Influence of Pedestal Fiber Splice on Tm-Doped Fiber Laser Performance

Sijie Wang, Hui Shen, Xiaolong Chen, Qiubai Yang, Meng Wang, Yunfeng Qi, and Xisheng Ye

***Abstract*—The influence of Tm-doped pedestal fiber splice on the output performance of a large-mode-area (LMA) Tm-doped fiber laser (TDFL) has been investigated. Arc-fusion induced refractive-index deformation leads to laser leakage from the core to the pedestal, resulting in a periodic decrease in the output power of TDFL. Based on the measured refractive-index of splice with different arc-fusion parameters, the influence of the Tm-doped pedestal splice on laser propagation was analyzed using the beam propagation method (BPM). The simulation results indicate that optimizing the arc-fusion parameters can improve the efficiency of laser coupling into the fiber core at the splice. Experimental comparisons were made to assess the impact of different arc-fusion parameters on laser performance. By optimizing arc-fusion parameters of the TDFL, the near-periodic power degradation is reduced effectively. A hundred-watt-level all-fiber TDF setup was established. Compared to the initial splice, the optical conversion efficiency increased from 39.6% to 48.4% and the beam quality factor M^2 was reduced from 10.55 to 2.17 in the horizontal direction and from 11.89 to 2.26 in the vertical direction. Understanding these mechanisms behind the abnormal power fluctuations hold practical value for the design of TDF pedestal fiber and further power scaling.**

***Index Terms*—Large mode area, pedestal fiber splice, Tm-doped fiber laser.**

I. Introduction

THULIUM-DOPED fiber lasers (TDFLs) operating in the 1900–2100 nm wavelength region have been used in a wide variety of applications, such as light detection and ranging systems, surgery treatment and plastic material processing [1], [2], [3], [4], [5] during the last decade. In the previous works, several groups have performed remarkable experiments, setting a series of records for large-mode-area (LMA) high average output power TDFLs. In 2010, Ehrenreich et al. demonstrated the first kilowatt-class TDFL using two high power stages in a master oscillator power amplifier (MOPA) configuration [6]. In 2021, a 1.1kW thulium-doped fiber amplifier (TDFA) was developed by Anderson et al. with narrow linewidth operation [7]. Recently, a widely-tunable all-fiber Tm-doped MOPA system is reported with the power of >1kW [8]. These progresses have largely been enabled by introducing LMA [9] to mitigate parasitic nonlinear processes, such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) [10].

The requirement for further power scaling results in a fiber design criterion in which the core must have a high Tm^{3+} dopant concentration. In this scenario, the core has a large refractive-index compared with the cladding. Thus, a raised index layer known as pedestal [11] is commonly used to reduce the numerical aperture (NA) of the core. Such a pedestal is typically doped with germanium. Arc-fusion splicing is a preferred process used in all-fiber lasers. Since the splicing temperature of the pedestal is significantly lower than the core and cladding, the splice is more challenging [12]. In our recent experiments, an abnormal power degradation caused by arc-fusion has been observed in LMA TDFLs with pedestal structures. In order to achieve efficient and stable laser amplification, it is necessary to investigate the characteristics of different arc-fusion splice on the refractive index and laser propagation of Tm-doped pedestal fiber.

In this paper, employing a combination of the measured refractive-index data and the beam propagation method (BPM), the impact of the arc-fusion splice on the laser propagation and fiber core coupling efficiency in Tm-doped fibers (TDFs) incorporating a pedestal was investigated. The simulation result revealed the phenomenon for abnormal power degradation in TDFL. The influence of different arc-fusion parameters was experimentally verified by comparing laser performance.

II. Abnormal Power Degradation in LMA TDFA

A. Observation of the Power Degradation

The abnormal power degradation was observed in the MOPA configuration TDFA system, as shown in Fig. 1. The oscillator operating at 1940 nm was pumped by laser diodes (LDs) at a central wavelength of 793 nm. A $(2+1)\times 1$ combiner was used to couple the pump light to the gain fiber. The high-reflection fiber Bragg grating (HR FBG) and the low-reflection fiber Bragg grating (LR FBG) had a reflectivity of 99.5% and 9.8% with a bandwidth of 2.2 nm and 0.8 nm. The active fiber in the oscillator was a TDF with the core/cladding diameter of 10/130 μm. The residual pump power was filtered using a cladding pump stripper (CPS). The seed laser was injected through a mode field adaptor (MFA) and an isolator was employed to block the backward light. In the main amplifier an LMA TDF with a 25 μm core, 65 μm pedestal around the core, and 400 μm cladding was used

Manuscript received 14 August 2023; revised 22 September 2023; accepted 30 September 2023. Date of publication 3 October 2023; date of current version 14 November 2023. This work was supported by the National Natural Science Foundation of China under Grant 62005300. *(Corresponding authors: Yunfeng Qi; Xisheng Ye.)*

The authors are with the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China and College of Materials Science and Opto-Electronic Technology, University of Chinese Academy of Sciences, Beijing 100049, China (e-mail: wangsijie@siom.ac.cn; nature0546@163.com; xl_chen@siom.ac.cn; yangqiubai@siom.ac.cn; wm542@siom.ac.cn; dreamer_7@siom.ac.cn; xsye@siom.ac.cn).

Digital Object Identifier 10.1109/JPHOT.2023.3321751

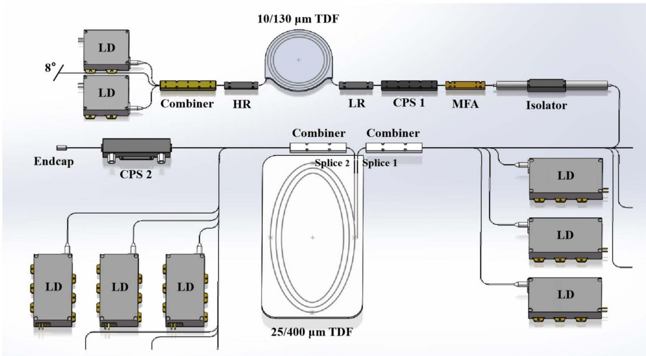

Fig. 1. Experimental setup of thulium-doped fiber amplifier.

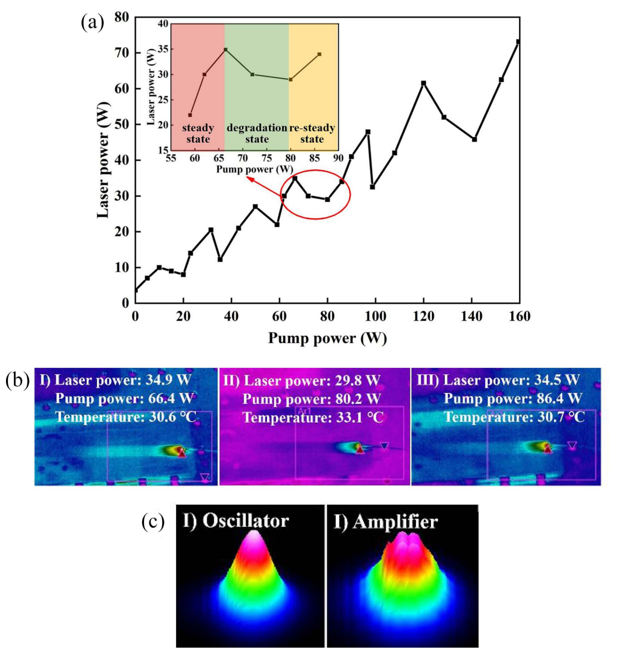

Fig. 2. Evolution of the output power, the CPS and beam images. (a) Output power versus launched pump power in TDFA system; (b) CPS output-side temperature of the I) steady state, II) degradation state, and III) re-steady state; (c) beam images of the I) oscillator and II) amplifier.

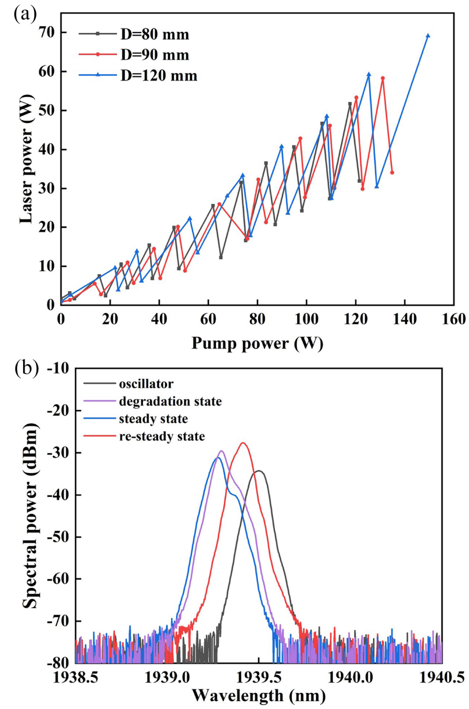

Fig. 3. (a) Relationship between output power versus launched pump power in TDFA system at different bending radii; (b) laser spectra for different output power of oscillator and amplifier.

as the gain fiber. The TDF was bi-directionally pumped by six LDs by using $(6+1)\times 1$ combiners and coiled in a water-cooled plate with a diameter of 95 cm. Define the splices at the start and end of the TDF as "splice 1" and "splice 2". An endcap was used at the end of the system to reduce the Fresnel reflection. All components were placed on a water-cooled heat sink.

During the process of increasing the seed power and the pump power in amplifier, a near-periodic output power degradation was observed, accompanied by an increase of the temperature at the output-side of the CPS. The evolution of the output power and the CPS temperature with respect to the input pump power is depicted in Fig. 2(a) and (b), respectively. One of these cycles is chose as an example for illustration. A slight increase in the amplifier input pump power from 66.4 W to 80.2 W resulted in a sudden decrease in output laser power from 34.9 W to 29.8 W accompanied by a temperature increase at the output side of the CPS from 30.6 °C to 33.1 °C. A continued increase of the input pump power returned the amplifier to a normal state of operation, while the output laser power and CPS temperature were observed as 34.5 W and 30.7 °C, respectively. These three states are defined as steady state, degradation state, and re-steady state. This near-periodic power degradation reduced the optical conversion efficiency of the amplifiers to 39.6%. Additionally, it is worth noting that the beam image of the oscillator is a stable fundamental mode, while the wavefront of the beam appeared chaotic after transmission through the amplifier, whether the amplifier has pump light or not, as shown in Fig. 2(c).

B. Further Experimental Investigations

Transverse mode instability (TMI) induced by the heat load [13] and photo-darkening [14] can leads to a degradation of output laser power. However, the power degradation observed in this work occurs at lower laser power and fluctuates periodically as the laser power increases, which is not consistent with the phenomenon caused by the above reasons. The output power of TDFLs at different bending radii is shown in Fig. 3(a). It shows that the abnormal power degradation is characterized as bending insensitivity. Consequently, the influence of the high-order modes bending loss can be ruled out. Experimental examinations were conducted to check the transmittance as well as the beam profile of the components (CPS, MFA, isolator, and combiner) used in TDFAs. These investigations determined that these components do not impact the laser transmission performance. The wavelengths of the oscillator and amplifier

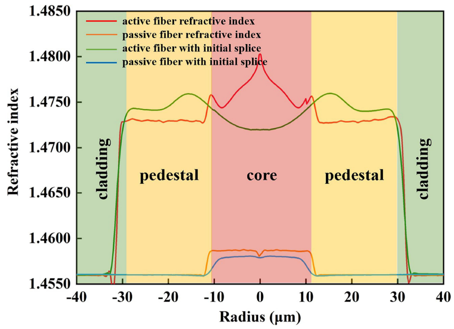

Fig. 4. Measured refractive-index profile of LMA active and passive fibers with initial splice.

were detected, as shown in Fig. 3(b). It shows that there is no multi-wavelength caused by mode competition in the amplifier.

The refractive-index of the splice was measured by using an IFA-100 Optical Fiber Analyzer [15]. It was found that arc-fusion (initial splice parameters) caused a decrease in the refractive-index of the fiber core and increase of the pedestal refractive-index. Fig. 4 shows the refractive-index distribution of original and spliced fiber. Since laser transmission can be affected by the refractive-index distribution of the fiber, it is inferred that the near-periodic power degradation was related to the splice between the active and passive fibers.

III. Numerical Simulation and Analysis

Beam propagation method (BPM) was used to simulate the laser propagation at a wavelength of 1940 nm. Several positions were chosen for each of the passive and active fibers near the splice to measure the refractive indices. The linear interpolation method was used to fit the refractive index between the measured longitudinal positions. By injecting a LP_{01} seed laser from passive fiber to the active fiber, the simulation results were shown in Fig. 5. The computation length for the longitudinal propagation was set as 12000 μm.

The initial splicing parameters induce the decrease in the refractive-index of the fiber core and the increase of the pedestal. It can be considered that there is no longer a definable core. The total reflection is not properly satisfied in the core-to-pedestal interface of TDF. Thus, the laser escapes from the core into the pedestal when passing through the splice. When the laser reaches the interface of the pedestal and cladding layer, part of the laser is re-transmitted from the pedestal to the core as the refractive-index of the cladding is still much smaller than that of the pedestal.

When the "splice 2" is implemented with the initial splicing parameters, a large part of the laser will leak into the cladding layer, as shown in Fig. 6. The laser propagating in the cladding will be filtered by CPS, which induces output power degradation and mode deterioration in TDFL. Laser leakage to the cladding caused by worse splice quality of "splice 1" and "splice 2" is the origin of the decrease of output efficiency in TDFL.

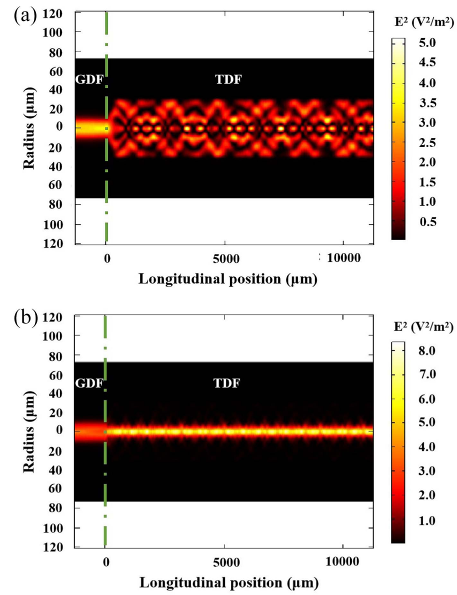

Fig. 5. Laser propagation for "splice 1" with (a) initial splice and (b) original fiber.

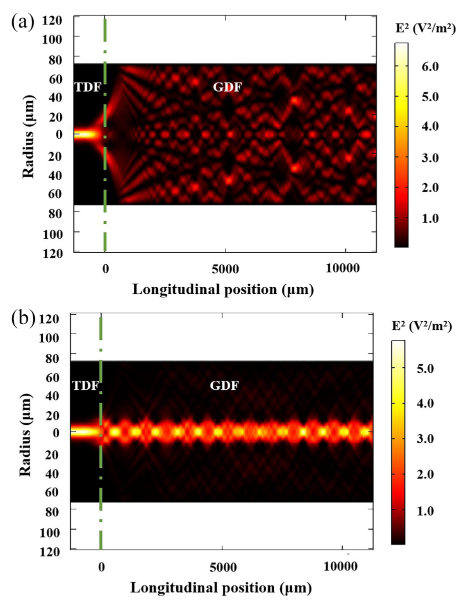

Fig. 6. Laser propagation for "splice 2" with (a) initial splice and (b) original fiber.

In the amplifier, with the increase of injected seed power and pump power, the number of the modes propagating inside the fiber is gradually increased. LP_{01} and LP_{11} modes with lower losses are mainly considered. As shown in Fig. 7, the laser propagation of LP_{01} and LP_{11} modes in the initial splice and the original fibers were simulated using the refractive index in Fig. 4. The core-to-pedestal energy ratio was defined as the amount of energy within the core relative to the pedestal at each fiber cross section along the longitudinal positions. The baseline simulation shows a weak oscillation within the core. The baseline of LP_{01} has an average core-to-pedestal energy ratio of 94.14% and the

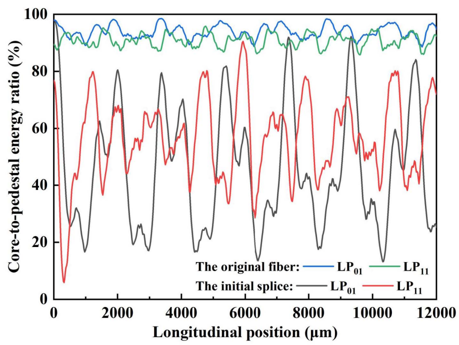

Fig. 7. Comparison of LP_{01} and LP_{11} modes core-to-pedestal energy ratio in the original fibers and the initial splice.

peak-to-peak deviation of 10.54%, and the baseline of LP_{11} has an average core-to-pedestal energy ratio of 90.67% and the peak-to-peak deviation of 11.04%. The core-to-pedestal energy ratio for different modes fluctuates near-periodically versus the propagation distance and the fluctuation period of LP_{11} mode is smaller than LP_{01} mode. As the number of propagating modes increases, the laser propagating within the fiber core fluctuates. The laser that leaks into the pedestal will be stripped by CPS, which results in the near-periodic degradation of the output power.

IV. Splice Optimization for Tm-Doped Pedestal Fibers

A. *Refractive-Index Distribution and Energy Ratio of Fiber Core for Different Splice Parameters*

Several pieces of active and passive fiber were spliced using different arc-fusion splice programs. More detailed refractive-index profiles at the positions near the splice for the passive and active fibers are presented in Fig. 8, for varying arc-fusion time and power, respectively.

For a set of fixed arc-fusion power parameters, the refractive-index deformation decreased with decreasing arc-fusion time. The refractive-index deformation is particularly severe at the position closest to the splice point. The indices measured further away from the splice had less deformation and gradually restored the same index as that of the original fiber. A minimum refractive-index decline was observed at the arc-fusion time 11500 ms, beyond which the refractive-index deformation rebounded. The minimum achievable refractive-index deformation for different arc-fusion powers (with 11500 ms arc-fusion time) is shown in Fig. 8(b). As can be seen from Fig. 8(a), (I) and (b), (V), when using the initial splice, diffusion effects will lead to a significant broadening of the fiber pedestal-core interface. Compared with the initial splice, the diffusion observed at the optimized splice is significantly reduced (from 10 to 2 μm).

The variation of the laser energy in the fiber core as it propagates through the fiber was calculated, as shown in Fig. 9. LP_{01} mode was injected into the TDF. The laser propagation in the original passive fiber and active fiber was simulated, which served as a reference baseline. In the case of the initial splice

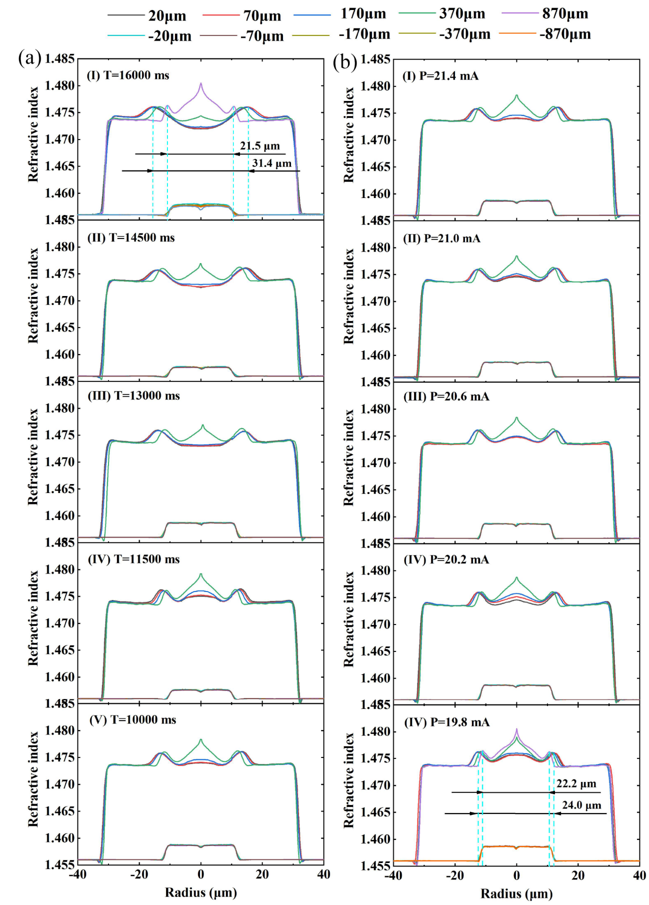

Fig. 8. Refractive-index profiles of splices with variation of (a) arc-fusion time and (b) arc-fusion power.

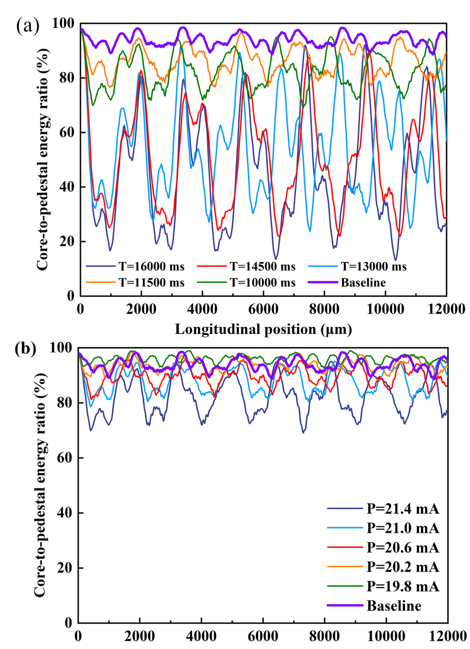

Fig. 9. Comparison of core-to-pedestal laser energy ratio due to refractive-index profile distortions along the splice position with (a) arc-fusion time variation and (b) arc-fusion power variation.

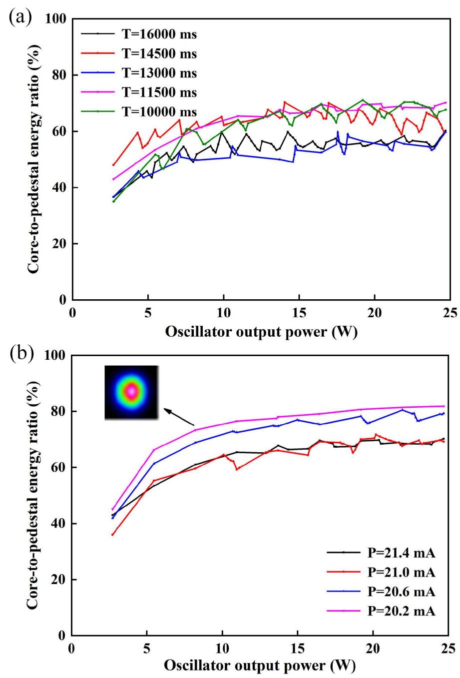

Fig. 10. Output power evolution in the fiber core versus the injected seed laser with (a) arc-fusion time variation and (b) arc-fusion power variation.

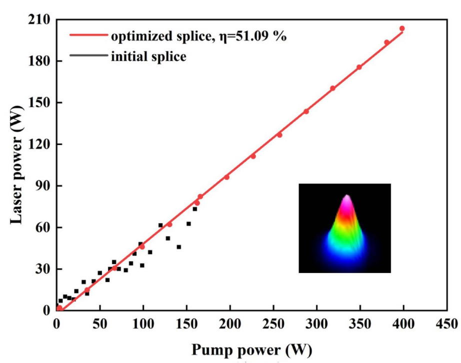

Fig. 11. Output performance of thulium-doped fiber amplifier using optimized splice.

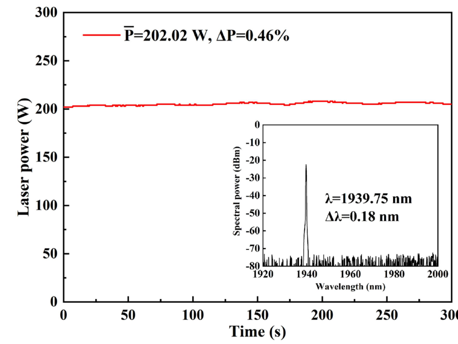

Fig. 12. Long-term output power stability.

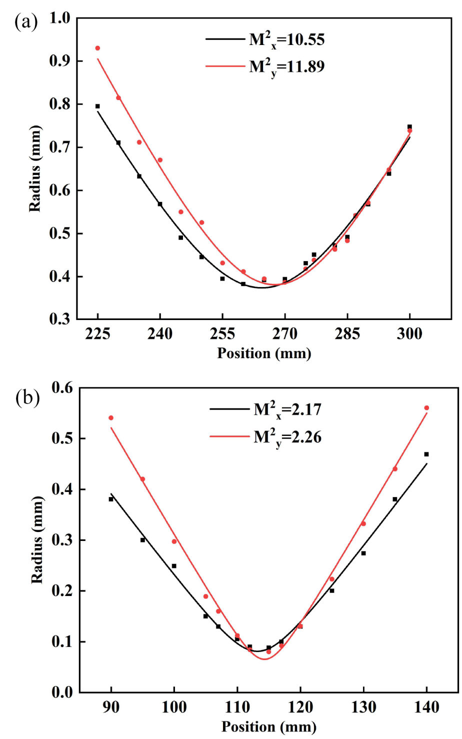

Fig. 13. Measured beam quality factor M^2 for (a) initial splice and (b) optimized splice.

(T = 16000 ms), the laser in the fiber core fluctuates between 20–80%. The energy ratio of fiber core can be stabilized at 89.97% by arc-fusion optimization, which has not yet reached the baseline (the average core-to-pedestal energy ratio of 94.14% and the peak-to-peak deviation of 10.54%). The arc-fusion time and power optimization plays an important role in fiber splice with pedestal structure, which minimizes laser leakage and, therefore, results in stable laser output power.

B. Experimental Optimization of Pedestal Fiber Splice

The experiments performed in this section were based on the TDFA setup depicted in Fig. 1. Combiners used in the amplification stage were removed. The 25/400 μm LMA TDFs were spliced into the corresponding matched passive fibers using different arc-fusion splice times and powers. Fig. 10 depicts the ratio of the laser power propagated in the core to that in the pedestal filtered by the CPS. The power propagating in the fiber core can be measured by adding a CPS (stripping efficiency >20 dB) in the end of the amplifier. For the measurement of the power in the pedestal, the CPS was removed and a 45° reflection mirror (HT > 99%@780–800 nm, HR > μm) was added at the output of the GDF to filter out pump power. Since there is no pedestal structure in the passive fiber, the total power of the pedestal and core can be measured after passing through the reflection mirror. The power in the pedestal can be obtained by subtracting the measured power in the fiber core from the total power. Thus, the power in core relative to the pedestal can be calculated. When the arc-fusion time was reduced from 16000 ms to 11500 ms, the splice-caused power leakage was significantly decreased and the output power stability was improved. However, when the arc-fusion time was further reduced to 10000 ms, the laser output power fluctuation became evident again. For the arc-fusion time of 11500 ms, the proportion of laser power in the fiber core increased as the arc-fusion power was reduced from 21.4 mA to 20.2 mA. When the arc-fusion power was further reduced to 19.8 mA, it was found that the splice temperature was high due to the pump power leakage in the cladding. The experimental results are consistent with the simulation results in Section IV that arc-fusion optimization can improve TDFL output performance.

After using the optimized arc-fusion splice, the output performance of the TDFA is improved as shown in the Fig. 11. In order to prevent any potential damage to the isolator, a seed laser with a power of 10 W was chosen to be injected into the amplifier. The maximum TDFA output laser power was increased to 204 W. Correspondingly, the optical conversion efficiency is improved from 39.6% to 48.4% and the near-periodic power degradation has been effectively inhibited. As shown in Fig. 12, the average power was measured as 202.02 W with the power fluctuation of 0.46% under 5 mins operation. At the maximum operating power, the measured M^2 beam parameters reduce from 10.55 to 2.17 in the horizontal direction and from 11.89 to 2.26 in the vertical direction, as shown in Fig. 13.

V. Conclusion

In summary, the splice quality of the pedestal fiber has a significant impact on the output performance of LMA TDFL. Numerical simulations demonstrated that arc-fusion power and time optimization can restrain the deformation of the fiber core refractive-index, which improve the core-to-pedestal energy ratio from 20–80% fluctuating to 89.97%. A splice quality evolution system has been established, and it has been verified that optimized splice can improve the amplification efficiency, output power stability and beam quality for a pedestal fiber amplifier. Compared to the unsuitable splice under the same TDFL configuration, the near-periodic power degradation can be suppressed effectively by using optimized splice parameters. The optical conversion efficiency of the TDFL system using optimized splice is increased from 39.6% to 48.4%, and the beam quality factor M^2 is reduced from 10.55 to 2.17 and from 11.89 to 2.26 in the horizontal and vertical directions, respectively. The aforementioned investigation results can play guiding role for the further laser power scaling, beam quality optimization and fiber design in LMA TDFL with pedestal fiber.

References

[1] Q. Q. Hao, W. X. Liu, Y. Q. Zu, Y. X. Wang, J. Liu, and L. B. Su, “Highly efficient dual-wavelength acousto-optically Q-switched Tm,La:CaF2 laser,” *Chin. Opt. Lett.*, vol. 20, no. 11, 2022, Art. no. 111402.

[2] K. Scholle, S. Lamrini, P. Koopmann, and P. Fuhrberg, “2 µm laser sources and their possible applications,” in *Frontiers in Guided Wave Optics and Optoelectronics*. London, U.K.: IntechOpen, 2010, pp. 491–496.

[3] L. Y. Yang et al., “Record power and efficient mid-infrared supercontinuum generation in Germania fiber with high stability,” *High Power Laser Sci. Eng.*, vol. 10, 2022, Art. no. e36.

[4] J. H. Yuan, J. R. Li, Z. Y. Wu, S. C. Li, J. Han, and L. J. Li, “Passively Q-switched operation of a 1.94 µm thulium-doped solid-state laser based on MXene V2CTx,” *Chin. Opt. Lett.*, vol. 21, no. 2, 2023, Art. no. 021402.

[5] W. C. Huang et al., “Emerging mono-elemental bismuth nanostructures: Controlled synthesis and their versatile applications,” *Adv. Funct. Mater.*, vol. 31, 2020, Art. no. 2007584.

[6] T. Ehrenreich, R. Leveille, I. Majid, K. Tankala, G. Rines, and P. Moulton, “1-kW, all-glass Tm:Fiber laser,” *Proc. SPIE*, vol. 7580, 2010, Art. no. 758016.

[7] B. M. Anderson, J. Soloman, and A. Flores, “1.1 kW, beam-combinable thulium doped all-fiber amplifier,” *Proc. SPIE*, vol. 11665, pp. 35–40, 2021.

[8] C. Y. Ren et al., “Widely-tunable all-fiber Tm-doped MOPA with >1 kW of output power,” *Opt. Exp.*, vol. 31, no. 14, pp. 22733–22739, 2023.

[9] E. X. Liu and J. J. Liu, “Quasiperiodic photonic crystal fiber,” *Chin. Opt. Lett.*, vol. 21, no. 6, 2023, Art. no. 060603.

[10] M. L. Gong, Y. Y. Yuan, C. Li, P. Yan, H. T. Zhang, and S. Y. Liao, “Numerical modeling of transverse mode competition in strongly pumped multimode fiber lasers and amplifiers,” *Opt. Exp.*, vol. 15, no. 6, pp. 3236–3246, 2007.

[11] F. Möller et al., “Influence of pedestal diameter on mode instabilities in Yb/Ce/Al-doped fibers,” *Opt. Exp.*, vol. 28, no. 22, pp. 33456–33474, 2020.

[12] Z. M. Gu et al., “High-efficiency cladding-pumped 4-core erbium-doped fiber with a pedestal for space division multiplexing amplification,” *Opt. Exp.*, vol. 30, no. 19, pp. 34973–34983, 2022.

[13] X. X. Luo et al., “Power of all-fiber amplifier increasing from 1030 W to 2280 W through suppressing mode instability by increasing the seed power,” *Chin. Phys. B*, vol. 28, no. 2, 2019, Art. no. 024208.

[14] L. H. Xie et al., “Experimental investigation of quasi-static mode degradation in a high power large mode area fiber amplifier,” *Opt. Exp.*, vol. 29, no. 6, pp. 7986–7997, 2021.

[15] T. Walbaum, M. Heinzig, T. Schreiber, R. Eberhardt, and A. Tünnermann, “Monolithic thulium fiber laser with 567 W output power at 1970 nm,” *Opt. Lett.*, vol. 41, no. 11, pp. 2632–2635, 2016.