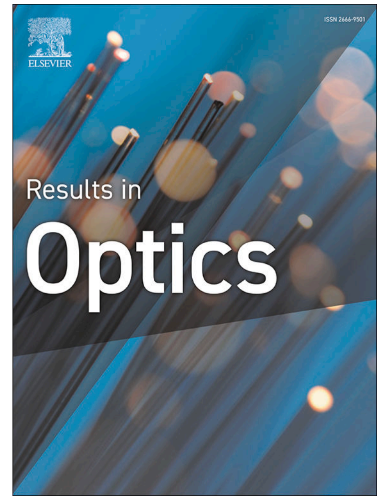
Journal Pre-proofs



Invited Article

(INVITED)Switchable multi-wavelength mode-locked Yb-doped fiber laser using a polarization maintaining 45°-tilted fiber gratings based Lyot filter

Yanlv Lin, Zinan Huang, Qianqian Huang, Lilong Dai, Yunliang Bao, Tao Chen, Qingguo Song, Zhijun Yan, Chengbo Mou, Kaiming Zhou, Lin Zhang

PII: S2666-9501(21)00019-5
DOI: https://doi.org/10.1016/j.rio.2021.100071
Reference: RIO 100071

To appear in: *Results in Optics*

Received Date: 19 January 2021
Revised Date: 22 February 2021
Accepted Date: 22 February 2021

(INVITED)Switchable multi-wavelength mode-locked Yb-doped fiber laser using a polarization maintaining 45°-tilted fiber gratings based Lyot filter

Yanlv Lin[a], Zinan Huang[a], Qianqian Huang[a], Lilong Dai[a], Yunliang Bao[a], Tao Chen[b], Qingguo Song[c], Zhijun Yan[c], Chengbo Mou[a,b,*] ,Kaiming Zhou[d] and Lin Zhang[d]

[a]*Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science, Shanghai University, Shanghai, China*

[b]*Key Laboratory of Space Active Opto-electronics Technology, Chinese Academy of Sciences, Shanghai, China*

[c]*School of Optical and Electronic Information, National Engineering Laboratory for Next Generation Internet Access System, Huazhong University of Science and Technology, Wuhan, China*

[d]*Aston Institute of Photonic Technologies, Aston University, Aston Triangle, Birmingham, B4 7ET, United Kingdom*

E-MAIL ADDRESS: mouc1@shu.edu.cn (Chengbo Mou)

Abstract

We demonstrate a multi-wavelength mode-locked Yb-doped fiber laser by incorporating a pair of polarization maintaining 45° tilted fiber gratings (PM-45°TFG) based Lyot filter. Thanks to the functions of the polarizer and the comb filtering introduced by the Lyot filter, dissipative soliton (DS) pulses centered at 1035.26 nm, 1044.93 nm, 1055.62 nm, 1066.11 nm and 1076.63 nm can be generated respectively by finely tuning the intracavity polarization controllers (PCs). Moreover, the laser also can operate in a multi-wavelength regime via appropriately adjusting the pump power and polarization orientation. The high nonlinearity induced by the long cavity length leads to the generation of *h*-shaped mode-locked pulse with a repetition rate of 566.27 kHz. In the absence of any disturbance, the laser can operate steadily, that can potentially be used in various fields including wavelength division multiplexing systems etc.

Keywords: Yb-doped fiber laser, multi-wavelength, dissipative soliton, Lyot filter, tilted fiber grating.

1. Introduction

Multi-wavelength mode-locked fiber lasers have excellent performance in spectral selection, which cater the needs of light sources in laser processing, wavelength division multiplexing communication systems and sensing [1-3]. As a popular research subject, a number of methods to realize multi-wavelength operation of the fiber laser have been proposed. A straightforward and effective way is to introduce a wavelength selector into the laser cavity. It has been reported that six-wavelength dissipative solitons (DSs) mode locking in an Yb-doped fiber laser by using a Lyot-Sagnac filter as the wavelength selector and a semiconductor saturable absorption mirror (SESAM) as the saturable absorber (SA) [4]. By incorporating a Mach-Zehnder (MZ) interferometric filter and carbon nanotube (CNT) in the laser cavity, dual-wavelength mode locking can be obtained [5]. The CNT or SESAM can achieve stable mode locking, however, the low thermal damage threshold of these physical SAs limits the operation of lasers at high pump power. Also, the use of circulator and fiber connectors would increase the insertion loss and complexity of the cavity. Fortunately, the artificial SA, such as nonlinear optical loop mirror (NOLM), nonlinear polarization evolution (NPE) or nonlinear polarization rotation (NPR) *etc*., have the characteristics of high thermal damage threshold, and can also be used to realize multi-wavelength mode locking. Xiaojun Zhu *et al.* used the phase-shift long-period fiber gratings (PS-LPFG) to generate dual- and triple-wavelength mode locking in an NPE based Yb-doped fiber laser [6]. Combing a hollow-core fiber based Fabry-Perot interferometer (FPI) and NOLM, dual-wavelength mode locking can be obtained [7]. But in fact, in the aforementioned lasers, although the wavelength selectors effectively achieve the multi-wavelength operation of the lasers, the realization of mode locking still requires additional mode lockers. This undoubtedly increase the complexity of the laser cavity.

In order to reduce the complexity of the laser cavity, recently, Ling Yun *et al.* generated dual-wavelength DS pulse by using NOLM only [8]. By virtue of the intensity-dependent loss induced by NPR, Huaiqin Lin *et al.* reported a tunable and switchable dual-wavelength fiber laser in an all single-mode fiber cavity [9]. However, the comb filtering generated by the weak birefringent medium is highly dependent on the intracavity polarization state, which greatly limits the number of lasing wavelengths. A section of polarization maintaining fiber (PMF) is integrated into the NPR based laser to enhance the birefringent and generate comb filtering, then dual- and triple-wavelength DS can be obtained [10-11]. Nevertheless, it is not easy to control comb filtering and NPR effects at the same time. Alternatively, the all-fiber Lyot filter integrating two polarization-maintaining 45° tilted fiber gratings (PM-45°TFG) and a section of PMF, proposed by Zhijun Yan *et al.*, can be used as an integrated polarizing wavelength selector [12]. In such scheme, the integrated PM-45°TFG acts as a polarization maintaining in-fiber polarizer and provides sufficient polarization dependent loss (PDL) to realize effective NPR mode locking. More importantly, by using a PM-45°TFG, the filter can be more robust, compact when compared to use bulk polarizing beam splitter even sometimes these devices are fiberized. Using the comb spectrum generated by such Lyot filter, soliton Kelly sideband suppression [13-14] and 5-wavelength mode locking [15] are demonstrated in Er- or Tm-doped fiber laser. It is anticipated that such Lyot filter possess strong capability in multiwavelength DS generation in Yb-doped fiber laser.

In this work, a wavelength switchable DS mode-locked Yb-doped fiber laser by incorporating a PM-45°TFG based Lyot filter is firstly proposed and demonstrated. The Lyot filter composing of a section of PMF sandwiched between two PM-45°TFGs provides functions including both comb filter and polarizer, so that the proposed laser can generate DS pulse at 1035.26 nm, 1044.93 nm, 1055.62 nm, 1066.11 nm and 1076.63 nm, respectively. In addition, multi-wavelength mode locking has also been obtained when increasing the pump power. The operation wavelengths are simultaneously lasing at 1036.89 nm, 1046.74 nm, 1057.45 nm, 1068.18nm, 1079.41 nm and 1090.46 nm. Furthermore, due to the high nonlinearity in the cavity, the generated pulse with the repetition rate of 566.27 kHz has the *h*-like shape. The maximum output power can reach 32.7 mW. The comb filtering generated from this filter does not need rely on the intracavity polarization orientation. There is no doubt that this is a reliable and integrated component for designing multi-wavelength light sources.

2. Experimental setup

Two PM-45°TFG separated by a section of PMF with a special splicing angle, the Lyot filter, which is used in the experiment, can not only be used as a comb filter with an all-fiber structure, but also as an in-fiber polarizer. The 45°TFG structure is inscribed in the principal axis of PMF (slow-axis) by UV inscription using the phase mask scanning technique. More details of such all-fiber Lyot filter and PM-45°TFG fabrication have been reported in [16-17]. The schematic of the filter is given in Fig. 1(a). The first PM-45°TFG couples the TE polarization component out of the fiber and makes the TM polarization propagate in the fiber core to generate linearly polarized light [17]. The linearly polarized light is perfectly maintained when propagating in the PM fiber pigtail. Then the linearly polarized light accumulates a relative phase shift in PMF due to the designated splicing angle between PMF and PM-45°TFG. Finally, the relative phase shift converts to amplitude modulation in the second PM-45°TFG to generate comb filtering [18]. In order to get the maximum modulation depth of the comb filtering, the splicing angle between the axis of the two PM-45°TFG and PMF is designed to be 45°. The corresponding transmission spectrum of such all-fiber Lyot filter measured by a home-made broadband light source is depicted in Fig. 1(b). A 10.2 nm free spectral range (FSR) determined by the ~24 cm PMF is given in Fig. 1(b).

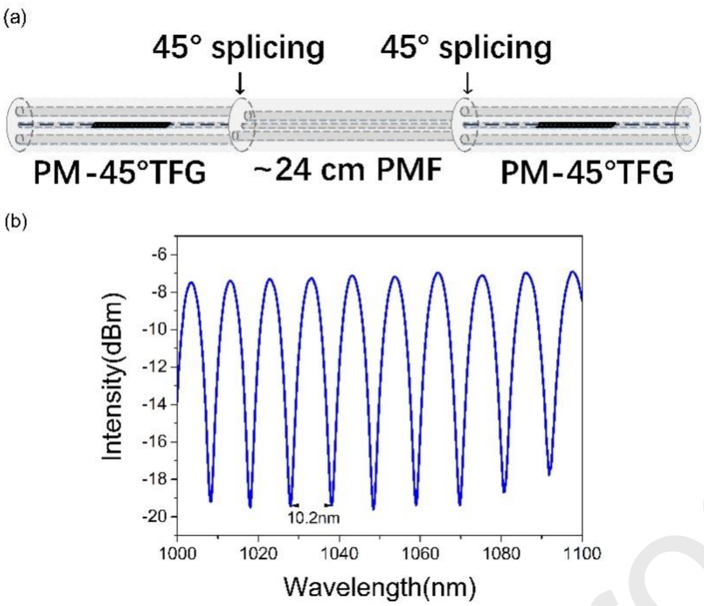


Fig. 1 The (a) schematic, (b) transmission spectrum of the PM-45°TFG based Lyot filter with ~24 cm PMF.

The experimental setup of the Yb-doped fiber laser designed for this experiment is shown in Fig. 2. A 96 cm Yb-doped fiber (YDF) is driven by a 980 nm bench-top pump source (Thorlabs CLD1015) through a wavelength division multiplexer (WDM). Then, 10% of the light is extracted out of the cavity by a 10:90 coupler. In order to make it easier to achieve multi-wavelength mode locking, ~350 m HI1060 is used to increase the intracavity nonlinearity. An all-fiber Lyot filter also delivers the function of a polarizer and is placed between two polarization controllers (PCs) to form an artificial SA to realize NPR mode locking. The filter provides an FSR of 10.2 nm, and the corresponding filtering bandwidth is 5.4 nm. Unidirectional operation of the laser is ensured by an isolator (ISO). The total cavity length is ~360 m, and all the intracavity fibers and components have normal dispersion.

The extracted 10% light is simultaneously measured to analyze the optical characteristics of the laser pulse. The laser spectrum is displayed by an OSA (Yokogawa AQ6370B). A photodetector (PD, Newport 818-BB-51F) is connected to a 40GSa/s oscilloscope (OSC, KEYSIGHT DSO90804A) to measure the output pulse sequence and a spectrum analyzer (SA, SIGLENT SSA3032X) to monitor the radio frequency (RF) response. And the autocorrelation trace is recorded by an autocorrelator (A.P.E PulseCheck600).

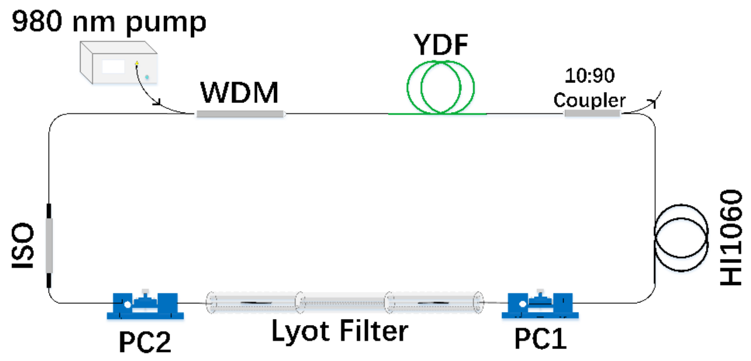


Fig. 2 Experimental configuration of the Yb-doped fiber laser.

3. Results and discussion

Until the pump power reaches the mode-locking threshold, the demonstrated laser operated in continuous wave (CW) state. By fine-tuning PCs as the pump power increases, stable mode-locked pulse sequence displayed on the OSC can be observed. While the ~350 m HI1060 provides sufficient nonlinearity, the mode-locking threshold is 69.2 mW. The characteristics of the generated pulse from the designed fiber laser are depicted in Fig. 3. Fig. 3(a) depicts the optical spectrum with 3 dB bandwidth of 3.21 nm at 1035.26 nm. From the figure, there is an un-mode-locked pulse at 1044.90 nm, which shows the wavelength selection characteristics of the filter. Fig. 3(b) is the spectrum in the range of 10 nm, which is steep-edge rectangle-like, that is, typical spectral feature of dissipative solitons. Here, stable mode-locking pulse sequence with a temporal interval of 1.77 μs is shown in the inset of Fig. 3(c), giving a frequency repetition rate of 566.27 kHz. Generally speaking, multi-pulses can be observed in a multi-wavelength mode-locked laser. In order to verify the mode locking without wave breaking induced by the un-mode-locked pulse at 1044.90 nm, the single-pulse waveform is given in Fig. 3(c). It must be mentioned here that the autocorrelation cannot scan the complete output pulse (duration over 200 ps) due to the dispersion introduced by the ~350 m delay line. The time-domain waveform is recorded from the OSC with a sampling rate of 40 GSa/s. Such OSC would be able to support direct observation of long pulse which is similar to an autocorrelator. The RF spectrum with a signal-to-noise ratio (SNR) of 39 dB is shown in Fig. 3(d). The inset shows the RF spectrum with a scanning span of 100 MHz and a resolution bandwidth (RBW) of 1 kHz without obvious spectral modulation, which further proves the stability of the single-pulse mode locking. The output average power under this pump power is measured to be 0.55 mW.

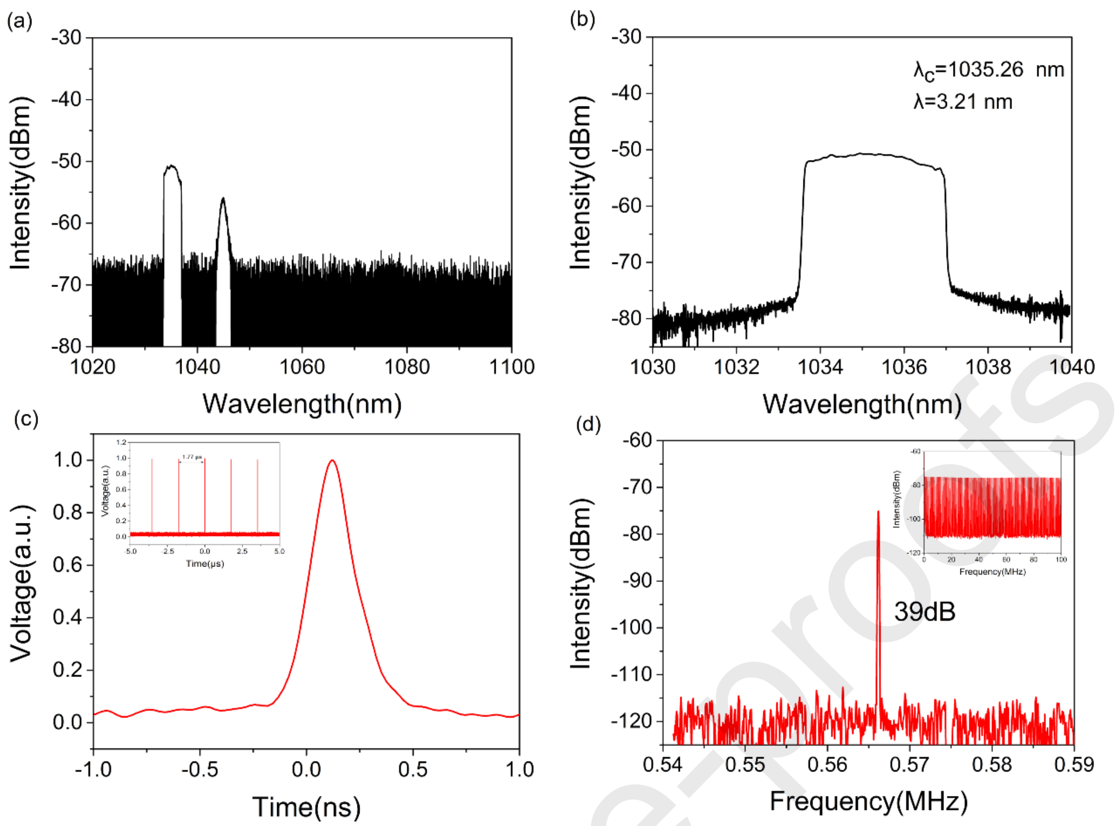


Fig. 3 Characteristics of dissipative-soliton pulses generated from the proposed fiber laser at 69.2 mW. (a) The optical spectrum in cover range of 80 nm. (b) The optical spectrum in cover range of 10 nm. (c) The pulse waveform. Inset, the pulse sequence. (d) The RF spectrum. Inset, RF spectrum with 100 MHz scanning span.

The wavelength switching operation of the laser can be observed by finely tuning PCs while keeping the pump power of 69.2 mW. These results are shown in Fig. 4(a). With the change of intracavity polarization orientation, the laser can operate at 1035.26 nm, 1044.93 nm, 1055.62 nm, 1066.11 nm, 1076.63 nm, respectively. At each wavelength, the laser maintains in the DS regime, which is shown in Fig. 4(b) - Fig. 4(f). Due to the uneven gain profile and the variation of polarization state at each wavelength, the edge-to-edge bandwidth of the spectra are slightly different. However, they are well matched the filtering bandwidth of the Lyot filter. The variation ranges of edge-to-edge bandwidth are from 3.4 nm to 4.75 nm and the average power varies from 0.55 mW to 0.7 mW, as presented in Fig. 5(a) and Fig. 5(b). It can be clearly seen from the figure, the DS pulse get the maximum gain at 1040 nm to 1070 nm, and the corresponding edge-to-edge bandwidth and output power obtain the larger values than the pulse at 1030 nm or 1080 nm. The mode locking at each wavelength can be maintained stable for more than 30 mins. When the pump power is increased after obtaining the mode-locking state, the spectrum tends to lose the shape of DS, and the pulses begin to split while the pump power is further increased more. However, once the pump power returns to 69.2 mW, the mode locking returns to single-pulse DS. This is a repetitive process.

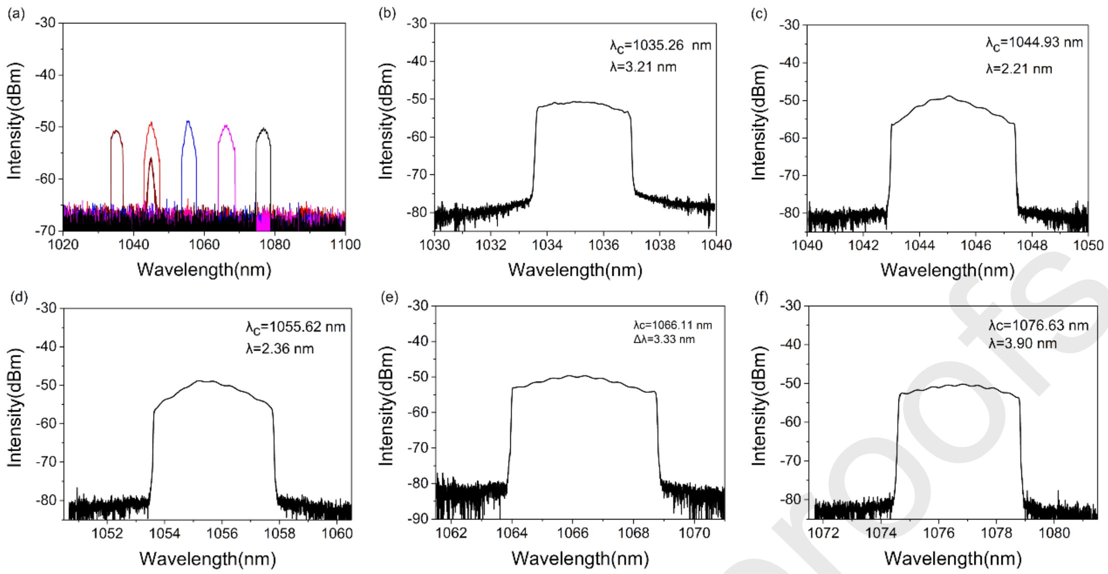


Fig. 4 Wavelength switching of single pulse DS. (a) The laser operates at different wavelength. (b) Center wavelength at 1035.26 nm, (c) 1044.93 nm, (d) 1055.62 nm, (e) 1066.11 nm, and (f) 1076.63 nm, respectively.

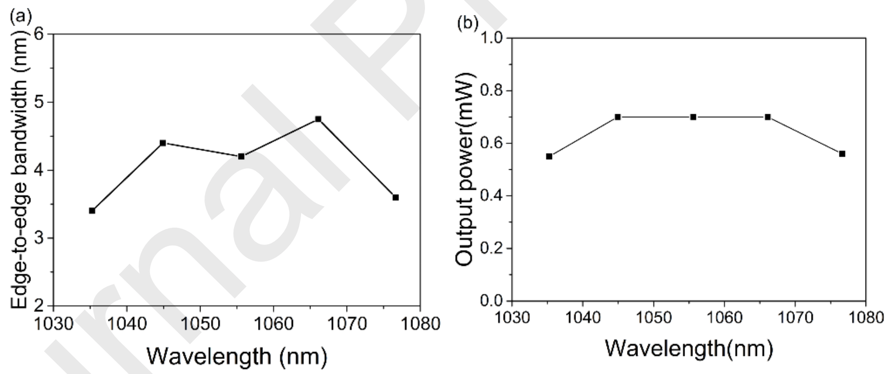


Fig. 5 Relationship of (a) edge-to-edge bandwidth, (b) output power at different center wavelength.

Further increasing the pump power to 430 mW while rotating the PCs, multi-wavelength mode locking can be achieved from the demonstrated laser. The output characteristic of the multi-wavelength operation is given in Fig. 6. The spectrum shown in Fig. 6(a) reveals the lasing wavelengths of 1036.89 nm, 1046.74 nm, 1057.45 nm, 1068.18nm, 1079.41 nm and 1090.46 nm. The spacing between the lasing wavelengths is approximately 10 nm, which agrees well with the FSR of the Lyot filter perfectly. The time-domain pulse sequence and the corresponding single pulse is exhibited in Fig. 6(b) and the inset respectively. The pulse sequence has the same repetition period of 1.77 μs as the single-wavelength mode locking, which matches the cavity length. The single pulse shows an h-like shape, which is normally generated from the laser cavity with high nonlinearity [19]. Meanwhile, it is also the results of the superposition of pulses from different wavelengths [15]. Fig. 6(c) depicts the RF spectrum with 50 kHz scanning range and 10 Hz RBW, revealing a 52 dB SNR and 566.27 kHz repetition rate. The broadband RF spectrum with 100 MHz span and 1kHz RBW given in Fig. 6(d), showing a slight periodic frequency modulation. The output power at this pump power is 19.03 mW. It is worth mentioning that such multi-wavelength mode locking can only be observed when the cavity length is long enough to provide sufficient nonlinearity. We also designed the frequency repetition rate of laser to the MHz scale, and such multi-wavelength mode locking has not been realized.

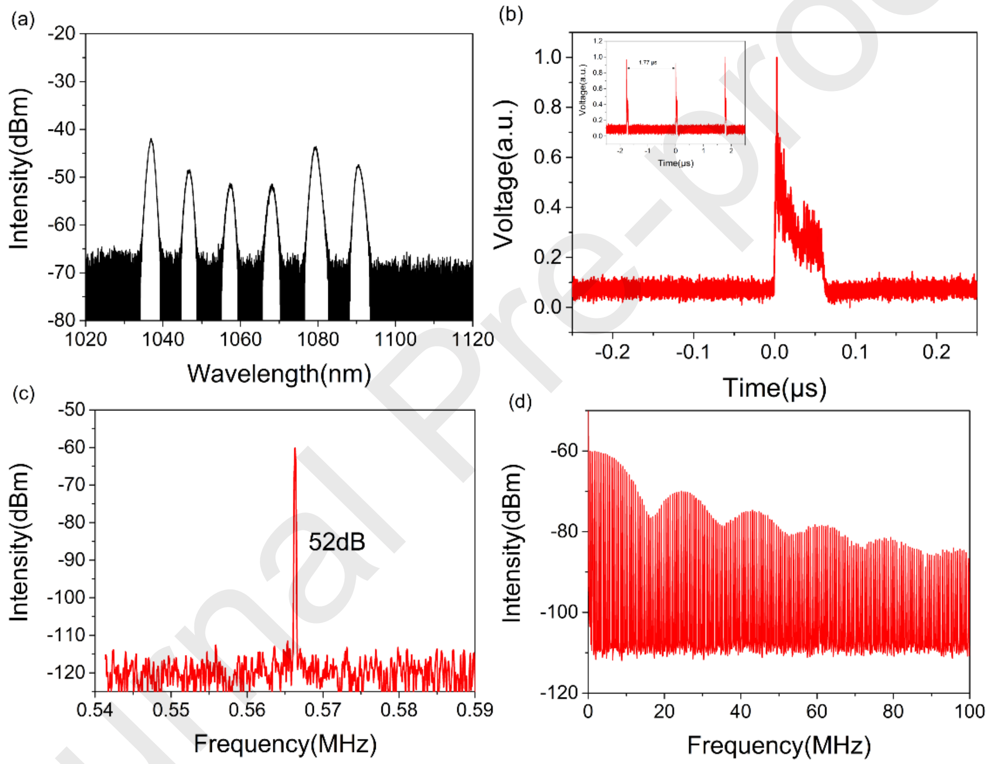


Fig. 6 Multi-wavelength mode locking with six lasing lines. (a) The optical spectrum. (b) The single pulse. Inset, the time-domain pulse sequence. (c) RF spectrum with 50 kHz span and 10 Hz RBW. (d) RF spectrum with 100 MHz span and 1 kHz RBW.

Once the laser enters the multi-wavelength mode-locked state, the mode-locked operation can be maintained within a larger range of pump power variation. To further study the effects of pump power on the multi-wavelength mode locking and *h*-shaped pulse, we change the pump power from 149 mW to 691 mW without any PCs rotation. In the time domain, the pedestal of *h*-shaped pulse is broadened continuously with the pump power enhancement, which is plotted in Fig. 7(a). However, there is no obvious change of wavelength number in the spectrum, only the intensity of the signal increases in Fig. 7(b). During this period, the mode-locking pulse sequence can be observed all the time. The average power varies from 2.6 mW to 32.7 mW, and the slope efficiency of 5.6% is given from Fig. 7(c). Without any disturbance, the multi-wavelength mode-locking laser can work steadily for more than 30 mins at the room temperature.

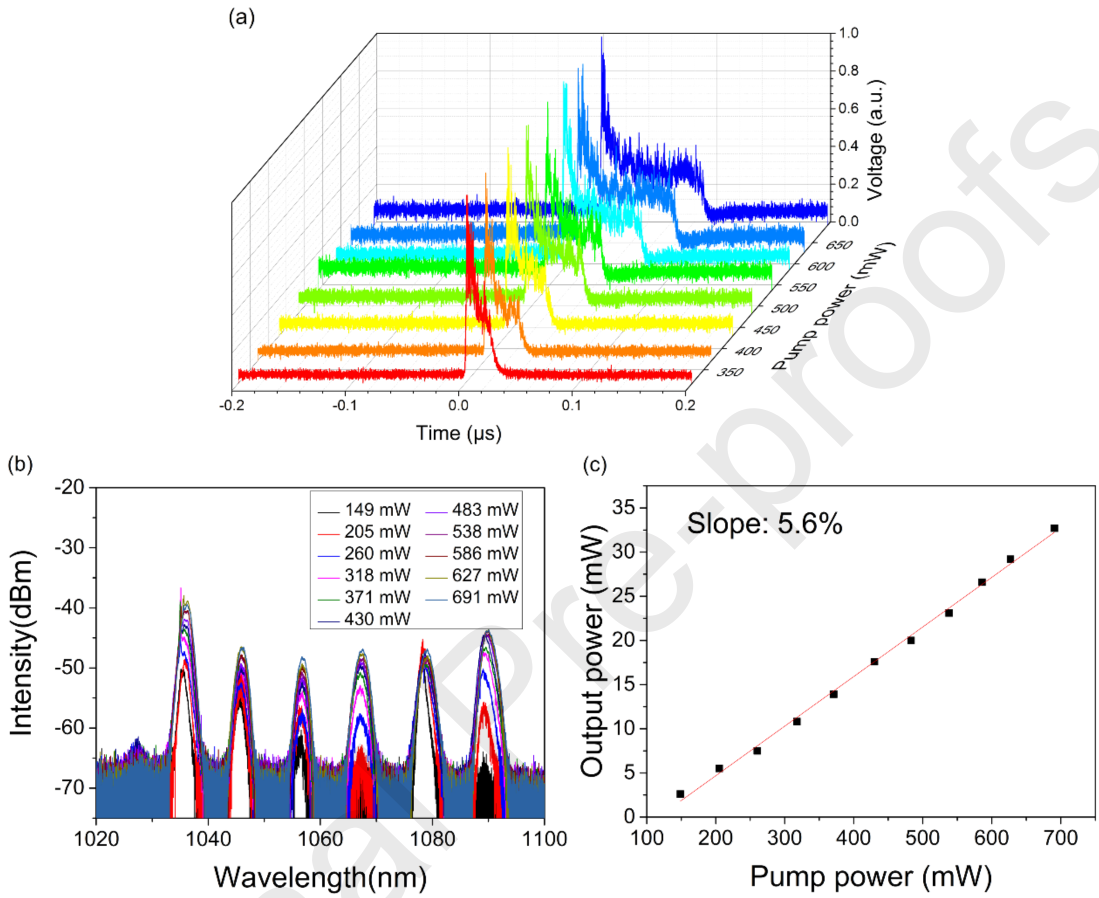


Fig. 7 The (a) single-pulse waveform, (b) spectrum, and (c) output power with the increasing of pump power.

4. Conclusions

In conclusion, we successfully incorporate an integrated all-fiber Lyot filter as an in-fiber polarizer and comb filter into the laser cavity. A single wavelength switchable DS and multi-wavelength mode-locked Yb-doped fiber laser has been demonstrated. When the pump power reaches the mode-locking threshold of 69.2 mW, stable DS pulse sequence with the repetition rate of 566.27 kHz are generated. The center wavelength of DS can be switched to 1035.26 nm, 1044.93 nm, 1055.62 nm, 1066.11 nm and 1076.63 nm respectively by rotating the PCs while keeping the pump power. In addition, multi-wavelength mode locking also can be obtained by increasing the pump power to 430 mW. The number of wavelengths for mode locking can reach up to 6-wavelength at the same time. The time-domain pulse has an h-shaped envelope, which is the result of high nonlinearity in the laser cavity. The corresponding SNR is 52 dB, and the max output power can reach 32.7 mW while the pump power is enhanced to 691 mW. However, the multi-wavelength mode locking is not in DS regime. For future work, such integrated Lyot filter can be applied to generate multi-wavelength DS mode locking. Furthermore, by optimizing the gain and loss in the cavity, multi-wavelength mode locking and single-wavelength switching with more wavelengths can be realized.

Acknowledgements

This work was supported in part by the National Natural Science Foundation of China under Grant 61975107, 62075071, 61605107, the Young Eastern Scholar Program at Shanghai Institutions of Higher Learning under Grant QD2015027, the “111” project (D20031). This work is also sponsored by Natural Science Foundation of Shanghai (20ZR1471500) and the open fund of Key Laboratory of Space Active Opto-electronics Technology, Chinese Academy of Sciences(2021-ZDKF-1).

References

[1] S. Huang, Y. Wang, P. Yan, J. Zhao, H. Li and R. Lin, Tunable and switchable multi-wavelength dissipative soliton generation in a grapheme oxide mode-locked Yb-doped fiber laser, Optics Express 22 (2014) 11417-11426.

[2] Z. Luo, A. Luo, W. Xu, H. Yin, J. Liu, Q. Ye and Z. Fang, Tunable Multiwavelength Passively Mode-Locked Fiber Ring Laser Using Intracavity Birefringence-Induced Comb filter, IEEE Photonics Journal 2 (2010) 571-577.

[3] H. Zhang, D. Tang, X. Wu and L. Zhao, Multi-wavelength dissipative soliton operation of an erbium-doped fiber laser, Optics Express 17 (2009) 12692-12697.

[4] M. Li, X. Zou, J. Qiu, W. Li, and W. Jian, Tunable Multi-wavelength Dissipative Soliton Generation in an Yb-doped Fiber Laser Based on SESAM and Lyot-Sagnac Filter, 2015 Opto-Electronics and Communications Conference (OECC) 2015 1-3.

[5] A. Sharbirin, M. Samion, M. Ismail and H. Ahmad, Ultrafast mode-locked dual-wavelength thulium-doped fiber laser using a Mach-Zehnder interferometric filter, Opto-Electronics Review 26 (2018) 312-316.

[6] X. Zhu, C. Wang, G. Zhang and R. Xu, Tunable dual- and triple-wavelength mode-locked all-normal-dispersion Yb-doped fiber laser, Applied Physics B

118 (2015) 69-73.

[7] M. Wang, Y. Huang, J. Yang, Y. Zhang and S. Ruan, Multi-wavelength mode-locked thulium-doped fiber laser based on a fiber-optic Fabry-Perot interferometer and a nonlinear optical loop mirror, Laser Physics Letters 15 (2018) 085110.

[8] L. Yun, X. Liu and D. Mao, Observation of dual-wavelength dissipative solitons in a figure-eight erbium-doped fiber laser, Optics Express 20 (2012) 20992-20997.

[9] H. Lin, C. Guo, S. Ruan, J. Yang, D. Ouyang, Y. Xu and L. Wen, Tunable and Switchable Dual-Wavelength Dissipative Soliton Operation of a Weak-Birefringence All-Normal-Dispersion Yb-Doped Fiber Laser, IEEE Photonics Journal 5 (2013) 1501807.

[10] Z. Zhang, Z. Xu and L. Zhang, Tunable and switchable dual-wavelength dissipative soliton generation in an all-normal dispersion Yb-doped fiber laser with birefringence fiber filter, Optics Express 20 (2012) 26736-26742.

[11] Z. Xu and Z. Zhang, All-normal-dispersion multi-wavelength dissipative soliton Yb-doped fiber laser, Laser Physics Letters 10 (2013) 085105.

[12] Z. Yan, C. Mou, H. Wang, K. Zhou, Y. Wang, W. Zhao and L. Zhang, All-fiber polarization interference filters based on 45°-tilted fiber gratings, Optics Letters 37 (2012) 353-355.

[13] Z. Yan, H. Wang, K. Zhou, Y. Wang, C. Li, W. Zhao and L. Zhang, Soliton mode locking fiber laser with an all-fiber polarization interference filter, Optics Letters 37 (2012) 4522-4524.

[14] J. Li, Y. Wang, H. Luo, Y. Liu, Z. Yan, Z. Sun and L. Zhang, Kelly sideband suppression and wavelength tuning of a conventional soliton in a Tm-doped hybrid mode-locked fiber laser with an all-fiber Lyot filter, Photonics Research 7 (2019) 103-109.

[15] M. Zou, Y. Ran, J. Hu, Z. Xing, Z. Yan, C. Liu, Q. Sun and D. Liu, Multiwavelength Mode-Locked Fiber Laser Based on an All Fiber Lyot Filter, IEEE Photonics Technology Letters 32 (2020) 1419-1422.

[16] Z. Yan, H. Wang, K. Zhou, Y. Wang, W. Zhao and L. Zhang, Broadband Tunable All-Fiber Polarization Interference Filter Based on 45° Tilted Fiber Gratings, Journal of Lightwave Technology 31 (2013) 69-73.

[17] Z. Yan, K. Zhou and L. Zhang, In-fiber linear polarizer based on UV-inscribed

45° titled grating in polarization maintaining fiber, Optics Letters 37 (2012) 3819-3821.

[18] K. Ozgoren and F. Ilday, All-fiber all-normal dispersion laser with a fiber-based Lyot filter, Optics Letters 35 (2010) 1296-1298.

[19] J. Zhao, L. Li, L. Zhao, D. Tang and D. Shen, Cavity-birefringence-dependent h-shaped pulse generation in a thulium-holmium-doped fiber laser, Optics Letters 43 (2018) 247-250.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: