Stable multi-wavelength thulium-doped fiber laser based on all-fiber Mach–Zehnder interferometer

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We propose and experimentally demonstrate a multi-wavelength thulium-doped fiber (TDF) laser based on all-fiber Mach–Zehnder interferometer (MZI) at 1.9 μm. Here a segment of 4 m single-mode TDF is pumped by 1568 nm fiber laser for 2 μm band optical gain. The MZI includes two cascaded 3 dB coupler. A segment of 3.5 m long un-pumped polarization-maintaining TDF and polarization controller (PC) are joined in the ring cavity to suppress the mode competition. Multi-wavelength lasers at 1.9 μm with wavelength number from one to four are obtained by adjusting the PC and the stability of output power of multi-wavelength fiber laser is analyzed.

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Thulium-doped fiber (TDF) laser sources operating in the eye-safe 2 μm spectral region have been researched over the past decade owing to their numerous potential applications in areas such as lidar, remote sensing, medical treatment, and free-space optical communications[1–3]. In recent years, high-power narrow linewidth, wide tuning range, and mode-locked 2 μm TDF laser have been researched[4–11] and TDF amplifiers have also been designed for free-space optical communications at 2 μm band optical gain[12].

As for most potential applications mentioned, multi-wavelength lasers have the great benefits of being compact and cost-effective. Multi-wavelength fiber lasers have been significantly researched in recent years. At room temperature, multi-wavelength 2 μm region fiber laser can be achieved by different approaches, such as the incorporation of high-birefringence fiber Bragg grating (FBG)[13], the use of a nonlinear loop mirror or the nonlinear polarization rotation effect[14,15], and the combination of highly nonlinear fiber[16]. However, high-birefringence FBG limits the number of lasing wavelengths due to the narrow transmission bands, and highly nonlinear fiber increases the insertion loss in the cavity. Multi-wavelength lasers based on linear loop mirror or the nonlinear polarization rotation effect limit the side mode suppress ratio (SMSR) and linewidth of lasing wavelengths.

In this letter, a stable multi-wavelength TDF laser operating at 1.9 μm is proposed and demonstrated by using an all-fiber Mach–Zehnder interferometer (MZI) and a segment of polarization-maintaining (PM) TDF. The all-fiber MZI works as a comb filter to select wavelength and the PM-TDF acts as a saturable absorber to ensure the operation of stable multi-wavelength. At room temperature, multi-wavelength laser with wavelength number from one to four can be obtained by tuning the polarization controller (PC) in the cavity. SMSR and 3 dB linewidth are 57 dB and 0.149 nm, respectively, as observed by optical spectrum analyzer (OSA) and the stability of multi-wavelength fiber laser is analyzed.

Figure 1 shows a schematic diagram of the multi-wavelength TDF laser with the ring cavity. The 1568 nm fiber laser with maximum power of 250 mW is injected into a segment of 4 m long TDF by a 1570/2000 nm wavelength division multiplexer (WDM). An optical isolator is used to ensure that the laser oscillates in a single direction around the ring. The MZI, as a comb filter, is used as the wavelength selector in the cavity. A 3.5 m long PM-TDF acts as a saturable absorber to weaken the homogeneous gain broadening and suppress the mode competition. The multi-wavelength lasing output is measured by an OSA (Yokogawa, AQ6375) from the 10% port of a coupler.

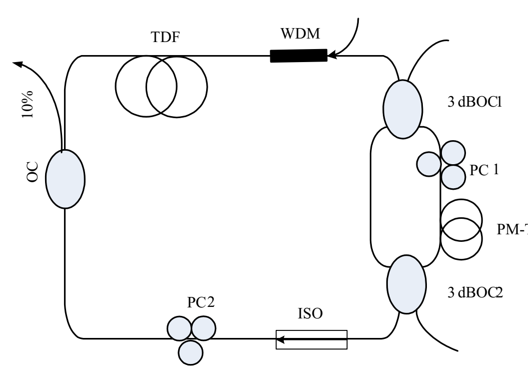

Fig. 1. Configuration of multi-wavelength TDF laser. OC, optical coupler; ISO, optical isolator.

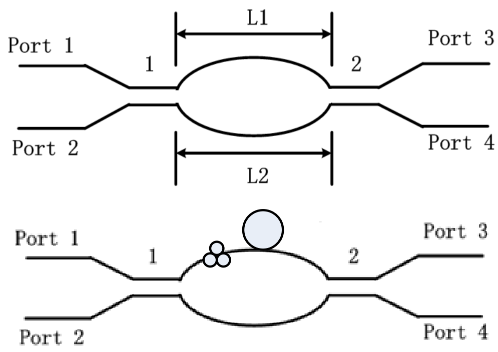

Fig. 2. Traditional MZI (top) and modified MZI (bottom).

The transmission spectrum of a MZI is characterized by a series of equally spaced transmission peaks in the frequency domain. The conventional MZI is formed by concatenating together the two 2 × 2 coupler as shown in Fig. 2. Optics launched into port 1 and the intensity transmission in port 3 is[17–19]

$$T_3 = \frac{1}{2}\left(1 + \cos(2\theta_1)\cos(2\theta_2) - \sin(2\theta_1)\sin(2\theta_2)\cos\varphi\right), \quad (1)$$

where $\varphi = \beta_0 \Delta L$ is the phase difference between the two arms of the MZI, $\Delta L = L_1 - L_2$ is a path difference, and $\beta_0 = n_2 k(1 + b\Delta)$ is the propagation constant of the fundamental mode in an optical fiber.

The overall spectral response of the interferometer is determined by ΔL, and the wavelength spacing ΔL between the transmission peaks is given as

$$\Delta\lambda = \frac{\lambda^2}{n\Delta L}, \quad (2)$$

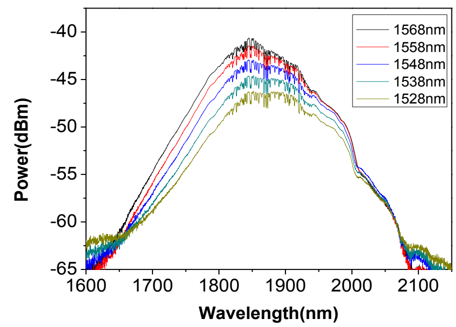

Fig. 3. ASE spectrum at different pump wavelengths.

where n is the effective refractive index of the laser mode and λ is the laser wavelength. Therefore, a conventional MZI can be used as a comb filter to generate multi-wavelength lasers.

It can be seen from Fig. 2 that the un-pumped TDF acts as a saturable absorber to suppress the unwanted, weaker modes and allow only the dominant wavelengths to oscillate in the cavity[20]. PC in one arm of MZI can be considered as a modified MZI[21]. The filter characteristics can be analyzed from the following Jones matrix representation:

$$\begin{bmatrix} [E_3] \\ [E_4] \end{bmatrix} = [C_1] \begin{bmatrix} [F_1][\mathrm{PC}][\mathrm{PMF}] & 0 \\ 0 & [F_2] \end{bmatrix} [C_2] \begin{bmatrix} [E_1] \\ [E_2] \end{bmatrix}, \quad (3)$$

where

$$[C_m] = \begin{bmatrix} \sqrt{1 - C_m}\,[I] & j\sqrt{C_m}\,[I] \\ j\sqrt{C_m}\,[I] & \sqrt{1 - C_m}\,[I] \end{bmatrix},$$

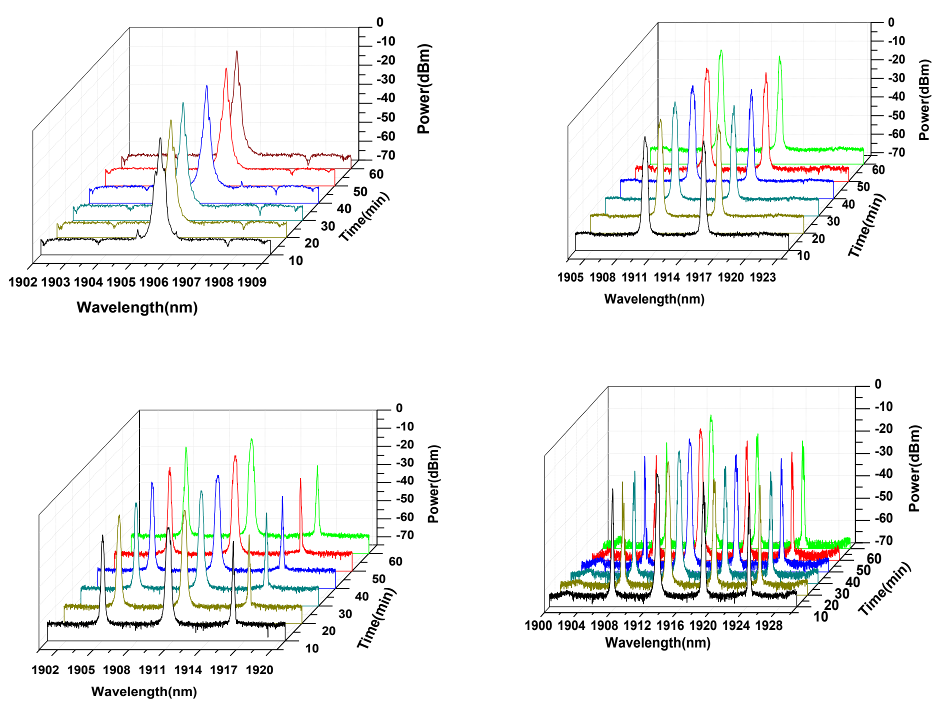

Fig. 4. Spectra of multi-wavelength TDF laser at 1.9 μm.

$$\left[\mathrm{PC}\right]=\begin{bmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{bmatrix},\ \left[\mathrm{PMF}\right]=\begin{bmatrix}e^{-\mathrm{j}\phi} & 0\\ 0 & e^{\mathrm{j}\phi}\end{bmatrix},$$

$$\left[F_1\right]=\begin{bmatrix}e^{\mathrm{j}kn_xL} & 0\\ 0 & e^{\mathrm{j}kn_yL}\end{bmatrix},\ \left[F_2\right]=\begin{bmatrix}e^{\mathrm{j}\left(kn_xL+\varphi\right)} & 0\\ 0 & e^{\mathrm{j}\left(kn_yL+\varphi\right)}\end{bmatrix},$$

where $[I]$ is the identity matrix, C_{m} is the coupling ratio, θ is the rotation angle of the propagating light through PC1, L is the length of the arm 1, n_x and n_y are the indices of the two axes of the fiber, and φ is the phase difference between the light on the fast axis and that on the slow axis in the same transmission distance, which is determined by the vast difference.

If E_1 is 1 and E_2 is 0, E_4 can be shown as

$$\left[E_4\right]=\begin{bmatrix}\cos\theta e^{\mathrm{j}(kn_xL-\phi)}+\frac{\mathrm{j}}{2}e^{\mathrm{j}(kn_xL+\varphi)} & \sin\theta e^{\mathrm{j}(kn_xL+\phi)}\\ -\sin\theta e^{\mathrm{j}(kn_yL-\phi)} & \cos\theta e^{\mathrm{j}(kn_yL+\phi)}+\frac{\mathrm{j}}{2}e^{\mathrm{j}(kn_yL+\varphi)}\end{bmatrix}. \tag{4}$$

It is well-known that this scheme can be used as a comb filter to generate multi-wavelength lasers based on $\cos\theta$ and $\sin\theta$ in Eq. (4). The spacing of multi-wavelength fiber lasers is determined by L, n_x, n_y, ϕ, and φ. And ϕ and φ are determined by the lengths of the arms and PM-TDF. The parameters cannot be easily changed in the experiment. And PC1 can be used to adjust the wavelength of fiber laser in small range according to θ in Eq. (4) and the number of wavelengths can be changed by PC1 and PC2 because of the limited pump power.

TDF has different absorption and conversion efficiency when the wavelength of the pump laser is tuned. Figure 3 shows the amplified spontaneous emission (ASE) spectrum at different pump wavelengths. The wavelength of pump laser is fixed at 1568 nm, and the pump laser is injected into the TDF to generate multi-wavelength fiber laser at 1.9 μm. Figure 4 shows that multi-wavelength laser at 1.9 μm with number from one to four is measured by OSA with 0.05 nm wavelength resolution. SMSR of generated laser is about 57 dB. Single and multi-peaks in Fig. 4 are generated by mainly adjusting PC2. And PC2 can be used to adjust the cavity loss for different wavelengths. PC1 may be used to adjust the wavelength in small range to coordinate PC2 because of the limited pump power. The 3 dB linewidth of laser is around 0.149 nm in Fig. 5. It can be found that the spacing of the multi-wavelength fiber laser is about 6 nm. The spacing of the multi-wavelength laser can be determined by the parameters of arms and PM-TDF as discussed later and 6 nm spacing is relatively stable.

The output optical spectrum is measured over a 10 min period within 60 min. The power and frequency fluctuations of multi-wavelength laser are determined as in Fig. 6. The frequency drift is less than ±0.02 nm, and the power fluctuation is almost less than ±0.5 dB from the average power. The power fluctuation of four-wavelength fiber laser is greater than the power fluctuation of single-wavelength laser as shown in Fig. 6. Power competition of four-wavelength laser by the limited pump power can exist. The fluctuations of power

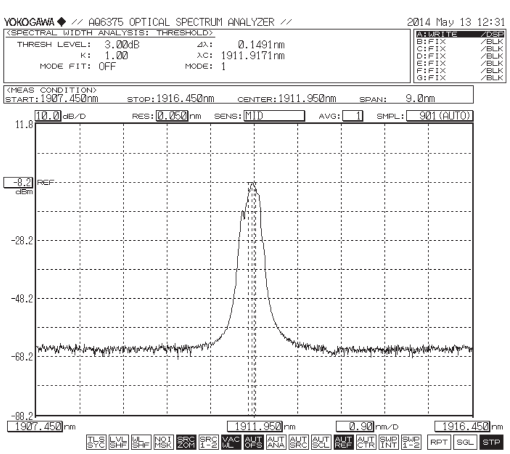

Fig. 5. Spectra of single-wavelength TDF laser at 1.9 μm.

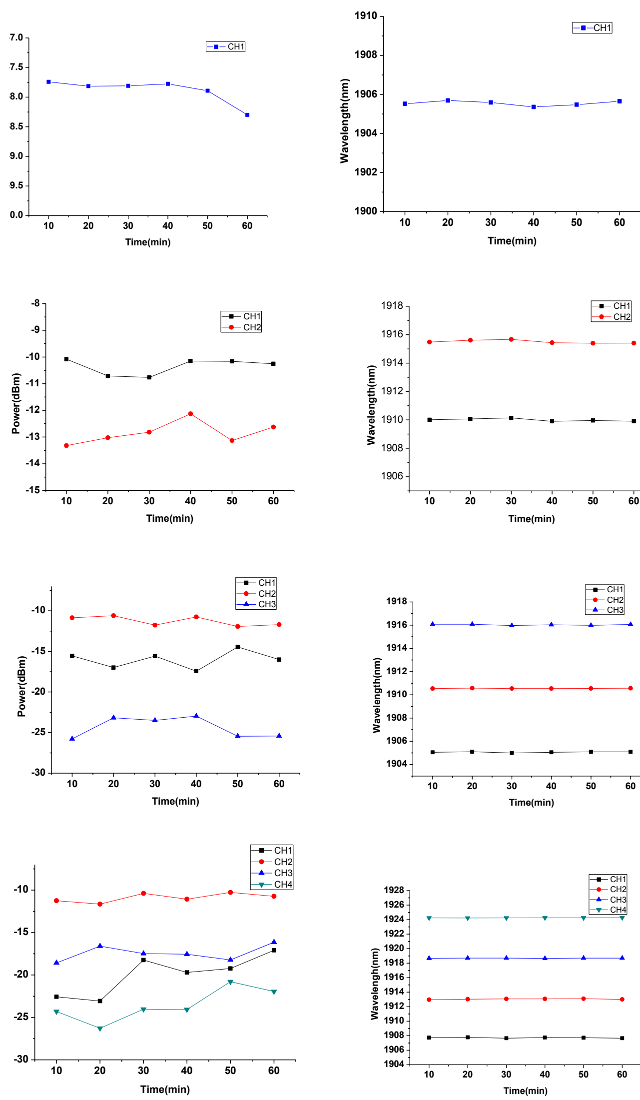

Fig. 6. Power variation and frequency drift of multi-wavelength laser in 60 min.

and frequency in the multi-wavelength signal can be reduced in stable experimental environment with more pump power. It also can be seen that the wavelength drift of multi-wavelength fiber laser is relatively stable because of the PM-TDF used.

In conclusion, we propose and demonstrate a stable multi-wavelength TDF laser around 1.9 μm based on all-fiber MZI. The output wavelength number can be tuned from one to four by adjusting PC. SMSR of the generated laser is about 57 dB and the 3 dB linewidth of laser is about 0.149 nm. The frequency drift is less than $\pm$0.02 nm and the power fluctuation is less than $\pm$0.5 dB from the average power. Furthermore, if we use a higher pump power, the laser for more wavelength number can be obtained.

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References

1. K. Bremer, A. Pal, S. Yao, E. Lewis, R. Sen, T. Sun, and K. T. V. Grattan, Appl. Opt. **52,** 3957 (2013).
2. S. D. Jackson, A. Sabella, and D. G. Lancaster, IEEE J. Sel. Top. Quant. Electron. **13,** 567 (2007).
3. N. P. Barnes, B. M. Walsh, D. J. Reichle, and R. J. D. Young, Opt. Mater. **31,** 1061 (2009).
4. Y. Tang, C. Huang, S. Wang, H. Li, and J. Xu, Opt. Express **20,** 17539 (2012).
5. L. Jiang and W. Pu, Chin. J. Lasers **40,** 0102001 (2013).
6. Y. Wei, K. Hu, B. Sun, and T. Wang, Laser Phys. **22,** 770 (2012).
7. C. Liu, C. Ye, Z. Luo, H. Cheng, D. Wu, Y. Zheng, Z. Liu, and B. Qu, Opt. Express **21,** 204 (2013).
8. M. Zhang, E. J. R. Kelleher, F. Torrisi, Z. Sun, T. Hasan, D. Popa, F. Wang, A. C. Ferrari, S. V. Popov, and J. R. Taylor, Opt. Express **20,** 25077 (2012).
9. L. Jiang and W. Pu, Chin. J. Lasers **39,** 0902001 (2012).
10. X. Yang, Y. Chen, C. Zhao, and H. Zhang, Chin. Opt. Lett. **12,** 031405 (2014).
11. C. Guo, D. Shen, J. Long, and F. Wang, Chin. Opt. Lett. **10,** 091406 (2012).
12. Z. Li, A. M. Heidt, J. M. O. Daniel, Y. Jung, S. U. Alam, and D. J. Richardson, Opt. Express **21,** 9289 (2013).
13. W. J. Peng, F. P. Yan, Q. Li, S. Liu, T. Feng, S. Y. Tan, and S. C. Feng, Appl. Opt. **52,** 4601 (2013).
14. M. A. Chernysheva, A. A. Krylov, P. G. Kryukov, and E. M. Dianov, IEEE Photon. Technol. Lett. **24,** 1254 (2012).
15. W. Peng, F. Yan, Q. Li, S. Liu, T. Feng, and S. Tan, Laser Phys. Lett. **10,** 115102 (2013).
16. S. Liu, F. P. Yan, B. L. Wu, S. Y. Tan, W. J. Peng, T. Feng, and Q. Li, J. Opt. **16,** 055201 (2014).
17. A. P. Luo, Z. C. Luo, and W. C. Xu, Opt. Lett. **34,** 2135 (2009).
18. H. L. An, X. Z. Lin, E. Y. B. Pun, and H. D. Liu, Opt. Commun. **169,** 159 (1999).
19. W. G. Chen, S. Q. Lou, S. C. Feng, L. W. Wang, H. L. Li, T. Y. Guo, and S. S. Jian, Laser Phys. **19,** 2115 (2009).
20. H. Ahmad, A. A. Latif, J. M. Talib, and S. W. Harun, J. Eur. Opt. Soc. Rapid Publ. **8,** 13038 (2013).
21. A. P. Luo, Z. C. Luo, and W. C. Xu, Opt. Lett. **34,** 2135 (2009).