Self-sweeping ytterbium-doped fiber laser based on a fiber saturable absorber

Zengrun Wen\textsuperscript{1,2,*}, Kaile Wang\textsuperscript{1,2,†}, Haowei Chen\textsuperscript{1,2}, Baole Lu\textsuperscript{1,2,*}, and Jintao Bai\textsuperscript{1,2,*}

\textsuperscript{1}National Key Laboratory of Western Energy Photonics Technology, International Joint Research Center on Photoelectric Technology and Functional Nanomaterials, Institute of Photonics & Photon-technology, Northwest University, Xi’an 710069, People’s Republic of China

\textsuperscript{2}Shaanxi Engineering Technology Research Center for Solid State Lasers and Application, Provincial Key Laboratory of Photo-electronic Technology, Northwest University, Xi’an 710069, People’s Republic of China

\textsuperscript{*}E-mail: lubaole1123@163.com; bajit@nwu.edu.cn

\textsuperscript{†}These authors contributed equally to this work.

Received July 24, 2020; revised December 9, 2020; accepted December 13, 2020; published online December 23, 2020

Generally speaking, the self-sweeping effect relies on the dynamical grating formed in active fiber. Here, the normal self-sweeping was generated in a ytterbium-doped fiber which serves as a fiber saturable absorber and is introduced to the laser cavity by a circulator in this experiment. The sweeping rate and the sweeping range alter as usual, both of which can be controlled by the pump power. Further, a new self-pulse signal is observed and discussed, which shows both the grating feature and saturable absorption of YDFSA. Our work provides a new self-sweeping way and can act as a platform to further deeply study this effect. © 2020 The Japan Society of Applied Physics

Tunable laser sources are widely used in a variety of applications such as optical communication, coherent beam combining and optical sensors.\textsuperscript{1–3} The proverbial methods that generate tunable light sources rely on the grating and band-pass filter. One of the special tunable sources is wavelength-sweeping fiber lasers, in which the central wavelength can be tuned periodically. To achieve the periodical and stable tuning operation, the scanning devices such as electric-driven PZT, heater or the scanning tunable filter have been utilized in the majority of modern lasers.\textsuperscript{4–10} In recent years, a kind of spontaneous sweeping fiber laser based on so-called self-sweeping or the self-induced laser line sweeping effect was found and deeply studied. The self-sweeping regime that a spontaneous, periodical, stable tuning running can be obtained by the spatial burning hole of the active medium in a stand-wave condition. In 2011, a self-sweeping fiber laser (SSFL) was reported in ytterbium-doped fiber (YDF) laser based on the non-Fabry–Perot cavity, which revealed a new wavelength-tunable phenomenon from shorter to longer wavelengths without tunable elements. Describing in detail the generation and annihilation in the self-sweeping regime later.\textsuperscript{11,12} SSFL reported only in YDF pushes the researcher to attempt in different doped fibers.\textsuperscript{13–15} Subsequently, neodymium-, bismuth-, erbium-, thulium-holmium-, holmium-, and thulium-doped fiber serve as active media, all of which can obtain the self-sweeping regime with broadly sweeping ranges.\textsuperscript{16–21} Besides, the SSFL with single frequency signals displays the remarkable features in the spectrum and intensity dynamics. Therefore, SSFLs have actively promoted the development of laser spectroscopy, spectrum of water absorption lines, the generation of ultra-short pulse and optical fiber sensor. Nowadays, the research on the self-sweeping effect has involved many phenomena. The sweeping direction can be defined by the normal self-sweeping and reverse self-sweeping in which the generated wavelength increases and decreases in the sweeping range, respectively.\textsuperscript{14} The SSFL laser in the linear cavity has produced multiple sweeping directions involving normal self-sweeping, reverse self-sweeping and a mixed state.\textsuperscript{22,23} The up-to-date bi-directional fiber ring lasers have reported for the generation of reverse self-sweeping effect in Tm and Yb active fiber.\textsuperscript{24,25}

The reported fiber lasers whatever in linear cavities or the bidirectional fiber ring cavities, the obvious dependence on self-sweeping effect on the standing-wave condition to allow us to make an attempt for forming a self-induced grating in fiber saturable absorber (FSA).\textsuperscript{26,27} In this Letter, we report a self-sweeping effect by generating a dynamic grating in YDFSA. A new self-pulse phenomenon is observed in temporal dynamic measurement, which reveals the building and duration of the dynamic induced grating. Besides, the fiber laser generates a normal sweeping with the largest coverage of 4.85 nm. These results will extend the knowledge and provide a new implementation method for the SSFL.

The schematic diagram of the proposed SSFL is illustrated in Fig. 1. The active medium is pumped by a 975 nm laser diode connected with a 975/1060 nm wavelength division multiplexer. In the present scheme, a 1 m long single-mode YDF (CorActive Yb 501) is used as the active medium. A circulator (CIR) is employed to introduce the 1.8 m YDFSA and fiber loop mirror (FLM). Besides, the CIR can ensure the unidirectional operation in the laser because of the high reverse isolation. The 20/80 coupler is served as the output coupler for measurement. The FLM consists of a 3 dB coupler whose two ports of output are spliced fusion. Note that this simple cavity cannot offer any narrowband wavelength elements. Therefore, the central wavelength is defined by the configuration of the cavity (active medium, wavelength and power of pump laser, intracavity losses and so on), in which the YDFSA underlies the new self-sweeping effect. The polarization controller (PC) in the cavity assures a better result in the experiment. The whole cavity length is measured at ∼7.1 m.

In our experiment, the self-sweeping phenomenon can be observed over the threshold pump power of 65 mW. With the increase of pump power, the self-sweeping of wavelength emerges spontaneously, and self-pulse is observed simultaneously. When the pump power is up to 260 mW, explosive chaotic spectrum born and self-pulse disappears immediately. In measurement, the output spectra are observed by the optical spectral analyzer (OSA Yokogawa, AQ6370C). Figure 2 shows the optical spectra information of the self-sweeping phenomena at a pump power of 180 mW. In Fig. 2(a), the spectra of laser at different times are exhibited, which have a high optical signal-to-noise ratio of more than 40 dB and a narrow linewidth of less than 0.034 nm. The
typical spectral dynamics is depicted in Fig. 2(b), in which the periodical normal sweeping of wavelength in the range of 4.83 nm with a rate of 0.24 nm s$^{-1}$ is recorded by the OSA in one point per second. The output power of the fiber laser is displayed in Fig. 2(c). Within the self-sweeping condition, the slope efficiency of 3.37% can be obtained through the linear fitting. Such a low slope efficiency can be attributed to the high absorption of two sections of YDF. Besides, with the pump power increases, the sweeping range varies like the parabola function [Fig. 2(d)]. The largest and narrow sweeping range that recorded by OSA are 4.85 nm and 1.5 nm, respectively. Such results can be achieved in a fixed state of PC. If we adjust the PC, the behavior of the self-sweeping effect changes. However, the results presented in this article are the best compared with the other states of the PC used in the measurement.

The temporal dynamics of the proposed fiber laser can be monitored by a detector (DET08CFC Thorlabs) and an oscilloscope (Tektronix DPO7254C). The intensity signal is displayed in Fig. 3. Figures 3(a) and 3(b) exhibit the pulse signal of stable self-sweeping at 100 mW and 220 mW, respectively. While the pump power is large enough, the unstable and chaotic temporal dynamics emerge, which are shown in Figs. 3(c) and 3(d). Consistent with all self-sweeping lasers, the stable self-sweeping running will be terminated with the emergence of disordered pulse signals [Figs. 3(c) and 3(d)]. In previous articles,13,28,29) the dynamics phase and gain gratings formed in an active medium. Owing to the laser running in the regimes of few longitudinal modes, the pulses are modulated with the inter-mode beating frequency and associated with self-sustained relaxation oscillation.12,24) Such a self-pulse regime exhibits regular microsecond pulses and irregular peak pulses. Differ from the microsecond self-pulsing signal, we observed a new self-pulse signal, as shown in Fig. 3(a), the pulse dynamical signal under the stable self-sweeping running exhibits...
periodicity and the continuous wave (CW) generates between the pulses.

In order to spell out these intensity dynamics, the variations of the average pulse repetition rate and the sweeping rate are summed up in Fig. 4(a), both of which increase with the increasing output power. When the pump power is increased, the average repetition rate increases from 1.5 to 2.7 kHz with a tendency of linear function versus the output power. At the same time, the sweeping rate increases from 0.145 to 0.284 nm s\(^{-1}\). One can see that the trend of pulse repetition rate is coincident with the sweeping rate, which manifests the change of central wavelength is synchronized with the reproduction of the pulse. The dynamics of longitudinal mode in the self-sweeping operation are depicted in Fig. 4(b). Note that the constant frequency change of \(~28.2\) MHz also can be calculated at any different output power by the average pulse repetition rate and the sweeping rate. Besides, the interval between pulses (the reciprocal of repetition rate) can be related to the lifetime of dynamic gratings according to the experiment of two-wave mixing, in which the relaxation rate of recording grating in the Yb-doped fiber reduces with an ascending input power.\(^{30}\) Therefore, the interval of the pulse also embodies the grating features.

Figure 5 exhibits the intensity dynamics of the fiber laser at a pump power of 90 mW by another oscilloscope (Agilent technologies DSO9104A) with a high resolution. Figures 5(a) and 5(b) shows the large time scale and the small-time scale, respectively. The strong modulation is depicted in Fig. 5(b), on which we can see the detail of beating frequency with a repetition rate of \(~28.57\) MHz that corresponds with the laser cavity. The RF spectra of fiber laser are depicted in the insets of Fig. 5(c). The fiber laser generates two longitudinal modes within the duration of the pulse. At the generation of CW, the fiber laser only generates the single-frequency signal. Figure 5(c) also reveals the observed single temporal pulse of this fiber laser in a small time window. The duration time is 37.17 \(\mu\)s at the pump power of 90 mW. We can see that the laser output before and after the duration of the pulse signal is CW, namely, the laser frequency is changed during the signal duration. Further, the duration of the pulse signal can be considered as the building time of dynamics induce gratings in the YDFSA. The moment of frequency change is accompanied by strong modulation (interference). The tail of the pulse still depicts the intensity oscillation obviously, which corresponds to the variation of photo density that we provide in Fig. 5(d). The photon density of our fiber laser is depicted in Fig. 5(d) which explains the damped pulse dynamics in simulation. In our experiment, the pulse represents the transformation of central frequency, on which the previous grating vanishes and the next grating builds. In other words, the upper-level particles that build the previous

---

**Fig. 3.** (Color online) The intensity dynamics of fiber laser. (a) Stable self-sweeping operation at a pump power of 100 mW. (b) Stable self-sweeping operation at a pump power of 220 mW. (c) Unstable self-sweeping operation at a pump power of 260 mW. (d) Chaotic spectrum running at a pump power of 300 mW.

**Fig. 4.** (Color online) (a) The change of repetition rate and sweeping rate as the increased output power. (b) Qualitative description of longitudinal-mode dynamics in self-sweeping operation.
grating have reached the end of their lives while the YDFSA absorbs other photons and build the next grating. In the process of frequency change, the formation of the induced grating in the YDFSA plays an important role. When the previous grating builds, the operating wavelength in the cavity may not go through the YDFSA completely, which leads to the cavity length decreasing and single-longitudinal-mode output generates. With time going on, the previous grating disappears due to the lifetime of upper-level particles. At this time, the next longitudinal mode with peak gain goes through the YDFSA to build its own grating. When the next grating is formed gradually, the reflected light amplifies in gain medium and the YDFSA absorbs the light to sustain the newly-built grating based on the saturable absorption characteristics. In this case, only considering the YDF as the saturable absorber, we simulate the photon density of laser to explain the damped pulse of intensity dynamics by the rate equation below.

$$\frac{d\phi}{dt} = \frac{\sigma}{\tau_e} \left[ 2\sigma_a n_s l_s - 2\sigma_{gs} \left( n_{g0} - n_{gs} - \left( n - \frac{1}{R} + \delta \right) \right) \right],$$ \hspace{1cm} (1)

$$\frac{dn}{dt} = R_p(t) \left( 1 - \frac{n}{N_0} \right) - \gamma \sigma a c \phi n - \frac{n}{\tau_a},$$ \hspace{1cm} (2)

$$\frac{dn_{gs}}{dt} = \frac{n_{g0} - n_{gs}}{\tau_{gs}} - \sigma_{gs} c \phi n_{gs}.$$ \hspace{1cm} (3)

The corresponding parameters: photon density $\phi$, inverted population density of gain fiber $n$, saturable absorber ground state particle density $n_{gs}$, saturable absorber excited state particle number density $n_{ex}$, saturable absorber total particle number density $n_{tot}$, emission cross-section of gain fiber $\sigma$, length of gain fiber $l$, ground-state absorption cross-section of saturable absorber $\sigma_{gs}$, saturable absorber excited-state absorption cross-section $\sigma_{ex}$, saturable absorber total length $l$, output ratio $R$, laser cavity loss $\delta$, cavity optical period $i$, inversion factor $\gamma$, the pumping rate $R_p(t)$, the total population density of the gain fiber $N_0$, the upper energy level lifetime of the gain $\tau_a$, and the recovery time of the saturable absorber $\tau_{gs}$. The Fourth-order Runge–Kutta method can be used to obtain the numerical solution. Using the parameters of our cavity at a low pumping rate, we can obtain the results in Fig. 5(d). The low absorption at 1070 nm of YDF and the long lifetime of the upper particle of $\sim 0.83$ ms at 1070 nm leads to the laser settles down the stable operation. \cite{31} Therefore, the entire process of intensity dynamics shows both features of YDFSA and grating. As for the self-sweeping in active fiber, the population density of the upper level was excited by signal light and pump light. The whole population of the upper level devotes to the light amplification which expands the

Fig. 5. (Color online) (a) The intensity dynamics of fiber laser at 90 mW. (b) The zoomed picture at a small-time scale. (c) Intensity dynamics of single interference signal at the pump power of 90 mW. (d) The CW operation at low population density and long decay time of SA.
population of absorber state and further cuts down the lifetime of the dynamic grating.

In summary, the effect of self-sweeping was observed in a fiber laser with a YDFSA. The damped pulse can be measured when the fiber laser operating in the self-sweeping regime, which reveals a different drive model of the wavelength self-sweeping effect. The change of laser frequency depends on the dynamics induced grating produced by the light interference in YDFSA. The repetition rate shows that the intensity dynamics show the grating characteristics of FSAs and promote the development of self-sweeping in fiber lasers.

Acknowledgments This work supported by the National Natural Science Foundation of China (61905193); National Key R&D Program of China (2017YFB0405102); the Key R & D project of Shaanxi Province-International Science and Technology Cooperation Project (No. 2020KW-018).

1) H. Lin, L. Ma, Y. Hu, Z. Hu, and Q. Yao, Opt. Lasers Eng. 51, 822 (2013).
2) T. N. Huynh, F. Smyth, L. Nguyen, and L. P. Barry, Opt. Express 20, B244 (2012).
3) H. Al-Taiy, N. Wenzel, S. Preu/ller, J. Klinger, and T. Schneider, Opt. Lett. 39, 5526 (2014).
4) R. R. Drobyshev, I. A. Lobach, E. V. Podivilov, and S. I. Kablukov, Opt. Express 27, 21335 (2019).
5) K. Fukushima, Q. H. Bui, K. Nakaya, M. G. Soares, A. Wada, S. I. Tanaka, and F. Ito, Opt. Express 28, 13081 (2020).
6) M. R. Majewski, R. I. Woodward, and S. D. Jackson, Laser Photonics Rev. 14, 1900195 (2020).
7) R. I. Woodward, M. R. Majewski, D. D. Hudson, and S. D. Jackson, APL Photonics 4, 020801 (2019).
8) J. U. Kang and K. Zhang, Opt. Express 16, 14173 (2008).
9) C. M. Eigenwillig, W. Wieser, S. Todor, B. R. Biedermann, T. Klein, C. Jirauschek, and R. Huber, Nat. Commun. 4, 1848 (2013).
10) C. Jirauschek, B. Biedermann, and R. T. Huber, Opt. Express 17, 24013 (2009).
11) A. V. Kir’yanyov and N. N. ‘Il’ichev, Laser Phys. Lett. 8, 305 (2011).
12) I. A. Lobach, S. I. Kablukov, E. V. Podivilov, and S. A. Babin, Opt. Express 19, 17632 (2011).
13) I. A. Lobach, S. I. Kablukov, E. V. Podivilov, and S. A. Babin, Laser Phys. Lett. 11, 045103 (2014).
14) P. Navratil, P. Peterka, P. Honzatko, and V. Kubecek, Laser Phys. Lett. 14, 035102 (2017).
15) I. A. Lobach, A. Y. Tkachenko, and S. I. Kablukov, Laser Phys. Lett. 13, 045104 (2016).
16) E. K. Kashirina, I. A. Lobach, and S. I. Kablukov, Opt. Lett. 44, 2252 (2019).
17) I. A. Lobach, S. I. Kablukov, M. A. Melkumov, V. F. Khopin, S. A. Babin, and E. M. Dianov, Opt. Express 23, 24833 (2015).
18) P. Navratil, P. Peterka, P. Vojtisek, I. Kasik, J. Aubrecht, P. Honzatko, and V. Kubecek, Opto-Electron. Rev. 26, 29 (2018).
19) X. Wang, P. Zhou, X. Wang, H. Xiao, and L. Si, Opt. Express 21, 16290 (2013).
20) J. Aubrecht, P. Peterka, P. Koška, O. Podražký, F. Todorov, P. Honzatko, and I. Kasík, Opt. Express 25, 4120 (2017).
21) A. E. Budarnykh, A. D. Vladimirkaya, I. A. Lobach, and S. I. Kablukov, Opt. Lett. 43, 5307 (2018).
22) A. E. Budarnykh, I. A. Lobach, and S. I. Kablukov, Laser Phys. Lett. 16, 025108 (2019).
23) P. Peterka, P. Navratil, J. Maria, B. Dussardier, R. Slavik, P. Honzatko, and V. Kubecek, Laser Phys. Lett. 9, 445 (2012).
24) H. B. Jiang, Z. H. Zhao, L. Jin, S. Y. Set, and S. I. Yamashita, Appl. Phys. Express 12, 042006 (2019).
25) K. L. Wang, Z. R. Wen, H. W. Chen, X. Y. Qi, B. L. Lu, and J. T. Bai, Opt. Express 28, 13913 (2020).
26) S. Stepanov, J. Phys. D: Appl. Phys. 41, 224002 (2008).
27) J. Liu, L. Zhan, L. Zhang, M. Qin, Z. Wang, and Z. J. Zou, Opt. Soc. Am. B 32, 1113 (2015).
28) P. Peterka, P. Koška, and J. Čtyroký, IEEE J. Sel. Top. Quantum Electron. 24, 0902608 (2018).
29) P. Peterka, P. Honzatko, P. Koska, F. Todorov, J. Aubrecht, O. Podražký, and I. Kasík, Opt. Express 22, 30024 (2014).
30) S. Stepanov, A. A. Potiadi, and P. Mégret, Opt. Express 15, 8832 (2007).
31) D. Marcuse, IEEE J. Quantum Electron. 29, 2390 (1993).