is investigated with birefringent plate as a spectral filter in this paper. Tunable triple-wavelength simultaneous operation is realized at central wavelengths of 1031.4, 1046.8 and 1066.5 nm, respectively. A maximum output power up to 161.4 mW is obtained at 1031.4 nm wavelength. By only changing the direction of the optical axis of the uniaxial birefringent filter, tunable range as wide as 19 nm is demonstrated. To the best of our knowledge, this is the widest tuning range and highest power reported so far for ANDi mode-locked ytterbium fiber lasers with triple-wavelength operation. Our analysis shows that the mechanism of the triple-wavelength mode-locked operation results mainly from the four-wave mixing in optical fibers; in addition, the wide gain bandwidth of Yb also plays a critical role for the stable oscillation of the third mode-locked wavelength. The energy conversion process governed by a set of four coupled equations is realized experimentally through the adjustment of the polarization controller, which is related to the phase matching.

## 1 Introduction

Stable tunable ultrashort pulse laser sources with simultaneous multiwavelength mode-locked operation have attracted widely interesting in pump-probe [1], photo echo spectroscopy [2], four-wave mixing (FWM), etc. With the rising requirements for applications, great efforts have been made on multiwavelength ultrafast lasers. In particular, synchronous dual-wavelength femtosecond lasers have been widely researched with Ti:sapphire crystal as gain [3], and long wavelength gap and sub-fs timing jitter were further realized by using two laser gain media [4, 5]. In addition,a dual-wavelength operation from a synchronously mode-locked Nd:CNGG laser has also been obtained, in which the separation between the two gain bands is 2.4 nm [6]. However, for synchronous triple-wavelength mode-locked ultrafast laser, it is few reported because of the challenge technology and complex configuration [7].

With the development of the fiber lasers, multiwavelength mode-locked fiber lasers have also been widely explored by using actively and passively mode-locked mechanisms in different wavelength regimes (1, 1.5, 2 μm) [8–12]. Compared to the actively mode-locked fiber lasers [8–10], passive mode-locking is technically easy to operate , is compact in structure as well as has low jitter in performance. Passively mode-locked multiwavelength (dual- or triple-wavelength) erbium-doped fiber lasers have been developed in recent years based on a semiconductor saturable absorber mirror (SESAM) and comb filter as well as polarization maintaining fiber [13–15], and even more prominent, up to 7-wavelength mode-locked erbium fiber laser has also been realized in 2011 by using the hybrid mode-locked components of the SESAM and inline birefringence fiber filter [16]. In addition, as an excellent candidate for the development of ultrafast laser

---

✉ Zhiyi Wei
zywei@iphy.ac.cn

Hao Teng
hteng@iphy.ac.cn

[1] School of Physics and Optoelectronic Engineering, Xidian University, Xi'an 710071, China

[2] Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

technology, ytterbium fiber-based multiwavelength mode-locked lasers are more beneficial for applications because of the broad emission bandwidth and higher efficiency as well as the availability of the high power pump laser. As a result, tunable and/or switchable multiwavelength passively mode-locked ANDi ytterbium fiber laser has also been demonstrated based on in-line birefringence fiber filter with periodic multiple passbands [17, 18], phase-shifted long-period fiber grating [19] and graphene oxide saturable absorber [20]. However, manufacturing the mentioned modulation components in Ref. [13–20] is complicated and of high cost. Up to now, to our knowledge, no triple-wavelength mode-locked NPR-based ANDi ytterbium fiber laser with a single birefringent plate as spectral filter has been reported.

In general, the introduction of the passive fiber in the mode-locked fiber laser makes the generation of the nonlinear effects possible, such as self-phase modulation (SPM),stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS) and parametric processes, which are all mediated by the third-order susceptibility $\chi^{(3)}$. For the parametric processes mentioned above in fiber, a typical application is the synchronously pumped fiber optical parametric oscillators (FOPOs) based on the FWM in the passive fiber, which have been widely reported in the past few years due to its widely tuning range, easy operation, compactness and low cost [21–23]. The core idea for the FOPOs, specifically, is generation of the signal and idler wavebands through high peak power pump photons from the external laser source interacting with the passive fiber. However, the passive optical fiber only mediates interaction among three optical waves without participating in the exchange of energy during the interaction process.

In this paper, we report on a simple low-cost tunable triple-wavelength mode-locked ANDi ytterbium fiber laser with birefringent plate as spectra modulation component. The mechanism of the triple-wavelength mode-locked laser, which we demonstrated, is a combination of the FWM and the dual-wavelength mode-locking, i.e., the generation of the third long wavelength is originated from the difference frequency effect caused by two lower-energy photons differentiating with one higher-energy photon in the dual-wavelength mode-locked process. In addition, the wide gain bandwidth of Yb also plays a critical role for the stable operation of the third long wavelength in the triple-wavelength mode-locked fiber laser. The output wavelength can be continuously tuned as wide as 19 nm. Simultaneously, the energy exchange process is also realized experimentally by changing the orientations of the waveplates which is related to phase match. The pulse durations are measured to be 330, 413 and 600 ps, respectively, for the longer, medial and shorter wavelengths by using high-speed photodiode (rise time: <12 ps) and an oscilloscope (8 GHz bandwidth).

## 2 Experiment and results

Figure 1 shows the triple-wavelength mode-locked ANDi fiber laser. By using two optical collimators, a polarization-dependent isolator and a wavelength-division multiplexer (WDM), a unidirectional clockwise ring cavity fiber laser is developed. A piece of Yb-doped fiber with a length of 50 cm is inserted into the laser cavity to provide the laser gain, which is pumped by a 976-nm diode laser with a maximum power of 530 mW through WDM. In order to make the real-time monitoring of laser performance possible in the process of the parameter measurement, a 50:50 optical coupler is employed, which couples 50 % power out of the laser cavity. The main output port of this laser is from the polarization beam splitter (PBS). For the fundamental mode-locking, the repetition rate is 1.77 MHz which is consistent with the total fiber length of 110 m. As the key component for initiating mode-locking, a birefringent plate at Brewster angle combined with polarizers as an equivalent Lyot filter is used to convert frequency chirp to self-amplitude modulation and realize passive mode-locking.

Firstly, we conduct an experimental study on single-wavelength mode-locking operation. The mode-locked laser pulses with significantly different spectral width $\Delta\lambda$ could be obtained under the same pump power (~400 mW) by adjusting the polarization controller. The narrowest single-wavelength mode-locked spectrum achieved is as short as 1.2 nm FWHM and the widest is 28 nm. Figure 2a illustrates these two major types of mode-locked spectra with a resolution bandwidth of 0.2 nm on linear scales. It should

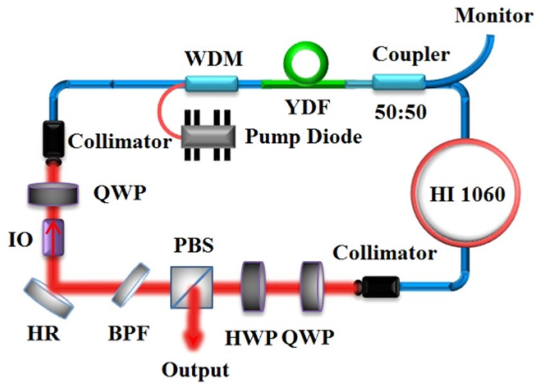

**Fig. 1** Schematic diagram of the triple-wavelength mode-locked fiber laser. *WDM* wavelength-division multiplexer, *QWP* (*HWP*) quarter (half)-wave plate, *PBS* polarization beam splitter, *BPF* birefringent filter, *IO* polarization-dependent isolator, *YDF* Yb-doped fiber

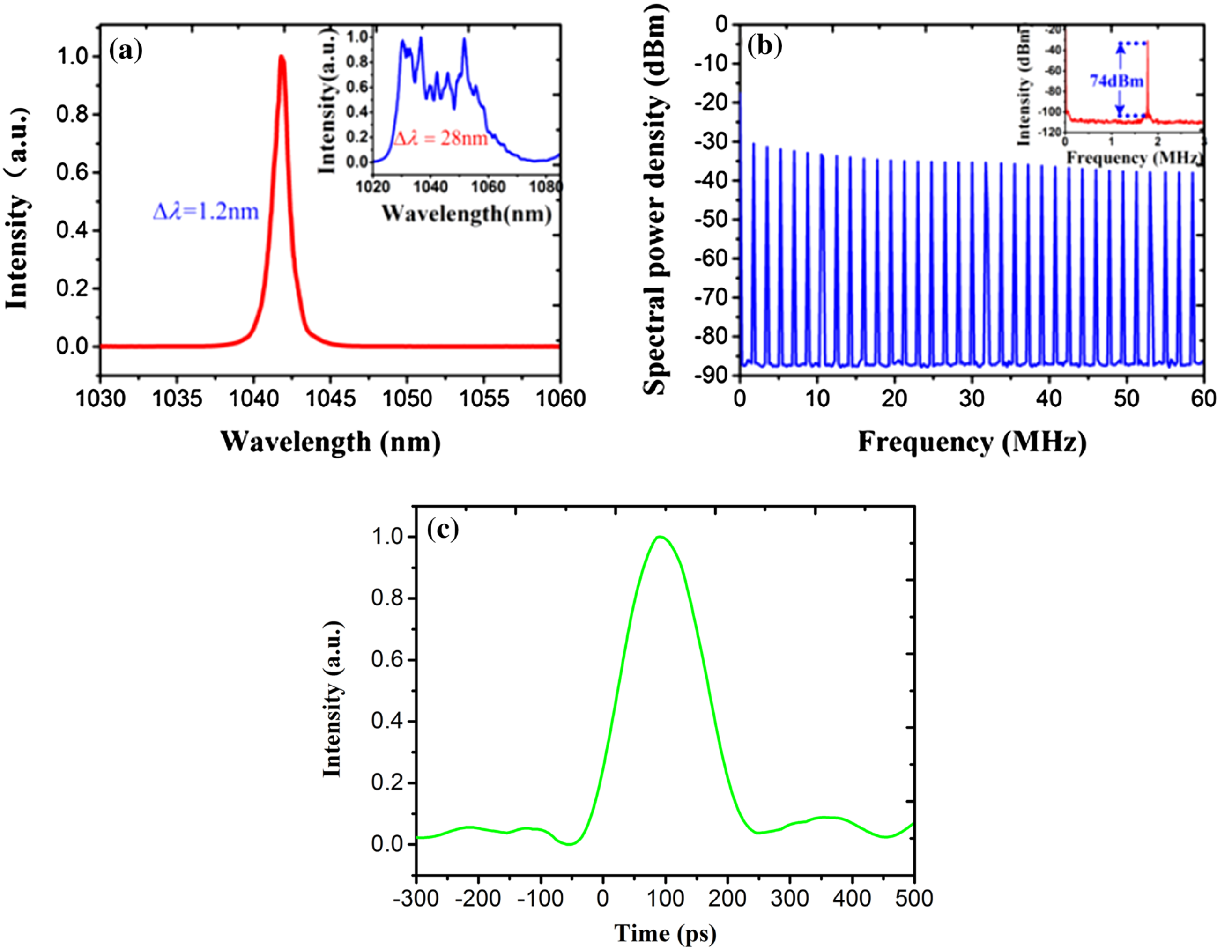

**Fig. 2** **a** Single-wavelength mode-locked output spectra on linear scale corresponding to the different orientations of the polarization controller; **b** RF spectra of the narrowest spectrum mode-locked pulses with 1 kHz resolution bandwidth; **c** measured pulse duration

be pointed out that these two mode-locked pulses are very stable, although it is found experimentally that the mode-locked operation with wide spectrum is difficult to realize compared to the narrow one. The radio-frequency (RF) spectra in Fig. 2b show a 74 dB super-mode suppression ratio for the narrowest mode-locked spectrum, and Fig. 2c shows the measured pulse duration with 145 ps pulse width at a central wavelength of 1042 nm with 1.2 nm spectral bandwidth in the single-wavelength mode-locked operation.

In addition, triple-wavelength mode-locking operation can also be realized by our ANDi fiber laser by slight adjustment of the orientations of the polarization controller. Figure 3 shows the output spectrum characteristics of a typical triple-wavelength mode-locking under a maximum pump power. The center wavelengths of the three separated triangular-like spectra shown in Fig. 3 are 1042 nm ($\lambda_S$), 1060 nm ($\lambda_M$) and 1081 nm ($\lambda_L$), respectively. The 3 dB

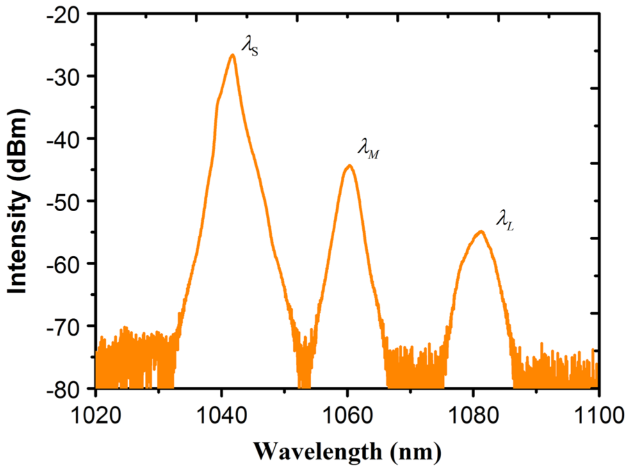

**Fig. 3** Triple-wavelength mode-locked output spectrum on logarithmic scale. $\lambda_L$, $\lambda_M$ and $\lambda_S$ stand for the longer, medial and shorter mode-locked central wavelengths, respectively

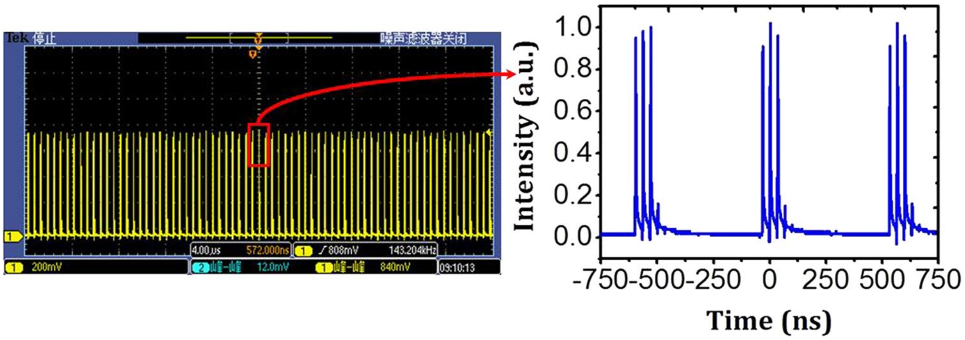

**Fig. 4** Pulse train of the triple-wavelength mode-locked ANDi fiber laser. *Inset* shows the expanded version on a short time scale

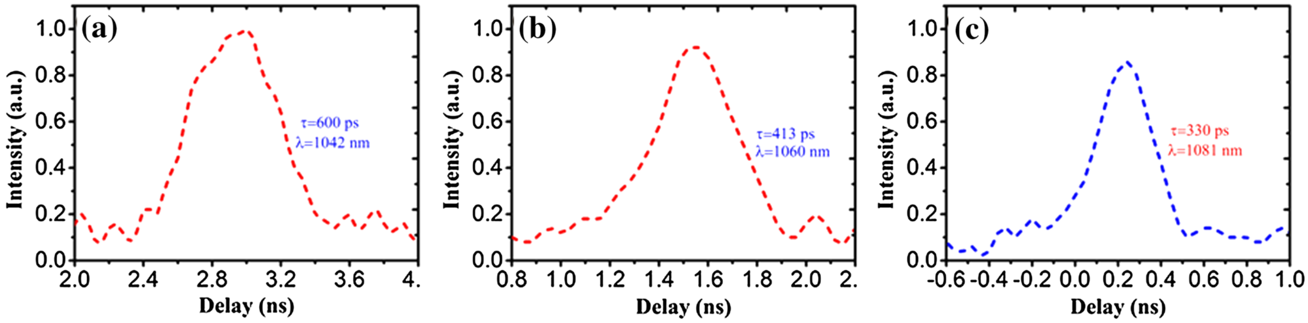

**Fig. 5** Typical output characteristics of the triple-wavelength mode-locking measured by a high-speed photodiode and 8 GHz oscilloscope

spectral bandwidths are 1.8, 2.5 and 3.8 nm, respectively, for these three mode-locked center wavelengths.

The triple-wavelength mode-locked pulse trains are also measured by a high-speed photodiode, as shown in Fig. 4. From the insert of Fig. 4, we can see that there are actually three separated pulses with time interval of tens of nanometers, which is also consistent with triple-wavelength mode-locked pulses.

The measured pulse durations are 330, 413 and 600 ps, respectively, for the longer (1081 nm), medial (1060 nm) and shorter (1042 nm) wavelengths, as shown in Fig. 5.

## 3 Discussion

Generation of the third mode-locked long wavelength is a combination of the dual-wavelength mode-locking and the FWM resulting from the third-order susceptibility $\chi^{(3)}$ in optical fibers when the pump power is sufficient and these three wavelengths satisfy the following equation:

$$\frac{2}{\lambda_M} = \frac{1}{\lambda_L} + \frac{1}{\lambda_S} \tag{1}$$

where $\lambda_L$, $\lambda_M$ and $\lambda_S$ stand for the longer, medial and shorter mode-locked central wavelengths, respectively. Its physical origin is that two mode-locked photons ($\omega_M$) are annihilated and the energies are converted into two waves upshifted and downshifted in frequency (one is from the mode-locked photon ($\omega_S$) and the other ($\omega_L$) is from the quantum noise). During this process, optical fibers just play a passive role, and thus, net energy is conserved. In addition, so as to obtain stable oscillation during the whole process, the wide gain bandwidth of Yb also provides a gain to overcome the loss when the third long wavelength originated from FWM oscillates in a cavity round-trip. The establishing process of the triple-wavelength mode-locking and the dynamic evolution of the energy conversion governed by a set of four coupled equations are realized experimentally by increasing the pump power and changing the orientation of the polarization controller, which is related to phase matching. Under low pump power (~430 mW), stable dual-wavelength mode-locking can be obtained, as shown in Fig. 6a. With increasing the pump power to 530 mW, the stable triple-wavelength mode-locking is realized. By slight adjustment of the orientations of the waveplates to introduce a different phase deviation, we observe the dynamic evolution of the energy exchange among the three wavelengths as shown in Fig. 6b–f. Initially, the relative spectral intensity of the medial wavelength ($\lambda_M$) is 20 dB higher than that of the third long wavelength ($\lambda_L$), as shown in Fig. 2b. However, there is a significant difference in spectral intensity between the medial and longer wavelengths with the adjustment of the polarization controller. The difference in spectral intensity between the

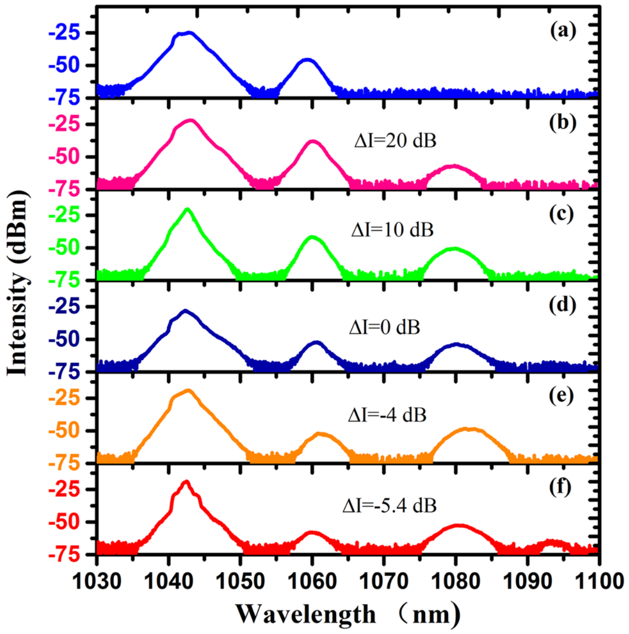

**Fig. 6** Energy conversion process from the FWM process: **a** dual-wavelength mode-locking; **b–f** triple-wavelength mode-locking with the different relative spectral intensity difference ($\Delta I$). The notation $\Delta I$ introduced here is defined by the difference of the spectral power density between the medial ($\lambda_M$) and longer wavelengths ($\lambda_L$)

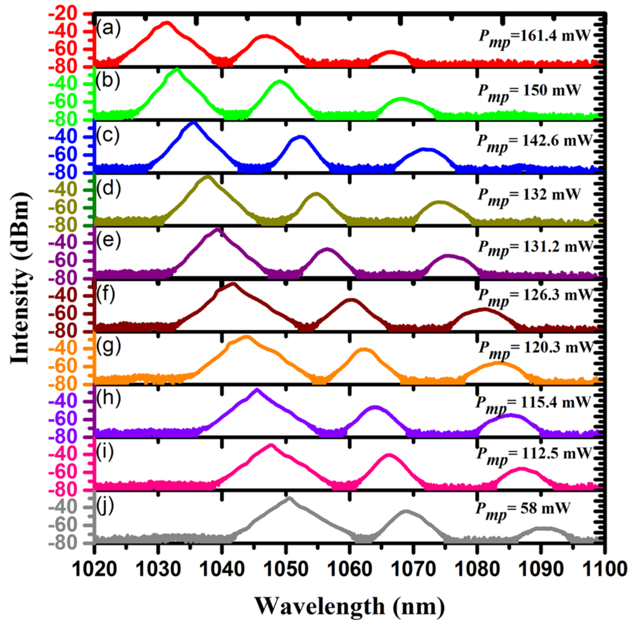

**Fig. 7** Tunability of the triple-wavelength mode-locking. The notation $P_{\mathrm{mp}}$ stands for the total output power from the PBS

wavelengths is changed from 20, 10, 0, −4 to −5.4 dB, respectively. The fourth weak signal shown in Fig. 6f is centered at the wavelength of 1093 nm, which results from the Raman shift caused by the intense shorter pulses at central wavelength of 1042 nm. So by changing the polarization controller, the FWM energy exchange could be conducted in one direction, i.e., the energy from the medial wavelength is gradually converted into the shorter and longer wavelengths and it is also immediately demonstrated that the polarization controller composed of wave plates is related to phase matching of the FWM. Considering the tunability of the birefringent plate filter, the triple-wavelength mode-locked fiber laser is also tunable, as shown in Fig. 7. By only changing the direction of the optical axis of the uniaxial birefringent plate filter, the three mode-locked wavelengths are simultaneously shifted over a 19 nm from 1031 to 1050 nm for the shorter wavelength without losing mode-locking. During the process of the tuning, the phase matching among three wavelengths given by Eq. (1) is automatically realized, as shown in Table 1, and the wavelength spacing between the three mode-locked wavelengths is changed.

## 4 Conclusion

In conclusion, a NPR-based tunable triple-wavelength mode-locked ANDi fiber laser with birefringence filter is developed, which demonstrates a way for simultaneous

**Table 1** Central wavelengths during the whole process of the tuning in the triple-wavelength mode-locked operation

| Mode-locked state during the whole process of the tuning | $\lambda_S$ (nm) | $\lambda_M$ (nm) | $\lambda_L$ (nm) |
|---|---|---|---|
| a | 1031.17404 | 1046.90129 | 1066.63184 |
| b | 1032.88974 | 1049.18889 | 1068.34754 |
| c | 1035.46329 | 1052.33434 | 1071.77894 |
| d | 1037.75089 | 1054.90789 | 1074.06654 |
| e | 1039.18064 | 1056.33764 | 1075.78224 |
| f | 1041.75419 | 1060.34094 | 1080.92934 |
| g | 1043.75584 | 1062.34259 | 1083.21694 |
| h | 1045.47154 | 1064.05829 | 1084.93264 |
| i | 1047.75914 | 1066.34589 | 1086.93429 |
| j | 1050.61864 | 1068.91944 | 1090.36569 |

triple-wavelength operation with simple configuration and low cost. The output mode-locked pulses at central wavelengths of 1081, 1060 and 1042 nm are realized, respectively, and can be continuously tuned as wide as 19 nm. Our measurement shows that the pulse duration is 330, 414, 600 ps, respectively, by using a high-speed photodiode and an oscilloscope. The energy conversion process is realized by changing the phase difference among three mode-locked pulses. The mechanism of the triple-wavelength mode-locked pulses is also analyzed, which results from FWM originating from the third-order susceptibility in optical fiber and the wide gain bandwidth of Yb. We strongly believe that this developed laser will find wide applications in scientific research and industry.

**Acknowledgments** The work is partly supported by the National Key Technology R&D Program of the Ministry of Science and Technology under Grant No. 2012BAC23B03, the National Key Basic Research Program of China under Grant No. 2013CB922401 and National Natural Science Foundation of China under Grants No. 11474002.

## References

1. T. Cimei, A.R. Bizzarri, G. Cerullo, S. De Silvestri, Vibrational coherence in Azurin with impulsive excitation of the LMCT absorption band. Chem. Phys. Lett. **362**(5), 497–503 (2002)
2. P. Vöhringer, D.C. Arnett, T.-S. Yang, N.F. Scherer, Time-gated photon echo spectroscopy in liquids. Chem. Phys. Lett. **237**(5), 387–398 (1995)
3. J.M. Evans, D.E. Spence, D. Burns, W. Sibbett, Dual-wavelength self-mode-locked Ti:sapphire laser. Opt. Lett. **18**(13), 1074–1076 (1993)
4. Z. Wei, Y. Kobayashi, Z. Zhang, K. Torizuka, Generation of two-color femtosecond pulses by self-synchronizing Ti:sapphire and Cr:forsterite lasers. Opt. Lett. **26**(22), 1806–1808 (2001)
5. D. Yoshitomi, Y. Kobayashi, H. Takada, M. Kakehata, K. Torizuka, 100-attosecond timing jitter between two-color mode-locked lasers by active–passive hybrid synchronization. Opt. Lett. **30**(11), 1408–1410 (2005)
6. G.Q. Xie, D.Y. Tang, H. Luo, H.J. Zhang, H.H. Yu, J.Y. Wang, X.T. Tao, M.H. Jiang, L.J. Qian, Dual-wavelength synchronously mode-locked Nd:CNGG laser. Opt. Lett. **33**(16), 1872–1874 (2008)
7. W. Shuicai, H. Junfang, X. Dong, Z. Changjun, H. Xun, A three-wavelength Ti:sapphire femtosecond laser use with the multi-excited photosystem II. Appl. Phys. B. **72**(7), 819–821 (2001)
8. L.R. Chen, G.E. Town, P.-Y. Cortès, S. LaRochelle, P.W.E. Smith, Dual-wavelength, actively mode-locked fibre laser with 0.7 nm wavelength spacing. Electron. Lett. **36**(23), 1921–1923 (2000)
9. S. Pan, C. Lou, Stable multiwavelength dispersion-tuned actively mode-locked erbium-doped fiber ring laser using nonlinear polarization rotation. IEEE Photon. Tech. Lett. **18**(13), 1451–1453 (2006)
10. D. Pudo, L.R. Chen, Actively mode locked, quadruple-wavelength fibre laser with pump-controlled wavelength switching. Electron. Lett. **39**(3), 272–274 (2003)
11. Z. Yan, X. Li, Y. Tang, P.P. Shum, X. Yu, Y. Zhang, Q.J. Wang, Tunable and switchable dual-wavelength Tm-doped mode-locked fiber laser by nonlinear polarization evolution. Opt. Express **23**(4), 4369–4376 (2015)
12. J. Sotor, G. Sobon, I. Pasternak, A. Krajewska, W. Strupinski, K.M. Abramski, Simultaneous mode-locking at 1565 and 1944 nm in fiber laser based on common graphene saturable absorber. Opt. Express **21**(16), 18994–19002 (2013)
13. H. Zhang, D.Y. Tang, X. Wu, L.M. Zhao, Multi-wavelength dissipative soliton operation of an erbium-doped fiber laser. Opt. Express **17**(15), 12692–12697 (2009)
14. Z.C. Luo, A.P. Luo, W.C. Xu, H.S. Yin, J.R. Liu, Q. Ye, Z-Jie Fang, Tunable multiwavelength passively mode-locked fiber ring laser using intracavity birefringence-induced comb filter. IEEE Photon. J. **2**(4), 571–577 (2010)
15. Y.D. Gong, X.L. Tian, M. Tang, P. Shum, M.Y.W. Chia, V. Paulose, J. Wu, K. Xu, Generation of dual wavelength ultrashort pulse outputs from a passive mode-locked fiber ring laser. Opt. Comm. **265**, 628–631 (2006)
16. Z.C. Luo, A.P. Luo, W.C. Xu, Tunable and switchable multi-wavelength passively mode-locked fiber laser based on SESAM and inline birefringence comb filter. IEEE Photon. J. **3**(1), 64–70 (2011)
17. Z.X. Zhang, Z.W. Xu, L. Zhang, Tunable and switchable dual-wavelength dissipative soliton generation in an all-normal-dispersion Yb-doped fiber laser with birefringence fiber filter. Opt. Express **20**(24), 26736–26742 (2012)
18. Z.W. Xu, Z.X. Zhang, All-normal-dispersion multi-wavelength dissipative soliton Yb-doped fiber laser. Laser Phys. Lett. **10**, 085105 (2013)
19. X. Zhu, C. Wang, G. Zhang, R. Xu, Tunable dual- and triple-wavelength mode-locked all-normal-dispersion Yb-doped fiber laser. Appl. Phys. B **118**(1), 69–73 (2014)
20. S. Huang, Y. Wang, P. Yan, J. Zhao, H. Li, R. Lin, Tunable and switchable multi-wavelength dissipative soliton generation in a grapheme oxide mode-locked Yb-doped fiber laser. Opt. Express **22**(10), 11417–11426 (2014)
21. Z. Luo, W.D. Zhong, M. Tang, Z. Cai, C. Ye, X. Xiao, Fiber-optic parametric amplifier and oscillator based on intracavity parametric pump technique. Opt. Lett. **34**(2), 214–216 (2009)
22. C. Gu, H. Wei, S. Chen, W. Tong, J.E. Sharping, Fiber optical parametric oscillator for sub-50 fs pulse generation: optimization of fiber length. Opt. Lett. **35**(20), 3516–3518 (2009)
23. L. Zhang, S. Yang, X. Wang, D. Gou, X. Li, H. Chen, M. Chen, S. Xie, Widely tunable all-fiber optical parametric oscillator based on a photonic crystal fiber pumped by a picosecond ytterbium-doped fiber laser. Opt. Lett. **38**(22), 4534–4536 (2009)