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Switchable Multi-Wavelength Thulium-Doped Fiber Laser Employing a Polarization-Maintaining Sampled Fiber Bragg Grating

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ABSTRACT A continuous wave, switchable multi-wavelength, thulium-doped fiber laser (TDFL) with a polarization-maintaining sampled fiber Bragg grating (PM-SFBG) is proposed and demonstrated for the first time. A length of 150 m highly-nonlinear fiber (HNLF) was used to introduce the four-wave mixing effect for the efficient suppression of the wavelength competition existing in the gain medium of thulium-doped fiber. By adjusting the state of polarization (SOP) of light in the laser cavity, two six-wavelength operations at two orthogonal SOPs and a ten-wavelength operation were obtained. When the TDFL ran at the six-wavelength operation mode with a pump power of 4.11 W, there were at least four lasing wavelengths with an optical signal-to-noise ratio (OSNR) higher than 30 dB, and when it ran at the ten-wavelength operation mode with a pump power of 4.60 W, there were nine lasing wavelengths with an OSNR higher than 30 dB. Regardless of the operation mode, the TDFL exhibited high stability.

INDEX TERMS Multi-wavelength, sampled fiber Bragg grating, thulium-doped fiber laser.

I. INTRODUCTION

Thulium-doped fiber lasers (TDFLs), especially narrow-linewidth and wavelength-tunable TDFLs, have recently become a research focus because they work at the eye-safe 2 μm band in which an atmospheric window exists, and they can be applied in free-space optical communication (FSOC), fiber optical sensors, optical measurement, and medical treatment [1]–[6]. Among the different kinds of reported TDFLs, the multi-wavelength TDFL can stably and simultaneously output numerous wavelengths, and because of its merits of high beam quality, low cost and compact structure, it can be widely used in wavelength-division-multiplexing FSOC [7]. It meets the requirements of reducing the cost and improving the communication capacity of FSOC networks, and has therefore attracted increasingly more and more attention. In addition, a switchable multi-wavelength fiber laser can easily change the number and wavelength of the lasing output, which is conducive to the flexible channel allocation for FSOC.

As one of the most important components inside a multi-wavelength TDFL cavity, the multi-wavelength filter has been studied extensively. Different filter structures have been utilized in reported TDFL systems, such as the Mach-Zehnder interferometer [8], the Sagnac loop filter [9], the cascaded Sagnac loop filter [10], the fiber-based Lyot filter [11], the multimode interferometer [12], and the micro fiber-optic Fabty-Perot interferometer [13]. Fiber Bragg grating (FBG) has also been used as a filter in fiber laser systems due to its simple structure, small size, and flexible tunability. We have proposed dual-wavelength TDFLs using a high-birefringence FBG-based filter and a polarization-maintaining, chirped-moiré FBG-based filter, respectively [14], [15]. Recently, we have studied the transmission characteristics of the sampled FBGs in the 2 μm band in detail [16]. However, a multi-wavelength TDFL using a sampled

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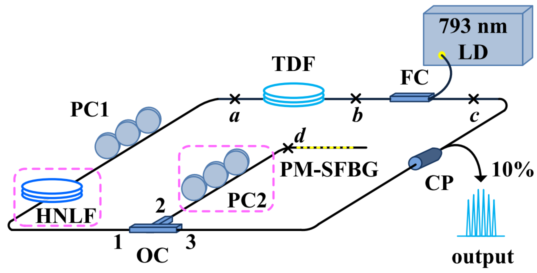

FIGURE 1. The experimental schematic of the proposed TDFL.

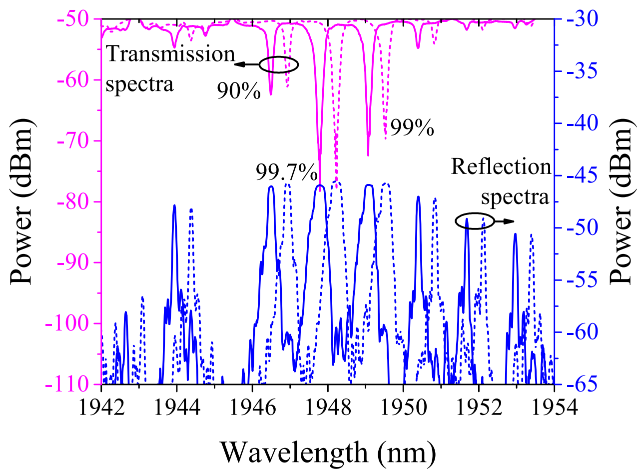

FIGURE 2. The transmission and reflection spectra of PM-SFBG.

FBG-based filter has not yet been reported in the existing literature.

Additionally, in order to achieve a stable multi-wavelength operation in a TDFL, the wavelength competition caused by the homogeneous gain-broadening effect in the thulium-doped fiber should be efficiently suppressed. Several methods have been used to achieve multi-wavelength lasing in rare-earth doped fiber lasers, such as frequency shift modulation, polarization hole burning, and nonlinear effects [13], [15], [17]–[21]. Nonlinear effects, such as the nonlinear optical loop mirror (NOLM), nonlinear polarization rotation (NPR), and four-wave mixing (FWM), are typically the most often used [13], [18], [19], [21]. After the introduction of the FWM effect, the power redistribution among all the lasing wavelengths inside the laser cavity can be achieved; part of the energy of the lasing wavelengths with greater power is transferred to those with lesser power to achieve a dynamic power balance, which can effectively reduce the severe competition between different lasing wavelengths.

In this paper, a continuous wave (CW), switchable multi-wavelength TDFL with polarization-maintaining sampled fiber Bragg gratings (PM-SFBG) has, to the best of the authors' knowledge, been proposed and demonstrated experimentally for the first time. The PM-SFBG was used as an excellent multi-wavelength filter, and a section of highly-nonlinear fiber (HNLF) was employed to introduce the FWM effect. The output characteristics of the TDFL with and without the HNLF were investigated and analyzed. By adjusting the state of polarization (SOP) of light in the laser cavity, the switchable multi-wavelength operations in different modes were obtained and studied in detail.

II. EXPERIMENTAL SETUP

Figure 1 presents the experimental schematic of the proposed fiber laser. The gain medium was a 4.5 m double-cladding TDF with a core/cladding diameter of 10/130 μm, and was made by Nufern Corporation. A multimode 793 nm laser diode was injected into the laser cavity through a $(6+1)\times 1$ fiber combiner (FC) as the pump source. Only one pump input port of the FC was used. The core/cladding diameter of the pump input fiber of the FC was 105/125 μm with a 0.22 numerical aperture (NA), and the signal input/output fiber was a 6/125 μm germanium-doped fiber. The 150 m HNLF with a cladding diameter and NA of 125 μm and 0.35, respectively, was used to suppress the gain competition via the FWM effect. An optical circulator (OC) connected the fiber grating filter to the laser cavity. Two polarization controllers (PCs) were used in the cavity. The PC1 was primarily used to adjust the intensity-dependent gain and the polarization of the cavity, and the PC2 mainly adjusted the polarization of the filter to achieve wavelength switching. Finally, 10% power was output through a 90:10 coupler.

The fiber grating filter was a 20 mm PM-SFBG, which was fabricated on hydrogen-loaded Nufern PM-TDF (the core/cladding diameter was 10/130 μm) using the phase mask method [14], [15], [20]–[22]. The tail fiber of the PM-SFBG in the laser cavity was a 150 mm unpumped PM-TDF. As a saturable absorber [23], this section of thulium doped fiber contributed to narrowing the laser linewidth and steadying the laser output. During the fabrication, a uniform phase mask (the period $\Lambda = 1347.3$ nm), a sampled mask (the sampled period $d = 2$ mm, the duty cycle $t = 0.5$), and a 248 nm KrF excimer laser were used. The focal point diameter of the ultraviolet laser was 5 mm, the pulse frequency was 25 Hz with an energy of 60 mJ, and the exposure processed continuously through the optical lens fixed on the displacement platform. The velocity and minimum step of the platform were 0.05 mm and 0.1 μm, respectively. According to the phase mask method, the center wavelength of the grating was around 1950 nm, corresponding to the large gain range of the amplified spontaneous emission (ASE) of the TDF. The transmission and reflection spectra of the PM-SFBG at two orthogonal SOPs are presented in Fig. 2, and were measured by an optical spectrum analyzer (OSA, YOKOGAWA AQ6375) with a resolution of 0.05 nm. During the measurement, a PC and a polarizer were used to select one of the two polarization directions for measurement. The solid line and dashed line denote the measured X-polarization and Y-polarization, respectively. For each SOP, the reflectivities of the three peaks in the middle were 90%, 99.7%, and 99%, respectively. Note that the reflectivities of the peaks on the two sides are not the same because of the errors introduced by the placement of the mask and fiber, as well as the jitters of

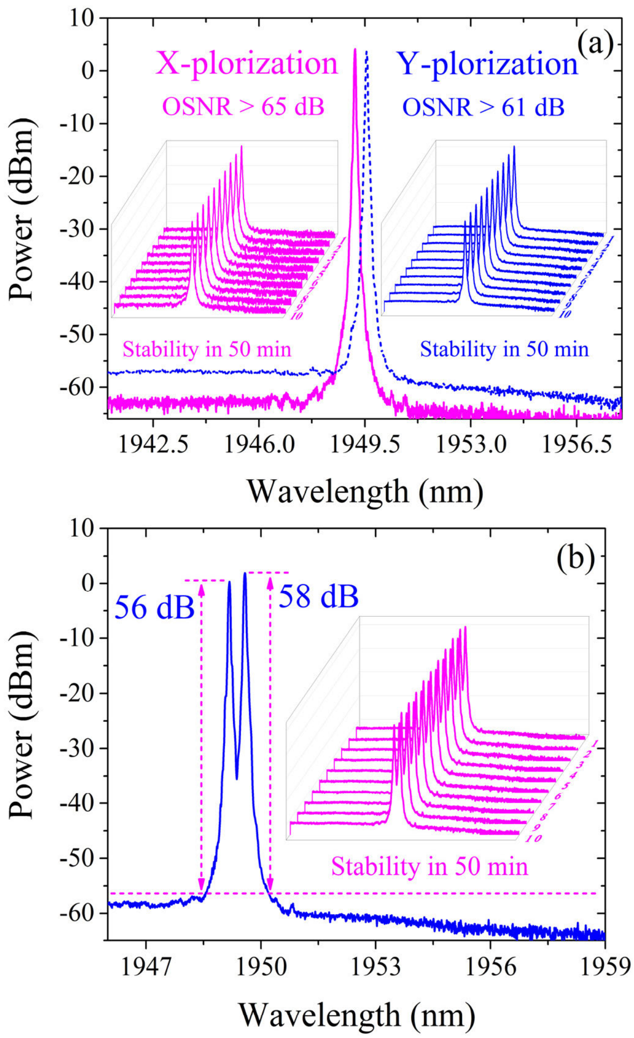

FIGURE 3. The output spectra of TDFL without HNLF. (a) single-wavelength and (b) dual-wavelength output.

the displacement platform and laser energy during the grating fabrication.

III. RESULTS AND DISCUSSION

First, the TDFL without the HNLF or the PC2 was investigated at room temperature (24 °C), and this TDFL, with a threshold of 2.34 W, could be switched between single-wavelength and dual-wavelength operations. This TDFL was not a multi-wavelength laser because there was no mechanism to suppress the gain competition; however the PM-SFBG had several reflective peaks, and the laser outputted at the wavelength with the highest reflective value of each SOP. The pump power was fixed at 4.11 W to observe the output characteristics. As shown in Fig. 3(a), the TDFL was in the single-wavelength operation. The output laser (X-polarization, the magenta solid curve) was 1949.18 nm, and the optical signal-to-noise ratio (OSNR) was about 65 dB. Then, the output wavelength was switched by adjusting the SOP through the PC1, and the laser (Y-polarization, the blue dashed curve) outputted at a wavelength of 1949.56 nm with an OSNR of ∼61 dB. The spectra obtained by repeatedly scanning within 50 min of the two polarizations indicated that the TDFL worked stably at both single-wavelength operations. With the help of the PC1 to adjust the polarization of the light inside the laser cavity to balance the loss and gain between two orthogonal polarizations, the switching between two orthogonal polarized single-wavelength operations and between single- and dual-wavelength operations were realized. As Fig. 3(b) presents, when the TDFL was in the dual-wavelength operation, the laser wavelengths were 1949.18 nm and 1949.56 nm, and the OSNRs were 56 and 58 dB, respectively. As demonstrated by the spectra obtained by repeatedly scanning within 50 min, the TDFL also worked stably at dual-wavelength operation.

The HNLF was then employed in the cavity to provide the intensity-dependent gain to suppress the gain competition by introducing the FWM effect, and the PC1 helped to balance the intensity-dependent gain between different lasing wavelengths. In order to realize the efficient FWM to simultaneously stabilize the multi-wavelength lasing and the SOP switching, the PC2 was introduced to adjust the SOP of light propagating to the PM-SFBG. The PCs, unlike a variable optical attenuator, were not used to directly cause an inter-cavity loss. Due to the power exchange caused by the FWM effect, the dominant wavelength in free competition transfers energy to the weaker wavelength, and multi-wavelength lasing can be achieved. The principle is as follows. Assuming that the power at frequency ω_i is P_i and the power at frequency ω_{i+1} is P_{i+1}, the power variations at ω_i and ω_{i+1} can be respectively expressed as

$$\Delta P_i = \alpha \left(\frac{\omega_i}{\omega_{i+1}} P_{i+1} - 2P_i \right), \quad (1)$$

$$\Delta P_{i+1} = \alpha \left(\frac{\omega_{i+1}}{\omega_i} P_i - 2P_{i+1} \right), \quad (2)$$

where α is the efficiency of the FWM process [24]. The variation of P_i/P_{i+1} is

$$\Delta \left(\frac{P_{i+1}}{P_i} \right) = \frac{1}{P_i^2} \left(P_i \Delta P_{i+1} - P_{i+1} \Delta P_i \right) = \alpha \frac{\omega_{i+1}}{\omega_i} \left[1 - \left(\frac{\omega_i P_{i+1}}{\omega_{i+1} P_i} \right)^2 \right]. \quad (3)$$

From Eq. (3), it can be determined that when $\omega_i P_{i+1} > \omega_{i+1} P_i (P_{i+1} > P_i$, approximately), $\Delta(P_{i+1}/P_i) < 0$, and the energy transfers from the wave at ω_{i+1} to the wave at ω_i. By contrast, when $\omega_i P_{i+1} < \omega_{i+1} P_i$ ($P_{i+1} < P_i$, approximately), $\Delta(P_{i+1}/P_i) > 0$, and the energy transfers from the wave at ω_i to the wave at ω_{i+1}. When $\omega_i P_{i+1} = \omega_{i+1} P_i$ ($P_{i+1} = P_i$, approximately), $\Delta(P_{i+1}/P_i) = 0$, and the powers of the two frequencies are balanced by the FWM effect.

The threshold of the multi-wavelength TDFL was 2.86 W, which is higher than that of the TDFL without HNLF due to the strong loss caused by the HNLF. By adjusting the PCs, the gain and loss of different lasing wavelengths were changed, as were the laser OSNRs of different wavelengths.

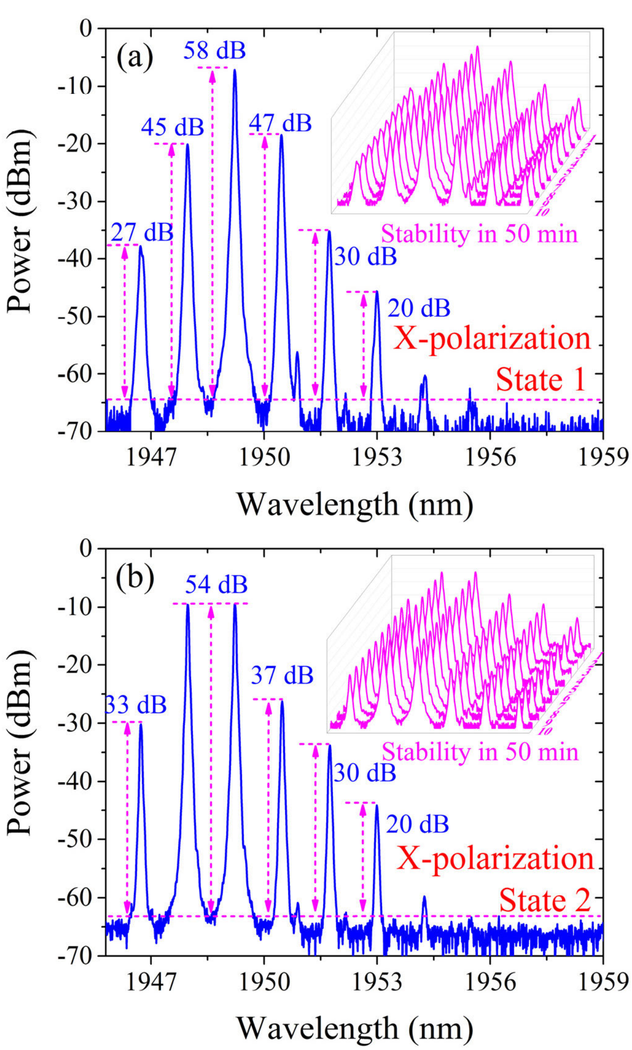

FIGURE 4. The output spectra of multi-wavelength TDFL. (a) X-polarization, State 1. (b) X-polarization, State 2.

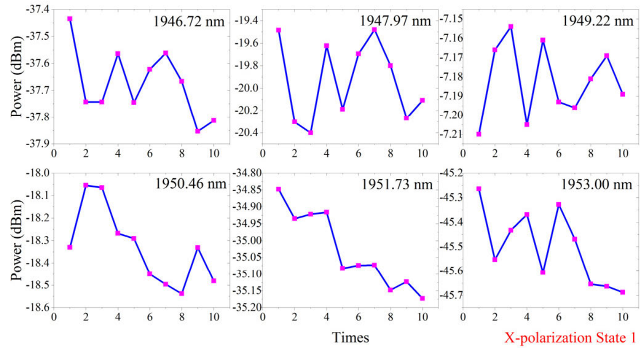

FIGURE 5. The laser power fluctuations of six wavelengths versus time (X-polarization, State 1)).

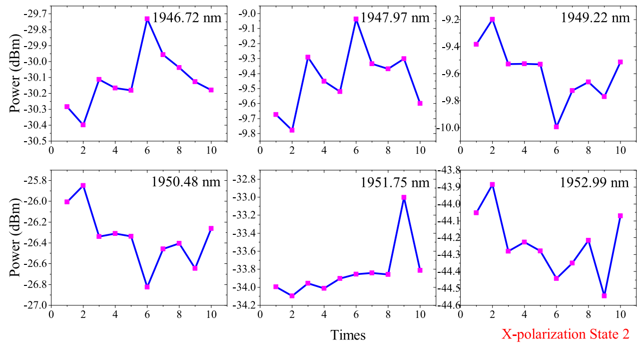

FIGURE 6. The laser power fluctuations of six wavelengths versus time (X-polarization, State 2)).

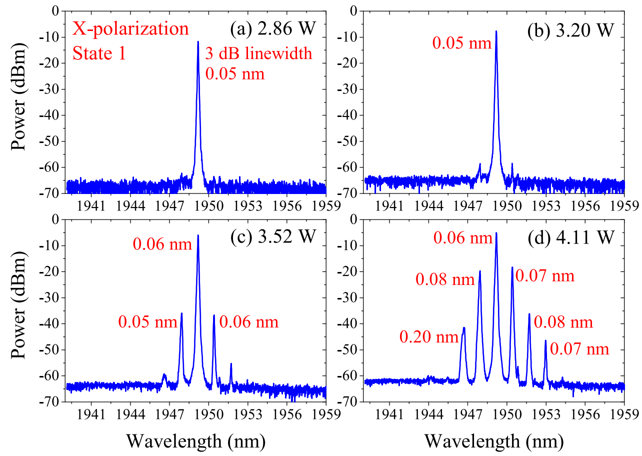

FIGURE 7. The output spectra of multi-wavelength TDFL (X-polarization, State 1))when the pump power was (a) 2.86 W, (b) 3.20 W, (c) 3.52 W and (d) 4.11 W.

To investigate the output characteristics, two typical different states of output OSNRs were chosen in X-polarization, as presented in Fig. 4. In Fig. 4(a), the laser at 1949.22 nm had the highest power, and six lasing channels were observed in total. The lasers were at 1946.72 nm, 1947.97 nm, 1949.22 nm, 1950.46 nm, 1951.73 nm, and 1953.00 nm, respectively, and the OSNRs were 27 dB, 45 dB, 58 dB, 47 dB, 30 dB, and 20 dB, respectively. In Fig. 4(b), the lasers at 1947.97 nm and 1949.22 nm had the same power. The OSNRs of the lasers at the six wavelengths were 33 dB, 54 dB, 54 dB, 37 dB, 30 dB, and 20 dB, respectively. The wavelength interval was around 1.26 nm. To investigate the stability of the multi-wavelength operation, the output spectra of the two states were scanned 10 times with intervals of 5 min, as shown in Figs. 4(a) and 4(b). During the measurement, no obvious wavelength fluctuation was observed within the resolution of the OSA, and the center-wavelength power fluctuations of the six channels of State 1 and State 2 are presented in Figs. 5 and 6, respectively. As Fig. 5 indicates, the fluctuations at the six center-wavelengths of State 1 were 0.418 dB, 0.920 dB, 0.049 dB, 0.483 dB, 0.325 dB, and 0.423 dB, respectively. The power fluctuations of the six wavelengths of State 2 were 0.668 dB, 0.739 dB, 0.796 dB, 0.975 dB, 0.281 dB, and 0.659 dB, respectively, as shown in Fig. 6. The above results indicate that the proposed multi-wavelength TDFL can operate stably at X-polarization.

The characteristics of multi-wavelength operations with different launched pump powers were then studied. Figs. 7(a-d) present the output spectra of State 1 with different

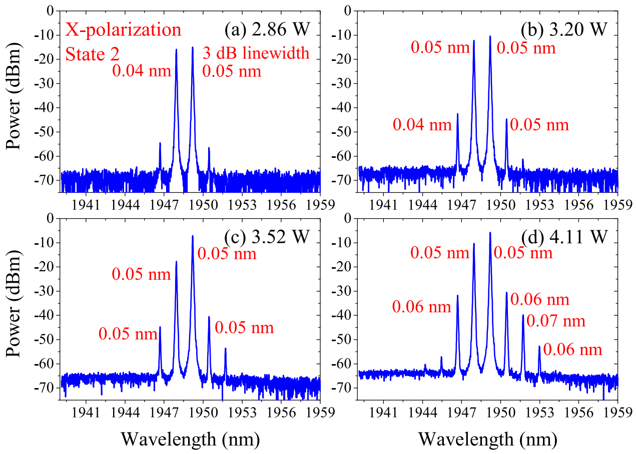

FIGURE 8. The output spectra of multi-wavelength TDFL (X-polarization, State 2))when the pump power was (a) 2.86 W, (b) 3.20 W, (c) 3.52 W and (d) 4.11 W.

pump powers. When the pump power was 2.86 W, the laser at 1949.22 nm began to output, and when the pump power was 3.20 W, the lasers at 1947.97 nm and 1950.46 nm started lasing. After increasing the pump power to 3.52 W, the lasers at 1946.72 nm and 1951.73 nm started lasing, and when the 4.11 W pump power was launched, simultaneous six-wavelength lasing was achieved. The 3 dB linewidths of the lasers were 0.20 nm, 0.08 nm, 0.06 nm, 0.07 nm, 0.08 nm, and 0.07 nm, respectively. Note that the 3 dB linewidths of the lasers became wider with the increase of pump power. This is because the proposed laser is not a single-longitudinal mode laser; when the pump power increased, the number of the longitudinal mode also increased, and the 3 dB linewidths widened. The output spectra of State 2 with different pump powers are exhibited in Figs. 8(a-d). As can be seen, unlike in State 1, when the pump power reached the threshold, the lasers at 1947.97 nm and 1949.22 nm emerged together. The 3 dB linewidths of the lasers were 0.06 nm, 0.05 nm, 0.05 nm, 0.06 nm, 0.07 nm, and 0.06 nm, respectively. Also, the 3 dB linewidths widened as the pump power increased. Note that if a greater pump power is employed, the laser OSNRs will be higher, and peaks, corresponding to the low-reflective peaks of the PM-SFBG, will appear in the output spectrum. However, a greater pump power will result in a severe thermal effect at the splicing point *a*, so the pump power of 4.11 W was used.

To further study the switching characteristic of the proposed TDFL, two PCs were adjusted, and the Y-polarization output operations of different states were obtained. In Fig. 9(a), the laser at 1950.86 nm achieved the highest power, and a total of five lasing channels was observed. The lasers were at 1948.19 nm, 1949.51 nm, 1950.86 nm, 1952.15 nm, and 1953.42 nm, respectively, and the OSNRs were 31 dB, 49 dB, 55 dB, 42 dB, and 24 dB, respectively. In Fig. 9(b), the laser at 1949.51 nm had the highest power, and the lasing channel at 1946.90 nm was achieved. The OSNRs of the lasers at the six wavelengths were 35 dB, 47 dB, 57 dB, 47 dB, 37 dB, and 21 dB, respectively. The wavelength interval was

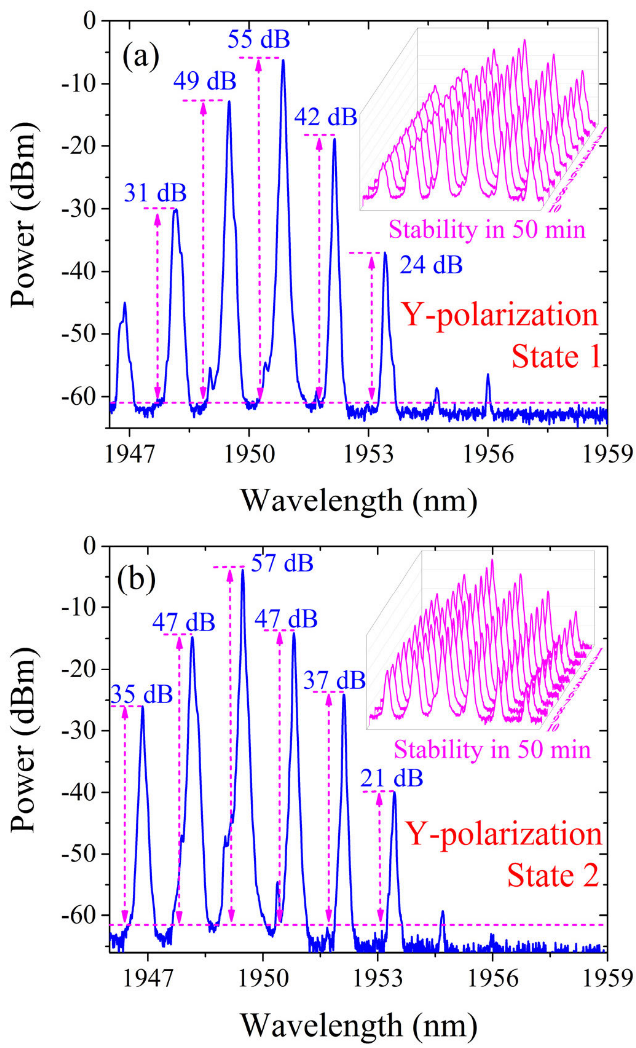

FIGURE 9. The output spectra of multi-wavelength TDFL. (a) Y-polarization, State 1. (b) Y-polarization, State 2.

around 1.30 nm, which is reasonable within the OSA resolution of 0.05 nm compared with the X-polarization interval of 1.26 nm. To study the stability of the multi-wavelength operation with Y-polarization, the output spectra of the two states were scanned 10 times with intervals of 5 min, and are displayed in Figs. 9(a) and 9(b). During the test, no obvious wavelength fluctuation was observed within the resolution of the OSA, and the output power fluctuations of the six wavelengths of the two states are presented in Figs. 10 and 11, respectively. As Fig. 10 shows, the power fluctuations of the five-wavelength laser of State 1 were 0.678 dB, 0.785 dB, 0.116 dB, 0.138 dB, and 0.848 dB, respectively. In Fig. 11, the power fluctuations of the six-wavelength laser of State 2 were 1.615 dB, 0.605 dB, 0.19 dB, 0.82 dB, 1.568 dB, and 1.838 dB, respectively.

Figs. 12(a-d) present the Y-polarization output spectra of State 1 with different pump powers. When the pump power was 2.86 W, the laser at 1950.86 nm appeared. As the pump power increased, multi-wavelength lasers emerged. When the

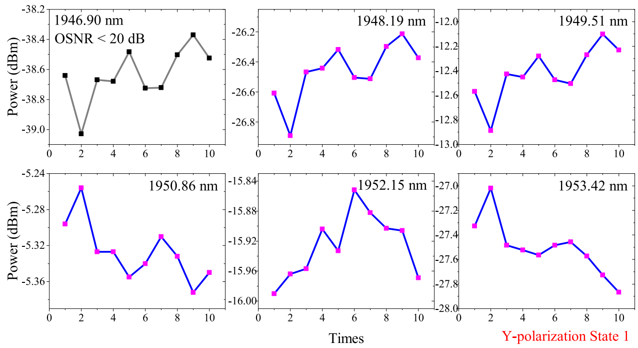

FIGURE 10. The laser power fluctuations of six wavelengths versus time (Y-polarization, State 1).

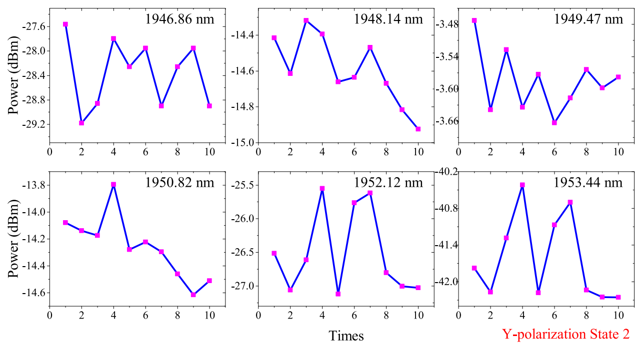

FIGURE 11. The laser power fluctuations of six wavelengths versus time (Y-polarization, State 2).

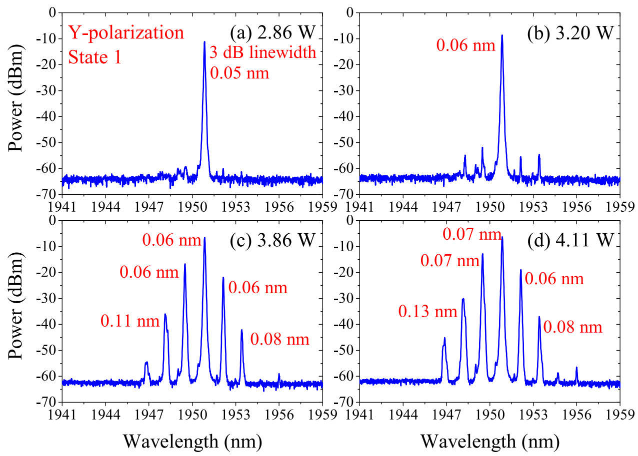

FIGURE 12. The output spectra of multi-wavelength TDFL (Y-polarization, State 1) when the pump power was (a) 2.86 W, (b) 3.20 W, (c) 3.86 W and (d) 4.11 W.

pump power was 4.11 W, the lasers of five wavelengths were output (1948.19 nm, 1949.51 nm, 1950.86 nm, 1952.15 nm, and 1953.42 nm). The 3 dB linewidths of the lasers were 0.13 nm, 0.07 nm, 0.07 nm, 0.06 nm, and 0.08 nm, respectively, which were widened as the pump power increased. Figs. 13(a-d) display the output spectra of State 2 with different pump powers. Unlike in State 1, the laser at 1949.51 nm emerged first, and when the pump power was 4.11 W, lasers of six wavelengths were achieved. The 3 dB linewidths of the lasers were 0.06 nm, 0.08 nm, 0.06 nm, 0.07 nm, 0.06 nm, and

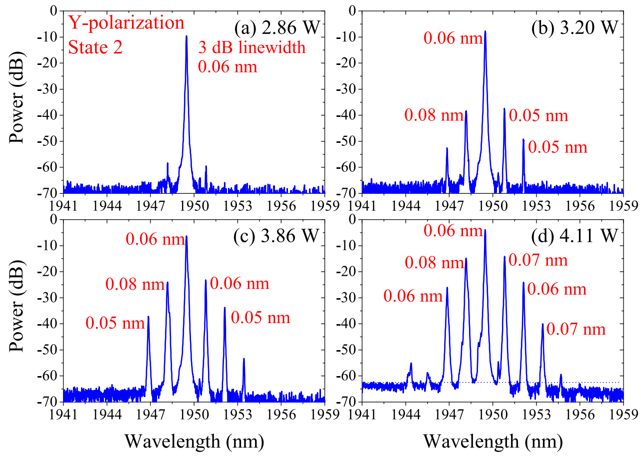

FIGURE 13. The output spectra of multi-wavelength TDFL (Y-polarization, State 2) when the pump power was (a) 2.86 W, (b) 3.20 W, (c) 3.86 W and (d) 4.11 W.

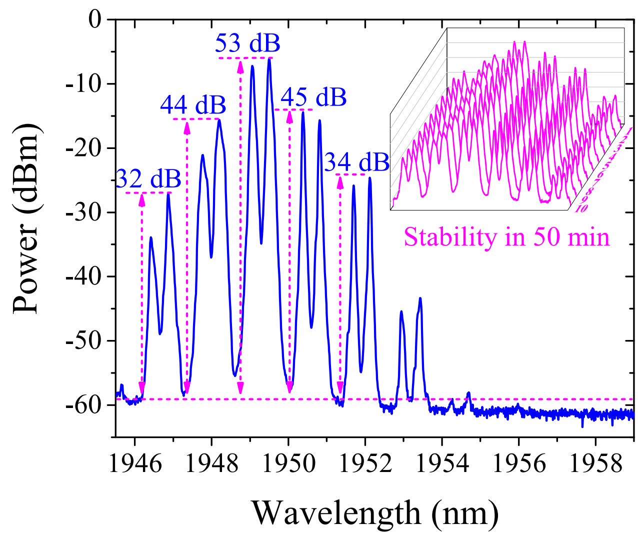

FIGURE 14. The output spectra of multi-wavelength TDFL (X- and Y-polarization).

0.07 nm, respectively. If a greater pump power is employed, the laser OSNRs will be higher, and corresponding peaks with the low-reflective peaks of the PM-SFBG will appear on the output spectrum.

Next, we adjusted the PCs to make the X- and Y-polarized lasers emerge together, and lasers with more wavelengths were achieved, as is evident in Fig. 14. The wavelengths and the OSNRs of the ten output lasers are listed in Table. 1. The highest OSNR was 53 dB at 1949.50 nm. Then, to study the stability of multi-wavelength operation, the output spectra were scanned 10 times at intervals of 5 min. No obvious wavelength draft was observed within the resolution of the OSA, and the power fluctuations of each wavelength are presented in Fig. 15 and Table. 1. The power fluctuations were less than 0.787 dB, which indicated that the proposed TDFL can stably work at ten-wavelength operation.

The output spectra with different pump powers were obtained, and are presented in Fig. 16. When the pump power

TABLE 1. **Wavelength, OSNR and power fluctuation of TDFL output (X- and Y-polarization).**

Wavelength (nm)	1946.42	1946.87	1947.76	1948.19	1949.06
OSNR (dB)	25	32	38	44	52
Power fluctuation (dB)	0.787	0.403	0.548	0.197	0.117
Wavelength (nm)	1949.50	1950.38	1950.81	1951.70	1952.12
OSNR (dB)	53	45	43	33	34
Power fluctuation (dB)	0.117	0.139	0.175	0.627	0.216

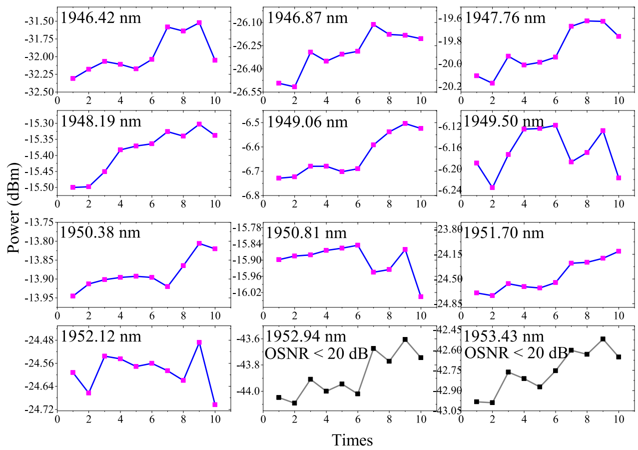

FIGURE 15. **The laser power fluctuation of ten wavelength versus time (X- and Y-polarization).**

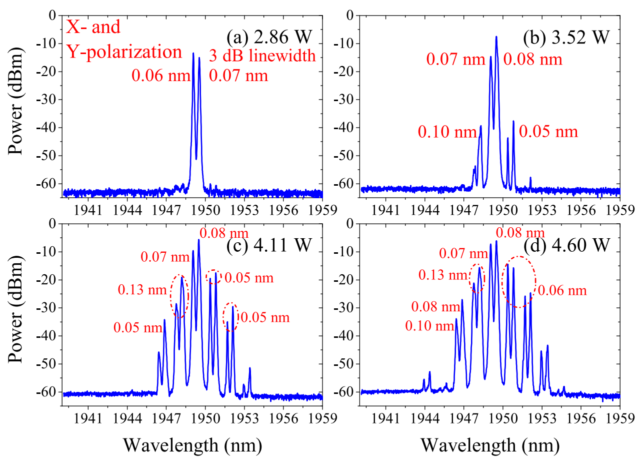

FIGURE 16. **The output spectra of multi-wavelength TDFL (X- and Y-polarization) when the pump power was (a) 2.86 W, (b) 3.52 W, (c) 4.11 W and (d) 4.60 W.**

was 2.86 W, lasers at 1949.06 nm and 1949.50 nm outputted. The number of laser wavelengths increased as the pump power increased. When the pump power was 4.60 W, ten-wavelength operation was obtained. The 3 dB linewidths of the lasers were 0.10 nm, 0.08 nm, 0.13 nm, 0.13 nm, 0.07 nm, 0.08 nm, 0.06 nm, 0.06 nm, 0.06 nm, and 0.06 nm, respectively. The 3 dB linewidths were widened as the pump

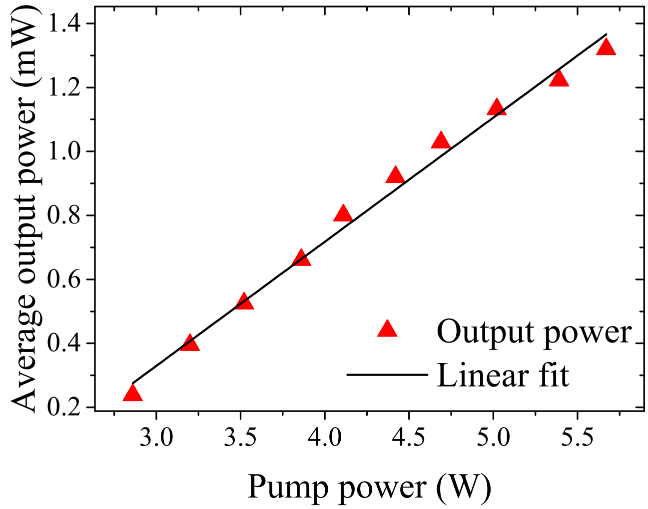

FIGURE 17. **The laser output power variation with pump power (X- and Y-polarization).**

power increased. Finally, the average output power of the ten-wavelength TDFL was measured by the power meter (Ophir StarLite) through the 10% output end of the coupler, as shown in Fig. 17. Due to the 150 m HNLF and the mode field mismatching loss caused by ion diffusion and size mismatch at the spliced points *a*, *b*, *c*, and *d*, the output power of the proposed TDFL was relatively low. The output power notably and near-linearly increased with the pump power, and the TDFL was not saturated. The output power increased with a higher pump power, and the number of laser wavelengths increased simultaneously. However, considering the bearing capacity of the injection point *b*, the highest pump power of 4.60 W was employed.

Note that the proposed TDFL performs as a switchable multi-wavelength laser. However, the wavelength of the output laser could be tunable if a wavelength tuning mechanism is employed, such as a stress regulator [25], curvature adjuster [26], displacement platform [27], and solutions with different refractive indices [28], and thus a wavelength-switchable and tunable TDFL can be obtained.

IV. CONCLUSION

In conclusion, a CW switchable multi-wavelength TDFL employing a PM-SFBG was proposed and demonstrated for the first time. The 150 m long HNLF was used to efficiently suppress the gain competition based on the FWM effect. By adjusting the SOP of light inside the laser cavity, two six-wavelength lasing modes and a ten-wavelength lasing mode were obtained. When the laser ran at any one of the six-wavelength operations with a pump power of 4.11 W, the OSNRs of at least four wavelengths were higher than 30 dB, and when the laser ran at the ten-wavelength operation with a pump power of 4.60 W, the OSNRs of nine wavelengths were higher than 30 dB. At all operation modes, the TDFL exhibited high medium-term stability. The proposed TDFL can be applied in DWDM and FSOC systems as the seed laser.

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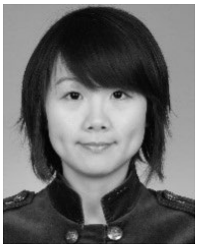

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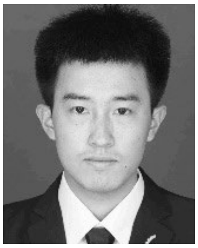

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