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Stable Multi-Wavelength Thulium-Doped Fiber Laser With Two Cascaded Single-Mode-Four-Mode-Single-Mode Fiber Interferometers

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ABSTRACT We propose and experimentally demonstrate a multi-wavelength thulium-doped fiber laser using two cascaded single-mode-four-mode-single-mode (SFS) fiber interferometers and a 150-m-long highly nonlinear fiber. The transmission properties of SFS fiber interferometers with two different four-mode fiber (FMF) lengths are analyzed theoretically. The interferometer with a longer FMF is used to select specific wavelengths, and the one with a shorter FMF is used to stimulate more laser lines. By adjusting the polarization controller and increasing the pump power, the number of output laser channels and the wavelength spacings can be changed and switched. By selecting the proper length of the FMFs, 31 lasing lines are achieved with covering a wavelength range of ∼22 nm. The power fluctuation and the wavelength drift of the 31-wavelength operation for the proposed fiber laser are within 0.706 dB and 0.02 nm, respectively.

INDEX TERMS Single-mode-four-mode-single-mode fiber interferometers, thulium-doped fiber laser, multi-wavelength.

I. INTRODUCTION

Thulium-doped fiber (TDF) has been widely investigated due to its advantages of high nonlinearity and large anomalous dispersion at the 2-μm band [1]. A fiber laser using a TDF as a gain medium outputs a special waveband laser, which is high transparent in the atmospheric window, within eye-safe range, and highly absorbed by human tissues. These features make it attractive for many potential applications, such as free-space optical communication systems, wind lidar systems, fiber sensors, surgical and dermatological treatment devices [2].

Various multi-wavelength thulium-doped fiber lasers (MWTDFLs) have been widely studied, such as the mode-locked fiber laser [3], [4], Q-switched fiber laser [5], [6], and narrow linewidth fiber laser [7]–[9]. Accordingly, the development of MWTDFLs using new filters or novel structures have been successfully exploited, such as all-fiber Mach-Zehnder interferometer [10], fiber-based Lyot filter [11], high birefringence fiber in a fiber optical loop mirror [12], polarization-maintaining sampled fiber Bragg grating [13], [14], coupled fiber Bragg grating cavities [15], and polarization-dependent narrow-band filter [16]. Thus, the multimode interferometer [17] has become a research hotspot. In addition, various cascaded filters have also been shown to have better filtering capability and tunability. For instance, two cascaded optical structures consisting of a standard single-mode fiber (SMF) and a fiber ring resonator were used to improve the mainlobe-to-sidelobe suppression ratio and Q-factor [18]. Also, a multichannel fiber filter, consisting of tunable cascaded long-period gratings, was used for multi-wavelength generation [19], and an equiva-

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lent Lyot birefringence fiber filter with two cascaded birefringence fibers was used for wavelength spacing switching [20]. However, most of these reports with cascaded filters were operated in the 1.55-μm band. In the 2-μm band, S. Fu *et al.* reported a two cascaded single-mode-multimode-single-mode fiber structure-based Tm^{3+}:Ho^{3+} co-doped fiber laser, to achieve a dual-wavelength operation [21]. However, due to the use of multimode fibers in the interferometers, a clear and regular output spectrum cannot be obtained. As a result, the filtering period cannot be tuned freely, and subsequently only uneven dual-wavelength lasing can be achieved. Those problems are expected to be solved by using a few-mode fiber, such as the two-mode fiber (TMF) [22] or the four-mode fiber (FMF) [23], in the interferometer instead of the multimode fiber. We have reported [22] a MWTDFL using a TMF-based interferometer filter. However, in this TDFL, the multi-wavelength lasing lines are not sufficiently uniform and the number of laser lines is limited to 11 within the bandwidth of 10 dB. Besides, in the TMF-based interferometer filter, the fusion between the SMF and TMF is core-offset spliced, which is complicated and has poor repeatability and robustness. In contrast, in the FMF-based interferometer filter, fiber fusion splicing does not need to be core-offset. Moreover, to the best of our knowledge, cascading two FMF-based interferometers to achieve a high performance MWTDFL has not yet been reported.

In addition, due to the strong mode competition in the homogeneous broadening rare-earth-doped fiber, an effective mechanism for suppressing it must be adopted to achieve stable multi-wavelength operation in a fiber laser. Various methods have been proposed for this purpose, for instance, using the polarization rotation (PR) and macro-bending to obtain sextuple stabilized wavelength outputs [24], using a polarization scrambler and a polarizer to induce polarization-dependent-loss (PDL) [25], employing the intensity-dependent loss based on the nonlinear polarization rotation (NPR) effect [26], and inserting a long SMF in the laser cavity to strengthen the four-wave-mixing (FWM) effect [27].

This article reports a MWTDFL using two cascaded FMF-based interferometers and a 150-m-long highly nonlinear fiber (HNLF). The transmission properties of the two cascaded FMF-based interferometers used as an excellent filter are analyzed theoretically and experimentally. The HNLF is used to introduce the FWM effect. The PDL [28], derived by the polarizer and the polarization controller (PC), is used to balance the gain and loss in the cavity. By adjusting the state of polarization in the laser cavity, multiple output channels are achieved and studied in detail. After changing the length of FMFs, stable and dense 31 laser output channels, covering a ~22 nm wavelength range, are achieved. Further research reveals that a two cascaded FMF-based interferometer can generate more uniform laser lines than only one FMF-based interferometer used.

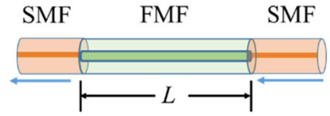

FIGURE 1. Schematic of the SFS Mach-Zehnder interferometer.

II. OPERATION PRINCIPLE OF THE CASCADED INTERFEROMETER FILTER

As shown in Fig. 1, a segment of step-index FMF (YOFC: ULL SI-4) with a core diameter of 19 μm is sandwiched between two SMFs in an axial-aligned single-mode-four-mode-single-mode (SFS) structure, and the fibers are fusion spliced with each other. The LP_{01} and LP_{02} modes are circumferentially symmetric distributions, which can be stimulated at the input splicing point between the SMF and FMF [23], [29]. As the LP_{01} and LP_{02} modes have different effective refractive indices ($n_1 = 1.44548$ and $n_2 = 1.44425$, respectively) in the 2-μm band, a Mach-Zehnder interferometer (MZI) forms at the output splicing point between the FMF and the SMF [30]. Therefore, the transmittance of the cascaded interferometer filter (CIF) including two SFS fiber interferometers (SFS-FIs) is extensively analyzed as follows.

Since the LP_{01} and LP_{02} modes are circumferentially symmetric distributions, the two SFS-FIs are polarization independent. An input field is given as $\begin{bmatrix} [E_{in}] \\ 0 \end{bmatrix}$ [31]. According to the MZI transmission matrix method [32], after traveling through the SFS-FI-1, the output electric fields are E_3 and E_4, which can be obtained from the Eq. (1) as follows.

$$\begin{bmatrix} [E_3] \\ [E_4] \end{bmatrix} = \begin{bmatrix} \sqrt{1-k_2} & j\sqrt{k_2} \\ j\sqrt{k_2} & \sqrt{1-k_2} \end{bmatrix} \begin{bmatrix} e^{j\varphi_1} & 0 \\ 0 & e^{j\varphi_2} \end{bmatrix} \times \begin{bmatrix} \sqrt{1-k_1} & j\sqrt{k_1} \\ j\sqrt{k_1} & \sqrt{1-k_1} \end{bmatrix} \begin{bmatrix} [E_{in}] \\ 0 \end{bmatrix} \quad (1)$$

where, k_1 and k_2 are the coupling ratios of LP_{01} and LP_{02}, respectively; λ is the free space wavelength; $\varphi_1 = (2\pi n_1 L_1)/\lambda$ and $\varphi_2 = (2\pi n_2 L_1)/\lambda$ are the phase delays of the LP_{01} and LP_{02} in the SFS-FI-1 respectively; L_1 is the length of the FMF1 in the SFS-FI-1. The transmittance can be described as:

$$T_1 = \frac{|E_3|^2}{|E_1|^2} = (\sqrt{k_1 k_2} - \sqrt{(1-k_1)(1-k_2)})^2 + 4\sqrt{k_1 k_2 (1-k_1)(1-k_2)} \sin^2(\frac{\varphi_1 - \varphi_2}{2}). \quad (2)$$

The free spectral range (*FSR*) of the SFS-FI-1 can be expressed as:

$$\Delta\lambda = \frac{\lambda^2}{L_1(n_1 - n_2)}. \quad (3)$$

Also, the same method is applied in the SFS fiber-interferometer 2 (SFS-FI-2) analysis, and the transmittance can be described as:

$$T_2 = (\sqrt{k_1 k_2} - \sqrt{(1-k_1)(1-k_2)})^2 + 4\sqrt{k_1 k_2 (1-k_1)(1-k_2)} \sin^2(\frac{\varphi_3 - \varphi_4}{2}) \quad (4)$$

where $\varphi_3 = (2\pi n_1 L_2)/\lambda$ and $\varphi_4 = (2\pi n_2 L_2)/\lambda$ are the phase delays of the LP_{01} and LP_{02} in the SFS-FI-2 respectively. L_2 is the length of the FMF2 in the SFS-FI-2. The *FSR* of the SFS-FI-2 can be expressed as:

$$\Delta\lambda = \frac{\lambda^2}{L_2(n_1 - n_2)}. \quad (5)$$

By setting the $k_1 = k_2 = 0.5$, the length of the FMF1 is 2.8 m and the length of the FMF2 is 0.3 m, the simulated transmittance spectra of the SFS-FI-1 and SFS-FI-2 can be obtained, as shown in Fig. 2(a) with the blue and red curves respectively. These results reveal that the *FSRs* of two interferometers are ~1.27 nm and ~11.88 nm, respectively. And the maximum transmittance of the CIF can be expressed as:

$$T = T_1 T_2 = \sin^2(\frac{\varphi_1 - \varphi_2}{2}) \sin^2(\frac{\varphi_3 - \varphi_4}{2}). \quad (6)$$

As shown in Fig. 2(b), by superimposing the two waveforms of the SFS-FI-1 and SFS-FI-2, the simulated transmittance spectrum of the CIF is obtained with better filtering capability. Here, the marked ~1.27 nm decided by the SFS-FI-1 is defined as the *FSR* of the CIF, and the marked ~11.88 nm decided by the SFS-FI-2 is defined as the period of the CIF.

If the length of the FMF2 is changed, as shown in Fig. 2(c) and (d), the filtering capability of the CIF can be changed. We obtained the transmittance of the CIF using three lengths of the FMF2, as shown in Fig. 2(b), (c) and (d). When the length of the FMF2 is 0.1 m, the period of the CIF is ~35.64 nm, which will weaken the filtering effect of the CIF due to the wide period. When the length of the FMF2 is changed to 0.5 m, the period of the CIF becomes ~7.13 nm, as shown in Fig. 2(d), and the output spectrum of the lasers may be uneven if the CIF is used for wavelength filtering. Therefore, as a tradeoff, ~0.3 m is selected as the length of the FMF2 for obtaining better filtering effect. When the length of the FMF1 is 5 m and the length of the FMF2 is 0.28 m respectively, the simulated transmittance spectra of the CIF are obtained, as shown in Fig. 2(e) and (f). And the *FSR* and period of the CIF are ~0.71 nm and ~12.73 nm, respectively, which used in a MWTDFL are expected to stimulate more laser lines. In Fig. 2(f), the transmittance is decreased because k_1 / k_2 equals to 9. Therefore, the greater the difference in the coupling ratio of LP_{01} and LP_{02}, the lower the transmittance of the CIF. All in all, compared with a single SFS-FI, a CIF is with higher flexibility and adjustability significantly.

Based on the parameters used in the simulation, we fabricated a CIF and investigated its filtering characteristics experimentally as follows. We used a 2-m-long TDF-based amplified spontaneous emission (ASE) as the light source. The transmission spectrum of the CIF was measured using a

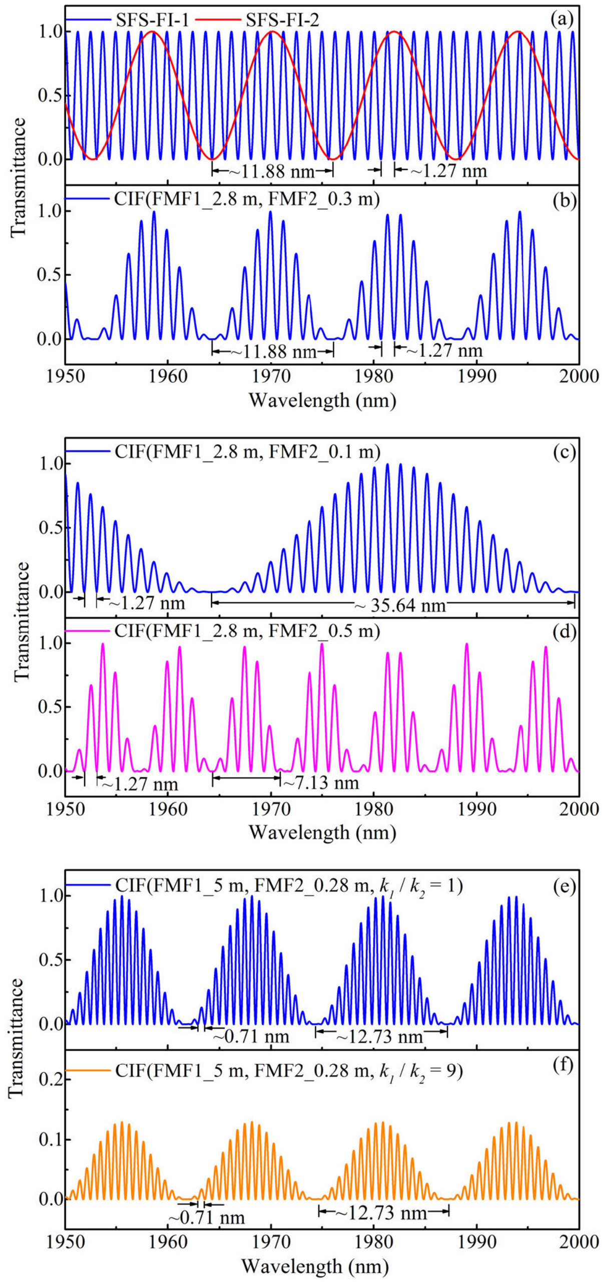

FIGURE 2. (a) Simulated transmittance spectra of SFS-FI-1 and SFS-FI-2, and (b), (c), (d), (e), (f) are simulated results obtained for five CIFs with different FMF lengths.

Yokogawa AQ6375 optical spectrum analyzer (OSA; Yokogawa Electric Corp., Tokyo, Japan) with a resolution of 0.05 nm and a data sampling interval of 0.01 nm. As shown in Fig. 3, the black curve is the relative transmittance obtained by subtracting the ASE spectrum from the transmission spectrum of the CIF. The black curve shows similar filtering characteristics as the simulated result in Fig. 2(b). The period of ~12.26 nm of the CIF is dependent on the length of the FMF2 used in the SFS-FI-2, and the *FSR* of ~1.28 nm of the CIF is dependent on the length of the FMF1 used in the SFS-FI-1.

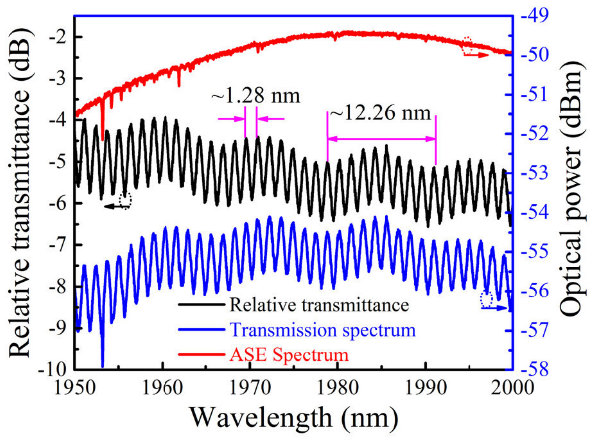

FIGURE 3. Spectrum of amplified spontaneous emission (ASE) source shown as a red curve, transmission spectrum of the CIF shown as a blue curve and relative transmittance shown as a black curve.

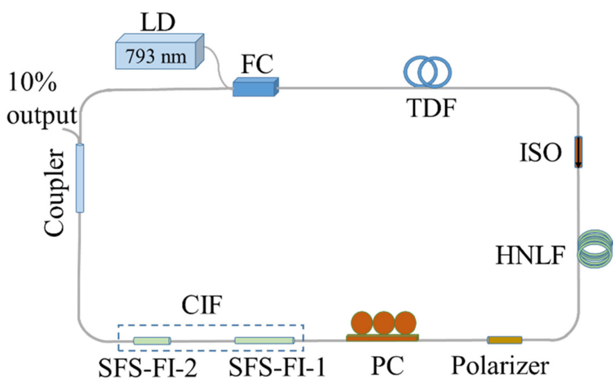

FIGURE 4. Experimental setup of the proposed MWTDFL.

III. EXPERMENTAL SETUP AND RESULTS

The illustration of the experimental setup is shown in Fig. 4. Through a 793/2000 nm fiber combiner (FC), the pump from a 793 nm laser diode (LD) is injected into a 2 m thulium-doped double cladding fiber manufactured by the Nufern Corporation (East Granby, CT, USA). The core/cladding diameter of the active fiber is 10/130 μm, and the core/cladding numerical aperture (NA) is 0.15/0.46. An isolator is used to ensure the unidirectional light propagation. A 150-m-long HNLF is introduced to provide the FWM effect and mitigate the mode competition caused by the homogeneous gain broadening in the TDF. The nonlinearity coefficient of the HNLF is -12 (W $\cdot$km)$^{-1}$, the NA and the cladding diameter are 0.35 μm and 125 μm, respectively. The laser is extracted from the cavity by the 10% port of a 90/10 optical coupler which is used since a smaller output coupling ratio is beneficial for obtaining a larger number of lasing lines for a MWTDFL [22]. A polarizer and a PC are used in the ring cavity to form the PDL effect.

In theory, as the pump power increases, the conversion efficiency of the FWM effect is enhanced and the wavelength competition inside the laser cavity is reduced. Therefore, the total cavity gain is shared by different laser lines. In addition, due to the use of the polarizer and the PC, for the wavelength lines paralleling with the transmission channels of the CIF, some of them with the same polarization direction as the operation axis of the polarizer experience less loss and can eventually oscillate in the cavity. So by rotating the paddles of the PC, the gain and loss of different modes are balanced in the cavity. Based on the effects above, stable and switchable multi-wavelength lasing lines are obtained in the 2-μm band. When the pump power was set at 3.25 W, as shown in Fig. 5(a) and (b), three different switchable operating modes were obtained, and these

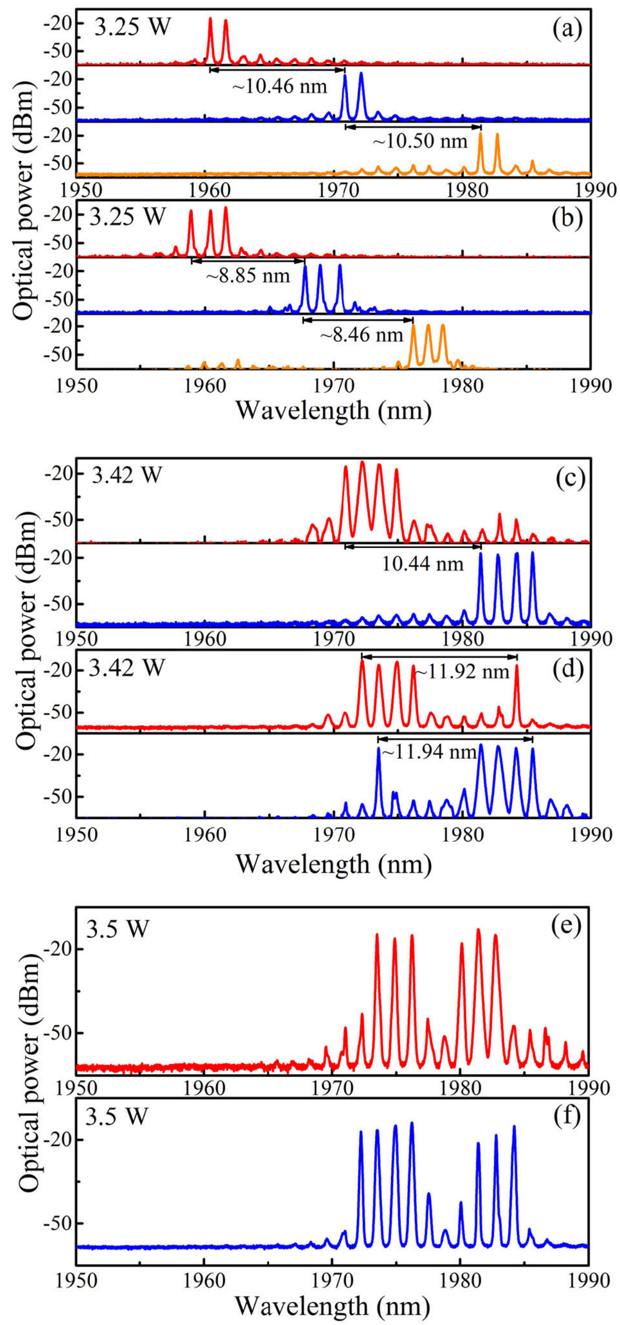

FIGURE 5. Output spectra of switchable operations: (a) dual- (b) three- (c) four- (d) five- (e) six- and (f) seven-wavelength operation.

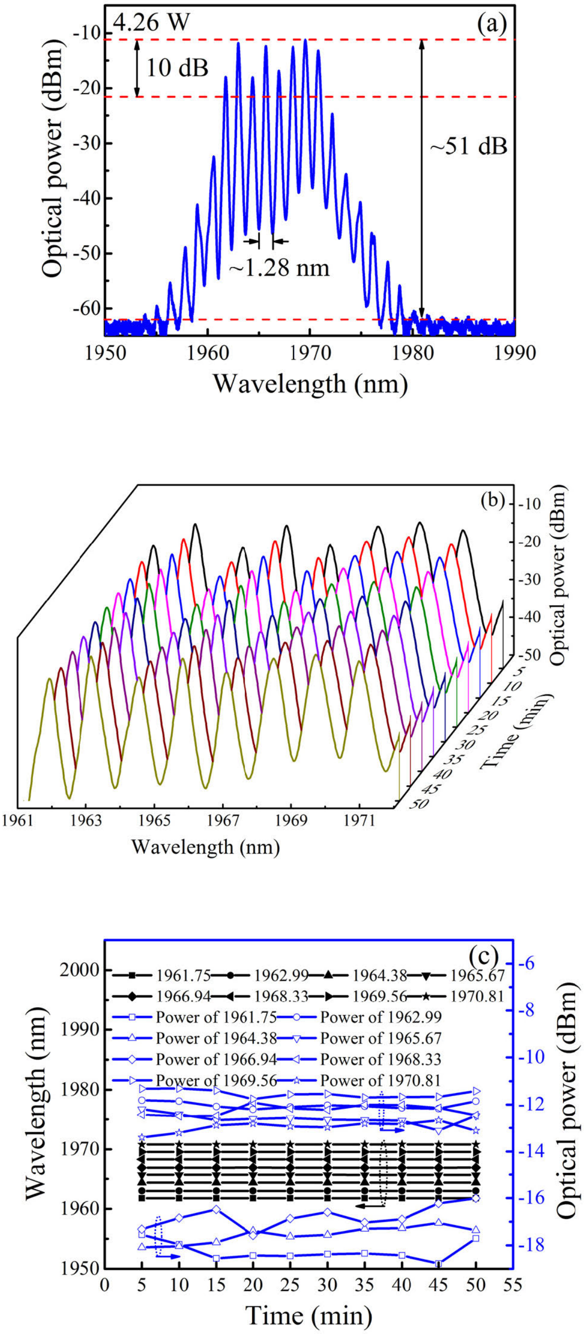

FIGURE 6. (a) Output spectra of the eight-wavelength operation, (b) measurement for ten repeated OSA scans of the eight-wavelength operation with a time interval of 5 min, (c) wavelength drifts and power fluctuations.

switchable wavelength spacings were respectively several times the *FSR* of the CIF. The dual-wavelength operations, with a switchable wavelength spacing of ~10.50 nm, were measured, as shown in Fig. 5(a). Similarly, by adjusting the PC, three-wavelength operations, with a switchable wavelength spacing of ~8.85 nm and ~8.46 nm, were achieved. Then, after increasing the pump power to 3.42 W, two four-wavelength operations, with a switchable wavelength

TABLE 1. Stability comparison of multi-wavelength lasing based on different techniques.

Filter	Stabilization technique	Maximal number of wavelengths	Maximal power fluctuation	Observ ation Time
Coupled microfiber MZI	PR + macro-bendin g [24]	6	±2 dB	30 min
F-P filter	SMF + NPR [33]	28	0.2 dB	60 min
PM-Sagnac	Graphene device [34]	11	1 dB	30 min
FBG	Highly nonlinear photonic crystal fiber [35]	4	0.45 dB	35 min
Taper non-adiabat ic microfiber-Sagnac	Taper non-adiabatic microfiber-Sa gnac [36]	3	3 dB	16 min
CIF	**This work**	**31**	**0.706 dB**	**50 min**

spacing of ~10.44 nm, were achieved, as shown in Fig. 5(c). Additionally, two switchable five-wavelength operations were achieved by carefully adjusting the PC, and the covered wavelength range was ~11.9 nm, exactly a period of the CIF. When the pump power was continuously increased to 3.5 W, the six- and seven- wavelength lasers were obtained, as shown in Fig. 5(e) and (f).

When the pump power was as high as 4.26 W, eight laser channels were achieved within a 10 dB bandwidth from 1961.75 to 1970.81 nm, with an adjacent spacing of ~1.28 nm, and an optical signal-to-noise ratio (OSNR) of ~51 dB, as shown in Fig. 6(a). For the eight-wavelength operation, the stability was evaluated with the OSA without changing any device in 50 min with a time interval of 5 min, and the results were displayed in Fig. 6(b) and (c). Then, each wavelength drift can be obtained by subtracting the minimum wavelength from the maximum wavelength observed by the OSA with a resolution of 0.05 nm and a data sampling interval of 0.01 nm in 50 min. These results show that the maximum power fluctuation is within 1.579 dB and the wavelength drift is less than 0.02 nm, indicating that our MWTDFL can operate with good switching performance and high stability in the 2-μm band.

In addition, we further improved the filtering capability of the CIF to achieve dense multi-channel lasing by using a 5-m-long FMF in the SFS-FI-1 and a 0.28-m-long FMF in the SFS-FI-2. When a pump power of 7.37 W was used, 31 output laser lines located at the range of 1973.89~1995.99 nm were obtained within a 10 dB bandwidth, as shown in Fig. 7(a). The adjacent wavelength spacing of ~0.72 nm was determined by the *FSR* of the SFS-FI-1. The stability of the 31-wavelength lasing was measured by repeatedly scanning the OSA in 50 min with a time internal of 5 min. The maximum power fluctuation was within 0.706 dB, and the wavelength drift was less than 0.02 nm, as shown in Fig. 7(c). To verify the spectrum stabilizing effect of the SFS-FI-2,

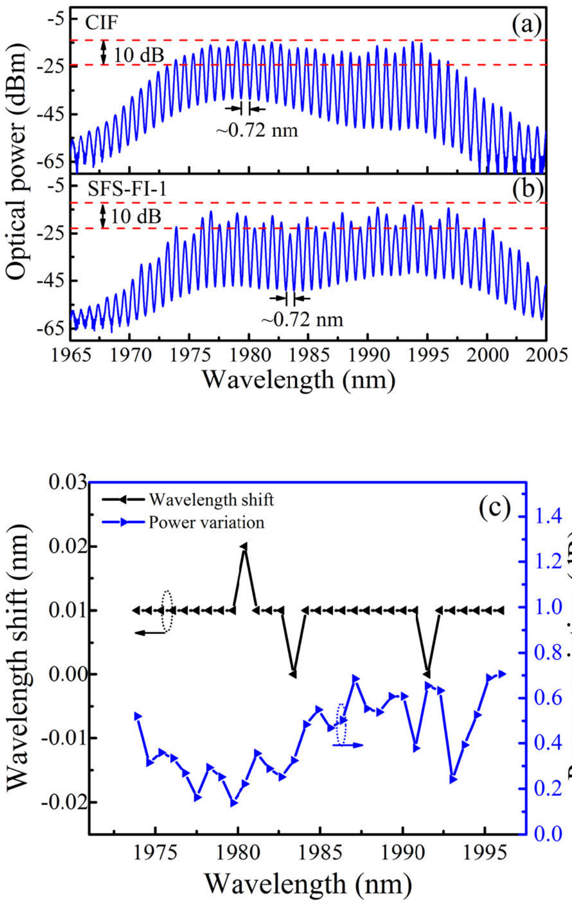

FIGURE 7. **(a) Output spectrum of the MWTDL based on the CIF, (b) output spectrum of the MWTDFL without the SFS-FI-2, (c) wavelength drifts and power fluctuations of the CIF in 50 min with a time interval of 5 min.**

we removed it from the laser structure. As shown in Fig. 7(b), compared to Fig. 7(a), a larger fluctuation among laser lines was observed and the number of laser lines was decreased to 24 within the 10 dB bandwidth at the same pump power. Therefore, the CIF is beneficial to obtain a more uniform dense multi-wavelength laser for the MWTDFL. Besides, the results in Fig. 7(a) reveal that the maximum central wavelength power among all of the lasing channels is ∼-14.5 dBm, which is relatively low. This is primarily due to the low conversion efficiency induced by the significant cavity loss from the components used in the cavity. The stability comparison of multi-wavelength lasing based on different techniques is shown in TABLE 1. The data indicate that our MWTDFL has an outstanding stability performance, which mainly benefits from the FWM effect, the PDL and the excellent capability of the CIF.

IV. CONCLUSION

A stable MWTDFL with two cascaded SFS MZIs and a 150-m-long HNLF has been proposed and demonstrated. The SFS-FI-1 was used to select specific wavelengths, which definitely determined the *FSR* of the global filter. The SFS-FI-2 was used to generate more laser lines. With the increasing of the pump power, the multi-channel output was attributed to the strong FWM effect. By carefully adjusting the PC, the switchable multi-wavelength laser lines were obtained by means of the PDL effect. When the power was increased to about 7.37 W, two cascaded filters could make the envelope more uniform. The stability of our fiber laser was measured in 50 min, and the maximum power fluctuation and wavelength drift were within 0.706 dB and 0.02 nm, respectively. Relatively, the low spectrum power of the MWTDFL obtained was attributed to the high cavity loss originating from the key components used inside the cavity. The performance of the proposed MWTDFL can be further improved by using a good vibration isolation and temperature compensation packaging.

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