This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSTQE.2020.3012667, IEEE Journal of Selected Topics in Quantum Electronics

Microfiber-based polarization beam splitter and its application for passively mode-locked all-fiber laser

Xiabing Zhou, Mingwei Qiu, Yuhao Qian, Mengmeng Chen, Zuxing Zhang, Lin Zhang

***Abstract*—Nonlinear polarization evolution based on polarization beam splitter (PBS) is a classical technique for passive mode-locking of fiber lasers. Different from commonly used bulky PBS, in this paper all-fiber PBSs composed of two parallel coupled microfibers have been proposed and fabricated under the condition of appropriate microfiber diameter and coupling length. Using our fabricated microfiber PBSs, passively mode-locked all-fiber lasers have also been demonstrated. The results indicate that the microfiber-based PBS has advantages of simple fabrication, compact size, and most importantly, variable polarization extinction ratio and operation bandwidth. The all-fiber mode-locked lasers with the microfiber PBSs generating stable pulses at both 1.0 µm and 1.5 µm wavelength bands have comparable performance with their counterparts based on bulky PBSs. It may be a step towards true all-fiber mode-locked laser and other all-fiber systems.**

***Key words*—polarization beam splitter, nonlinear polarization evolution, mode-locked fiber laser**

I. Introduction

OPTICAL polarization beam splitter (PBS) is an indispensable optical component that can separate light power in two orthogonal polarizations, and plays an important role in polarization multiplexed transmission, coherent optical communication and interference-based optical sensor systems [1]. The previous reported PBSs have relatively complex structures, such as directional couplers, multimode interferometers, photonic crystals and Mach-Zehnder interferometers [2]. The commercially available PBSs with fiber pigtails are mounted with tiny polarization beam splitting prisms, which strictly speaking are not of all-fiber. The demonstrated special-fiber-based PBSs belong to all-fiber polarization device [3-5], but nonetheless, they require sophisticated fabrication process and are not fully compatible with the existing fiber-based systems. Therefore, it is still a challenge to design a simple and feasible all-fiber-based device that can achieve flexible polarization beam splitting function.

Passively mode-locked fiber lasers with simple and compact configuration have attracted considerable interests due to their suitability for ultrafast pulse generation, which have been widely applied into telecommunication systems, material processing, nonlinear optics, and so on [6]. For a passively mode-locked fiber laser sustaining optical pulse formation against continuous-wave (CW) lasing, the underlined mechanism is intensity-dependent saturable absorption [7]. It may utilize the nonlinear absorption characteristics of optical materials and devices, including commercial semiconductor saturable absorber mirrors (SESAMs) [8, 9], and one-dimensional (1D) [10] and two-dimensional (2D) layered materials (graphene, MoS_2, WS_2) [13-[16]. However, these real saturable absorbers suffer from complicated preparation processes and relatively low damage threshold. Contrastively, artificial saturable absorbers utilizing nonlinear switching effect, such as the nonlinear polarization evolution (NPE), nonlinear optical loop mirror (NOLM) [17] and nonlinear amplifying loop mirror (NALM) [18], have relatively high optical power tolerance, broad operating wavelength range, and fast response time. The basic principle is to discriminate the intensity of light and favor (attenuate) the transmission of higher (lower) intensity light. Recently, nonlinear mode interference in single mode fiber (SMF)-multimode fiber (MMF)-SMF structures has also been employed for achieving mode-locking [[19]-[22][22]. But the length of the used MMF should be precisely controlled in the order of the self-imaging distance (micrometers), which is very difficult in practice.

NPE is a classical technique for passive mode-locking of fiber lasers and has been widely promoted, through simply incorporating an optical polarizer or a polarization sensitive isolator into a ring-cavity fiber laser [23]. Actually, NPE mode-locking method can be enforced, as long as the intensity-dependent transmission effect in laser cavity induced by polarization dependent loss (PDL) is sufficiently large [24]. An all-fiber NPE mode-locked fiber laser has been demonstrated using a 45 degree tilted grating as an in-fiber polarizer with PDL of 30 dB [25]. However, the fabrication of

Manuscript received xxxx. This work is supported by National Natural Science Foundation of China (91950105); Science and Technology Innovation Training Program (SZDG2019014); Nanjing University of Posts and Telecommunications Talents (NY214002, NY215002); 1311 talent plan of Nanjing University of Posts and Telecommunications. (Corresponding authors: zxzhang@njupt.edu.cn, chenmm@njxzc.edu.cn)

Xiabing Zhou, Mingwei Qiu, Yuhao Qian, and Zuxing Zhang are with the Advanced Photonic Technology Lab, College of Electronic and Optical Engineering & Microelectronics College, Nanjing University of Posts and Telecommunications, Nanjing 210023, China.

Mengmeng Chen is with School of Electronic Engineering, Nanjing Xiaozhuang University, Nanjing 211171, China.

Lin Zhang is with Aston Institute of Photonic Technologies, Aston University, Birmingham B4 7ET, UK.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSTQE.2020.3012667, IEEE Journal of Selected Topics in Quantum Electronics

the 45-degree tilted fiber grating with such performance is not trivial. The micro-fiber polarizer composing of two pieces of partly overlapped microfibers was proposed and demonstrated for the mode-locking of fiber lasers [26], but the polarizer fabrication involves rather delicate manipulation of equal length cleaving and exacting stacking of the fiber.

In the work reported in this paper, an all-fiber PBS composed of two parallel coupled microfibers has been proposed and fabricated, through controlling the diameter of microfibers and the coupling length. In addition to the simple fabrication and compact size, the microfiber PBS has advantages of variable polarization extinction ratio and operation bandwidth. In substitution of bulky PBS with our fabricated microfiber PBSs, passively mode-locked all-fiber lasers at both 1.0 μm and 1.5 μm have demonstrated comparable performance with their counterparts.

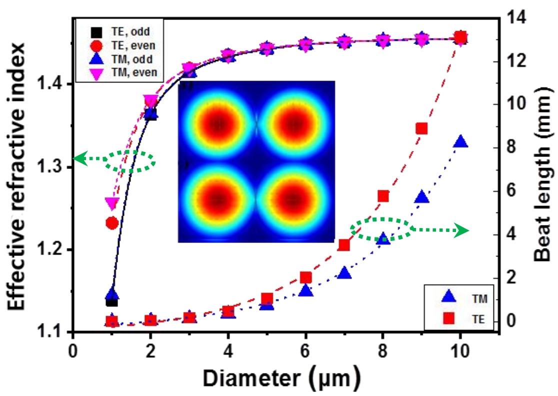

Fig. 1. Effective refractive index of TE (TM) odd (even) mode and beat length of TE mode and TM mode versus microfiber diameter; insets are field profiles of TM (above) and TE (below) even modes.

II. PBS Principle and Fabrication

The proposed microfiber-based PBS has a similar structure to a common optical fiber coupler with two parallel and clinging microfibers, which can be regarded as a new composite waveguide. According to the supermode theory [27], the optical coupling phenomenon can be interpreted as the interference of symmetrical and antisymmetrical supermodes in the composite waveguide. Considering there exist two different polarization states (TE and TM modes), each has a symmetrical supermode (even mode) and an antisymmetrical supermode (odd mode). They have different propagation constants $\beta_{(TE,even)}(\beta_{(TM,even)})$ and $\beta_{(TE,odd)}(\beta_{(TM,odd)})$, and corresponding effective refractive indexes $n_{eff}^{(TE,even)}(n_{eff}^{(TM,even)})$ and $n_{eff}^{(TE,odd)}(n_{eff}^{(TM,odd)})$, respectively. By full vector finite element method, the effective refractive indexes (ERIs) of the four supermodes were firstly calculated with respect to the diameter of the two identical microfibers for the diameter size varying from 1 to 10 μm. The results shown in Fig. 1 indicate that the ERIs decrease as the microfiber diameter decreases, while the ERI difference between TE and TM modes increases. The half beat length $L_{TE(TM)}$ of the TE(TM) mode is defined as the coupling distance through which TE(TM) light entering from one input port will be completely coupled to the cross output port, when the accumulated phase difference between even and odd supermodes reaches π. According to the ERIs, the beat length of TE(TM) can be obtained from the formula shown below [28]:

$$L_{TE(TM)} = \frac{2\pi}{[\beta(\lambda)_{i,even}-\beta(\lambda)_{i,odd}]} = \lambda/[\mathbf{n}(\boldsymbol{\lambda})_{\mathbf{eff}}^{\mathbf{i,even}} - \mathbf{n}(\boldsymbol{\lambda})_{\mathbf{eff}}^{\mathbf{i,odd}}] \quad (1)$$

where i indicates TE(TM) status. From the relation between the beat length of the TE(TM) mode and the microfiber diameter shown in Fig. 1, it is seen that the beat lengths of both modes and their beat length difference increase with the increase of the microfiber diameter. Also, the beat length of TM mode is shorter than that of TE mode under the same microfiber diameter. This stems from the stronger coupling effect of TM mode, which can be deduced from the larger distortion of the TM even mode than that of the TE even mode, as their field profiles shown in the inset of Fig. 1. Under the circumstances that the length of the coupling region is odd multiple of the half beat length of TE(TM), TE(TM) light will be fully coupled from one fiber to another. But if the coupling length is even multiple of the half beat length, TE(TM) light will return from another fiber to the original fiber. Therefore, only when the coupling zone length Lc is odd (even) multiple of half beat length of TE mode and even (odd) multiple of half beat length of TM mode at the same time, TE and TM light will enter the two different output terminals at the end of the coupling region to achieve desirable polarization effect. This is polarization beam splitting condition for the microfiber-based PBS.

In order to furthermore verify the polarization beam splitting feasibility of the proposed microfiber-based PBS, the characteristics of the PBS were simulated by three-dimensional full vector beam propagation method. The background refractive index and cladding refractive index are set to 1 and 1.46, respectively. The microfiber diameter and parallel coupling length are chosen to be 8.87 μm and 12.26 mm based on the polarization beam splitting condition, respectively. Two symmetrical curved waveguides are added at the end of the two microfiber outputs to observe the polarization beam splitting phenomenon. The simulated results are shown in Fig. 2. It can be clearly seen from the figure that the light is mostly output from the left-side waveguide in the case of TM-polarized light input, as shown in Fig. 2(a). On the contrary, the light is output from the right-side waveguide when the input light is TE polarized, as shown in Fig. 2(b). Not all TM (TE) mode polarized light is output from the left (right), because there is also slightly intercoupling at the bending waveguide parts.

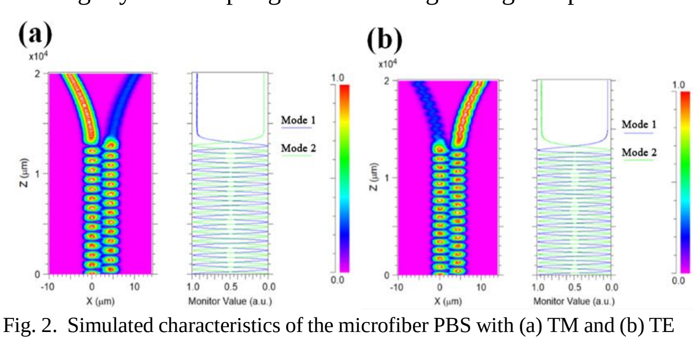

Fig. 2. Simulated characteristics of the microfiber PBS with (a) TM and (b) TE polarized input light.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSTQE.2020.3012667, IEEE Journal of Selected Topics in Quantum Electronics

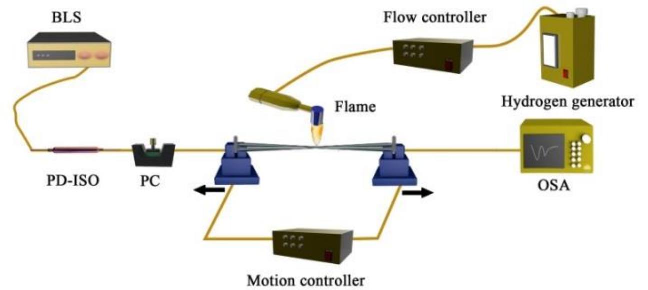

Fig. 3. Schematic diagram of the microfiber PBS fabrication experiment setup.

The fabrication process of the microfiber-based PBS, like that of common fiber coupler, is required to ensure the diameter and gradient region of the two microfibers are exactly the same, so as to maximize the coupling efficiency. But the coupling length should be optimized to satisfy the condition of polarization beam splitting. Here, online measured polarization extinction ratio (PER) of the fabricated device is employed to control the pulling length. Schematic diagram of the microfiber PBS fabrication experiment setup is illustrated in Fig. 3. A broadband light source (BLS) with wavelength range from 1250 nm to 1650 nm (for 1.5 μm PBS) or 480 nm to 2200 nm (for 1.0 μm PBS) is used as the light source for device characterization. A polarization-dependent isolator (PD-ISO) is utilized to convert input light into linearly polarized light. A polarization controller (PC) is followed for adjusting the polarization orientation of the linearly polarized light before it enters the fabricated device. The transmission spectrum of the fabricated device is measured by an optical spectrum analyzer (OSA) with a 0.02 nm resolution.

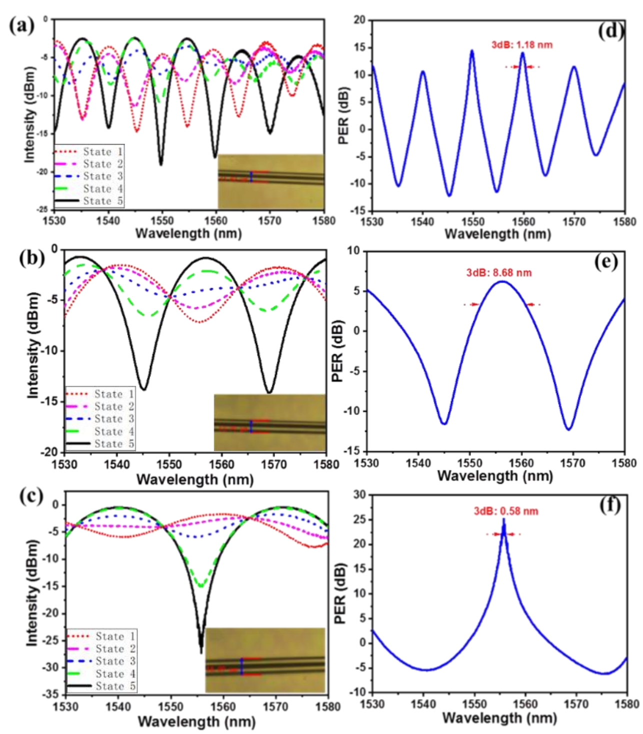

Fig. 4. (a)-(c) The transmission spectra under different polarization states of three PBS samples at 1.5 μm band, (d)-(f) their corresponding PER spectra. Insets in (a)-(c) are the microscopic photographs of the three samples.

For the fabrication of the PBS, two single mode fibers (SMFs) are aligned together and fused directly using the modified flame brushing technique. Two microfibers with the same diameter used for coupling are made by pulling two SMFs under the flame at the same time. When the diameter of the microfibers is drawn to the order of several tens of microns, the two fibers naturally stick together because of the action of van der Waals and electrostatic forces to form a coupling region consisting of two parallel microfibers. To ensure the prepared device meets the polarization beam splitting condition, the pull machine is manually operated step by step at the final pulling stage, as the PER is measured online for reference. The pulling process is terminated until a suitable PER is obtained. After simple and noncontact package with thin glass slot, the microfiber PBS is ready for use. Three microfiber PBSs at 1.5 μm wavelength band with different geometric parameters were fabricated and characterized in the experiment.

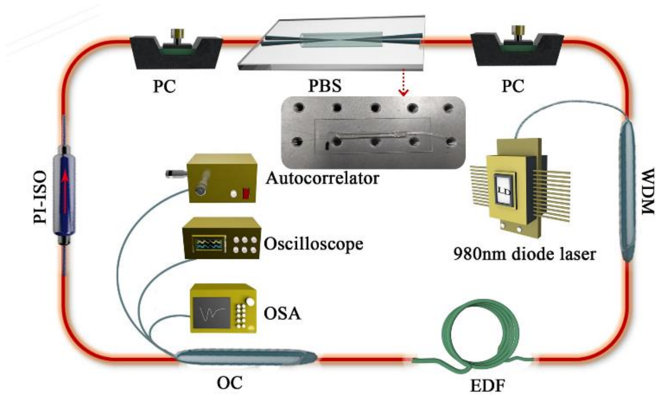

Fig. 5. Schematic of the all-fiber passively mode-locked EDF laser with microfiber PBS. Inset is the fabricated PBS with simple encapsulation.

The fabricated PBSs present relative low insertion loss of only ~3 dB. By adjusting the polarization orientation of the injected linearly polarized light with the PC, the transmission spectra of three samples under different polarization states are shown in Figs. 4(a)-(c), respectively. The corresponding PER spectra, which are the intensity difference between maximum and minimum transmission spectra across all possible polarization states, are shown in Figs. 4(d)-(f) respectively. Take sample 1 as an example, the PER is 14.1 dB at wavelength of 1559.7 nm, with a 3-dB bandwidth of 1.18 nm. For samples 2 and 3, the PERs are 6.3 dB at wavelength of 1556.2 nm and 25.23 dB at wavelength of 1555.7 nm, and the 3-dB bandwidths are 8.68 nm and 0.58 nm, respectively. The microfiber diameters of the three samples are ~5.9 μm, ~6.9 μm and ~8 μm, and the coupling lengths are ~23.1 mm, ~16.2 mm and ~10.3 mm respectively, evaluated from the microscopic photographs of the three samples shown in the insets of Figs. 4(a)-(c). It is obvious that the PER spectrum is closely related to the specific parameters of the microfiber polarizer, such as the microfiber diameter and coupling length. It should be noted that the PER variation with respect to wavelength seems periodic for all the three samples, and the periods are ~10.1 nm, ~27.9 nm, ~31.4 nm, respectively. This is because slightly fused coupler exhibits

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSTQE.2020.3012667, IEEE Journal of Selected Topics in Quantum Electronics

remarkable birefringence, due to the asymmetric cross section and the relatively large refractive index difference between TM and TE supermodes [29], 30]. Moreover, the birefringence becomes larger with the decrease of the microfiber diameter. Thus, the oscillation period of PER with respect to wavelength becomes small as the microfiber diameter decreases. The experimental results are consistent with this physical law.

III. MODE-LOCKING OF FIBER LASERS

In principle, any microfiber PBS with suitable PER can be used for passively mode-locking of fiber laser based on NPE. Here, sample 1 was adopted for the mode-locked erbium-doped fiber laser experiment. Figure 5 shows the all-fiber passive mode-locked laser configuration using the NPE technique based on the microfiber PBS. The laser cavity contains a 980/1550 nm wavelength division multiplexer (WDM), a 2.3-m long erbium-doped fiber (EDF) as gain medium, a fused optical coupler (OC) with 10% output, a polarization insensitive isolator (PI-ISO) to ensured unidirectional operation, two polarization controllers (PCs) and the microfiber-based PBS replacing the conventional bulky optical polarizer or PBS.

All the fibers utilized in the ring cavity are SMF-28e fiber with a dispersion parameter D of 17 ps/(nm•km), except the 2.3-m EDF with a dispersion parameter D of −48 ps/(nm•km). The total length of the cavity is 28.1 m, corresponding to a 7.39 MHz fundamental frequency, the net cavity dispersion is around -1.26 ps^2. The coupling length of our PBS is actually very short, only about 1 cm, which is much smaller than the cavity length of the laser. The nonlinearity introduced by the microfiber may be negligible. Of cause, the issue is worthy of further investigation. Stable mode-locking operation is readily achieved as the pump power is over the mode-locking threshold of about 140 mW.

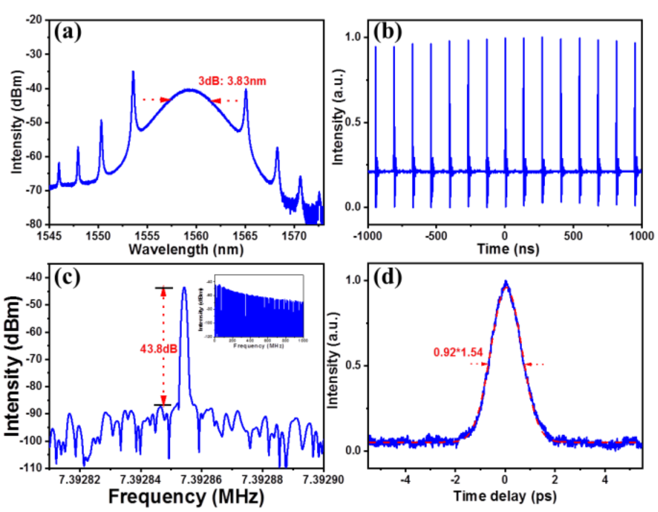

Fig. 6. Output characteristics of the mode-locked fiber laser with microfiber PBS at 1.5 μm: (a) Optical spectrum, (b) pulse train, (c) radio frequency spectrum, (d) autocorrelation trace.

The typical characteristics of the output pulses of the mode-locked laser are shown in Fig. 6. Figure 6(a) shows the optical spectrum of the mode-locked pulses, from which we can estimate that the 3-dB spectral bandwidth is about 3.83 nm with central wavelength at 1559.3 nm. The evident Kelly sidebands clearly state that the laser is under operation regime of anomalous-dispersion soliton. Figure 6(b) shows the oscilloscope trace of the output pulse train, with a period of 135 ns, which agrees well with the calculated value from the cavity length. The pulse energy and peak power are about 0.14 nJ and 152.17 W, respectively. Figure 6(c) shows the radio frequency power spectrum with a 43.8 dB signal-to-noise ratio, indicating that the laser is operating with low amplitude noise. A broad harmonic spectrum is also shown in the inset of Fig. 6(c) with a 1 GHz span. Figure 6(d) shows the autocorrelation trace, and the pulse duration is estimated to be about 0.92 ps, corresponding to a time-bandwidth product (TBWP) of 0.43. It is nearly Fourier transform limited.

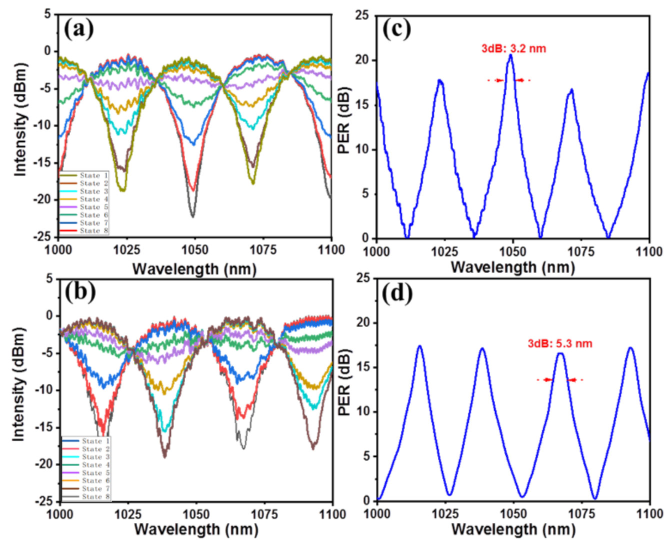

Fig. 7. (a) and (b) The transmission spectra under different polarization states of two PBS samples at 1 μm band; (c) and (d) their corresponding PER spectra.

The microfiber PBS has been successfully implemented for mode-locking of EDF laser in 1.5 μm region. In order to validate the feasibility and generality of the microfiber PBS in any wavelength band, similar experiments including PBS fabrication and application for mode-locked fiber laser at 1.0 μm wavelength band have also been conducted. Two samples at 1.0 μm with microfiber diameter of ~3.94 μm and ~4.27 μm, corresponding to coupling length of ~12.8 mm and ~10.3 mm, were prepared. The transmission spectra of the two samples under different polarization states are shown in Figs. 7(a) and (b). Their PER spectra are shown in Figs. 7(c) and (d), indicating good polarization characteristics and periodic oscillation. Samples 1 and 2 exhibit PERs of 20.7 dB at wavelength of 1049.1 nm and 16.6 dB at wavelength of 1067.5 nm, and their 3-dB bandwidths are 3.2 nm and 5.3 nm, respectively. The oscillation periods of the PERs with respect to wavelength are 24.7 nm and 25.6 nm respectively, which again confirms the previous conclusion, i.e. oscillation period decreases with the decrease of the microfiber diameter due to the increase of birefringence.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JSTQE.2020.3012667, IEEE Journal of Selected Topics in Quantum Electronics

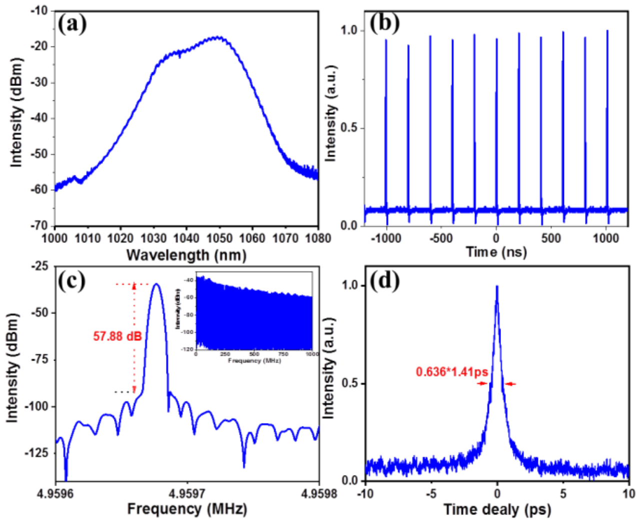

Fig. 8. Output characteristics of the mode-locked YDF laser with microfiber PBS at 1 μm: (a) Optical spectrum, (b) pulse train, (c) radio frequency spectrum, (d) autocorrelation trace.

The mode-locked fiber laser with the microfiber PBS at 1.0 μm is a ytterbium-doped fiber (YDF) ring laser dispersion-managed with a photonic crystal fiber (PCF), having a similar configuration but different fiber lengths with that in Ref [31]. Both YDF and SMF have anomalous dispersion, while the PCF has normal dispersion at 1.0 μm band. The net dispersion of the laser cavity with total length of 41.1 m is evaluated to be about 0.22 ps^2. The output characteristics are given in Fig. 8 with pump power of 280 mW. The 3-dB bandwidth of the output spectrum is 11.1 nm, as shown in Fig. 8(a). The pulse train monitored by an oscilloscope, as shown in Fig. 8(b), has a repetition rate of 4.9 MHz, which coincides with the laser cavity length. Figure 8(c) shows the radio frequency power spectrum with a signal-to-noise ratio of 57.9 dB, and the inset is a wide harmonic spectrum with 1 GHz frequency span. Figure 8(d) is the autocorrelation trace of the output pulse, which gives a pulse duration of ~636 fs. It is noted that the measured pulse has large chirp. We believe that transform limited pulses can be achieved if the dispersion used for pulse compression outside the laser cavity is optimized.

From the results above, at both 1.0 μm and 1.5 μm wavelength bands, passive mode-locking can be realized based on our proposed and fabricated all-fiber PBSs. Although in the experiments the laser cavity parameters such as net dispersion and nonlinearity are fixed and the mode-locking operation is limited to one operation regime, any other operation regime is definitely available through adjusting the laser cavity setup. Also, this technique can be generalized to any wavelength including visible and mid-infrared region, since the only involved material of fiber for PBS fabrication is ultra-broadband. The output pulse performance is comparable with that from traditional passively mode-locked fiber lasers, which can be further enhanced through either improving the fabrication process of the PBSs or optimizing the laser cavity design. The stability of both PBS and mode-locked fiber laser can be furtherly enhanced by using totally enclosed packaging method. Especially, passively mode-locked fiber lasers have extremely rich dynamics [[32][34], varying with saturable absorption power, modulation depth, and filtering bandwidth. The microfiber PBS with variable PER and bandwidth provides a novel manipulation dimension and way to explore the unknown lasing phenomena and dynamics of fiber lasers.

IV. Conclusion

In conclusion, we have demonstrated passively mode-locked all-fiber lasers at both 1.0 μm and 1.5 μm wavelength bands with comparable performance to their counterparts, through replacing commonly used bulky PBS with our fabricated microfiber PBS. The all-fiber PBSs composing of two parallel and clingy microfibers can provide variable PER and operation bandwidth, as well as simple fabrication and compact size. It may pave a step forward to a real all-fiber passively mode-locked laser, as well as other all-fiber systems.

References

[1] D. Dai, L. Liu, S. Gao, D. Xu, S. He, "Polarization management for silicon photonic integrated circuits," *Laser Photon. Rev.*, vol. 7, pp. 303-328, 2013.

[2] D. Dai, J. E. Bowers, "Novel ultra-short and ultra-broadband polarization beam splitter based on a bent directional coupler," *Opt. Express*, vol. 19, pp. 18614-18620, 2011.

[3] I. Yokohama, K. Okamato, J. Noda, "Fiber-optic polarising beam splitter employing birefringent-fiber coupler," *Electron. Lett.*, vol. 21, pp. 415-416, 1985.

[4] K. Saitoh, Y. Sato, M. Koshiba, "Polarization splitter in three-core photonic crystal fibers," *Opt. Express*, vol. 12, pp. 3940-3946, 2004.

[5] L. Zhang, C. Yang, "Polarization splitter based on photonic crystal fibers," *Opt. Express*, vol. 11, pp. 1015-1020. 2003.

[6] M. E. Fermann, I. Hartl, "Ultrafast fibre lasers," *Nat. photonics*, vol. 7, pp. 868-874, 2013.

[7] L. Nelson, D. Jones, K. Tamura, H. Haus, E. Ippen, "Ultrashort-pulse fiber ring lasers," *Appl. Phys. B*, vol. 65, pp. 277-294, 1997.

[8] L. Zhao, D. Tang, H. Zhang, X. Wu, "Bunch of restless vector solitons in a fiber laser with SESAM," *Opt. Express*, vol. 17, pp. 8103-8108, 2009.

[9] Z. Luo, A. Luo, W. Xu, "Tunable and switchable multiwavelength passively mode-locked fiber laser based on sesam and inline birefringence comb filter," *IEEE Photon. J.*, vol. 3, pp. 64-70, 2011.

[10] Z. Zhang, Y. Cai, J. Wang, H. Wan, and L. Zhang, "Switchable dual-wavelength cylindrical vector beam generation from a passively mode-locked fiber laser based on carbon nanotubes," *IEEE J. of Selected Topics in Quantum Electron*., vol. 24, pp. 1100906, 2018.

[11] X. Liu and Y. Cui, "Revealing the behavior of soliton bulid-up in a mode-locked laser," Adv. Photon., vol. 1, no. 1, 016003, 2019.

[12] X. Liu, D. Popa, N. AKhmediev, "Revealing the transition dynamics from Q switching to mode locking in a soliton laser," Phys. Rev. Lett., vol. 123, pp. 093901, 2019.

[13] Z. Sun, T. Hasan, F. Torrisi, et al., "Graphene mode-locked ultrafast laser," *ACS Nano*, vol. 4, pp. 803-810, 2010.

[14] W. Liu, M. Liu, J. Yin, et al., "Tungsten diselenide for all-fiber lasers with the chemical vapor deposition method," *Nanoscale*, vol. 10, pp. 7971-7977, 2018.

[15] Y. Q. Ge, S. Chen, Y. J. Xu, et al., "Few-layer selenium-doped black phosphorus: synthesis, nonlinear optical properties and ultrafast photonics applications," *J. Mater. Chem. C*, vol. 5, pp. 6129-6135, 2017.

[16] X. Jin, G. Hu, M. Zhang, et al.. "102 fs pulse generation from a long-term stable, inkjet-printed black phosphorus-mode-locked fiber laser," *Opt. Express*, vol. 26, pp. 12506-12513, 2018.

[17] F. Ö. Ilday, F. W. Wise, T. Sosnowski, "High-energy femtosecond stretched-pulse fiber laser with a nonlinear optical loop mirror," *Opt. Lett., vol.* 27, pp. 1531-1533, 2002.

[18] C. Aguergaray, N. G. R. Broderick, M. Erkintalo, et al., "Mode-locked femtosecond all-normal all-PM Yb-doped fiber laser using a nonlinear amplifying loop mirror," *Opt. Express*, vol. 20, pp. 10545-10551, 2012.

[19] H. Li, Z. Wang, C. Li, J. Zhang, S. Xu, "Mode-locked Tm fiber laser using SMF-SIMF-GIMF-SMF fiber structure as a saturable absorber," *Opt. express*, vol. 25, pp. 26546-26553, 2017.

[20] Z. Wang, D. N. Wang, F. Yang, et al., "Er-Doped Mode-Locked Fiber Laser With a Hybrid Structure of a Step-Index–Graded-Index Multimode Fiber as the Saturable Absorber," *J. Lightwave Technol.*, vol. 35, pp. 5280-5285, 2017.

[21] Z. Wang, D. N. Wang, F. Yang, et al., "Stretched graded-index multimode optical fiber as a saturable absorber for erbium-doped fiber laser mode locking," *Opt. Lett.*, vol. 43, pp. 2078-2081, 2018.

[22] U. Teğin, B. Ortaç, "All-fiber all-normal-dispersion femtosecond laser with a nonlinear multimodal interference-based saturable absorber," *Opt. Lett.*, vol. 43, pp. 1611-1614, 2018.

[23] F. Ö. Ilday, J. Buckley, W. Clark, F. Wise, "Self-similar evolution of parabolic pulses in a laser," *Phys. Rev. lett.*, vol. 92, pp. 213902, 2004.

[24] A. Komarov, H. Leblond, F. Sanchez, "Theoretical analysis of the operating regime of passively-mode-locked fiber laser through nonlinear polarization rotation," *Phys. Rev. A*, vol. 72, pp. 63811, 2005.

[25] Z. Zhang, C. Mou, Z. Yan, et al., "Sub-100 fs mode-locked erbium-doped fiber laser using a 45°-tilted fiber grating," *Opt. Express* vol. 21, pp. 28297-28303, 2013.

[26] Z. Zhang, J. Gan, T. Yang, et al., "All-fiber mode-locked laser based on microfiber polarizer," *Opt. Lett*., vol. 40, pp. 784-787, 2015.

[27] I. Yokohama, K. Okamoto, J. Noda, "Analysis of fiber-optic polarizing beam splitters consisting of fused-taper couplers," *J. of Lightwave Technol.*, vol. 4, pp. 1352-1359, 1986.

[28] J. Yu, D. Yao, Y. Xiao, et al., "High performance micro-fiber coupler-based polarizer and band-rejection filter," *Opt. Express,* vol. 20, pp. 17258-17270, 2012.

[29] Y. Jung, G. Brambilla, K. Oh, D. J. Richardson, "Highly birefringent silica microfiber," *Opt. Lett*., vol. 35, pp. 378-380, 2010.

[30] S. Lacroix, F. Gonthier, J. Bures, "Modeling of symmetric 2×2 fused-fiber couplers," *Appl. Opt.*, vol. 33, pp. 8361-8369, 1994.

[31] Z. Zhang, Şenel Ç, R. Hamid, F. Ö. Ilday, "Sub-50 fs Yb-doped laser with anomalous-dispersion photonic crystal fiber," *Opt. Lett.*, vol. 38, pp. 956-958, 2013.

[32] X. Liu, X. Yao, Y. Cui. "Real-time observation of the buildup of soliton molecules," *Phys. Rev. Lett.*, vol. 121, pp. 023905, 2018.

[33] Z. Wang, K. Nithyanandan, A. Coillet, P. Tchofo-Dinda, Ph. Grelu, "Optical soliton molecular complexes in a passively mode-locked fibre laser," *Nat. Commun.*, vol. 10, pp. 830, 2019.

[34] X. Liu, M. Pang, "Revealing the Buildup Dynamics of Harmonic Mode-Locking States in Ultrafast Lasers," *Laser Photon. Rev.*, vol. 13,pp. 1800333, 2019.

Xiabing Zhou is with Nanjing University of Posts and Telecommunications, Nanjing, China.

She is currently working toward the B.S. degree in Optical engineering with Advanced Photonic Technology Lab, College of Electronic and Optical Engineering & Microelectronics College, Nanjing University of Posts and Telecommunications, Nanjing, China. Her research interests include fiber lasers and fiber optics.

Mingwei Qiu received the B.S. degree from Nanjing University of Posts and Telecommunications, Nanjing, China.

He is currently working toward the M.S. degree in Optical engineering with Advanced Photonic Technology Lab, College of Electronic and Optical Engineering & Microelectronics College, Nanjing University of Posts and Telecommunications, Nanjing, China. His research interests include fiber lasers and fiber optics.

Yuhao Qian received the B.S. degree from Nanjing University of Posts and Telecommunications, Nanjing, China.

He is currently working toward the M.S. degree in Optical engineering with Advanced Photonic Technology Lab, College of Electronic and Optical Engineering & Microelectronics College, Nanjing University of Posts and Telecommunications, Nanjing, China. His research interests include fiber lasers and fiber sensors.

Mengmeng Chen received the Ph.D. degree from Nanjing University, Nanjing, China.

She is currently a lecturer in School of Electronic Engineering, Nanjing Xiaozhuang University, Nanjing, China. Her research interests include fiber lasers, nonlinear optics, fiber optics, and fiber sensors.

Zuxing Zhang received the Ph.D. degree from Shanghai Jiao Tong University, Shanghai, China.

He is currently a Professor in the Advanced Photonic Technology Lab, School of Optoelectronic Engineering, Nanjing University of Posts and Telecommunications, Nanjing, China. His research interests include fiber lasers, nonlinear optics, fiber optics, and optical communications.

Lin Zhang received the Ph.D. degree in physics from the University of Sussex, Sussex, U.K., in 1990.

She was a Research Fellow at the University of Sussex, where he was involved in the field of passive and active planar waveguide devices and lasers. She joined the Photonics Research Group, Aston University, Birmingham, U.K., in 1994, and was a Professor in the School of Engineering and Applied Science in 2005. She has been involved mainly in the field of fiber grating technologies and applications and extensively involved in a number of LINK, Engineering and Physical Sciences Research Council, European Union, Defence Evaluation and Research Agency, European Regional Development Fund, and Science Research Investment Fund funded research programs. She has authored or coauthored more than 400 international standard journal and conference papers and two books. Her research interests include fiber and waveguide optics and devices, interferometric optics, fiber grating devices, optical sensors and sensing technologies, UV and femtosecond inscription techniques and photosensitivity, and biophotonics.