第 42 卷第 10 期　　光　子　学　报　　Vol. 42 No. 10
2013 年 10 月　　ACTA PHOTONICA SINICA　　October 2013

doi:10.3788/gzxb20134210.1147

基于分布泵浦结构的高功率掺 Tm 光纤激光器

龙井宇[1,2],沈德元[1],王屹山[1],赵卫[1],郭成正[1,3]
(1 中国科学院西安光学精密机械研究所 瞬态光学与光子技术国家重点实验室, 西安 710119)
(2 西安应用光学研究所,西安 710065)
(3 中国科学院研究生院,北京 100049)

摘　要:为了实现掺 Tm 光纤激光器的高功率连续运转,需要解决半导体激光器输出的低光束质量泵浦光到增益光纤包层的高效耦合问题,以及增益光纤的热管理问题.利用柱面透镜组成的望远镜光学系统对半导体激光器输出泵浦光束进行扩束,使其水平方向的光束发散角获得降低,利用 45°反射切割镜对扩束后的光束进行切割,经整形处理后水平方向的光束参量积为 84 mm·mrad,实现了约 70%的光纤端面耦合传输效率.设计了两段增益光纤串联的结构,增加了泵浦光接收端面数,获得了 528 W 的可用泵浦功率.光纤的热管理方面,在泵浦光的输入端部(约 250 mm),采用了水冷金属热沉散热.基于该实验装置,利用总长度 6.4 m 的掺 Tm 增益光纤,获得了最高 280 W 的连续输出功率,激光中心波长 2 015 nm,对应于耦合泵浦功率的斜率效率达 55.6%.实验结果表明:通过对半导体泵浦光束的整形处理,可以提高光束对增益光纤的耦合传输效率;双光纤串联的结构在增加可用泵浦功率的同时,降低了光纤端部的热负载,并使整个光纤长度上的热分布更加均匀.

关键词:光束整形;掺 Tm 光纤激光器; 分布泵浦
中图分类号:TN242; TN248　　**文献标识码**:A　　**文章编号**:1004-4213(2013)10-1147-5

High Power Operation of a Tm-doped Fiber Laser with Distributed Pump Configuration

LONG Jing-yu[1,2], SHEN De-yuan[1], WANG Yi-shan[1], ZHAO Wei[1], GUO Cheng-zheng[1,3]
(1 *State Key Laboratory of Transient Optics and Photonics*, *Xi'an Institute of Optics and Precision Mechanics*, *Chinese Academy of Sciences*, *Xi'an* 710119, *China*)
(2 *Xi'an Institute of Applied Optics*, *Xi'an* 710065, *China*)
(3 *University of Chinese Academy of Sciences*, *Beijing* 100049, *China*)

Abstract: In order to realize the high-power operation of the Tm doped silica fiber laser, there are two issues to be resolved. One is how to couple the pump light with low beam quality into the inner cladding of gain fiber efficiently, the other is on thermal management of gain fiber. For an efficient coupling, firstly the output beam of high power LD modules were collimated to reduce their beam diverge in the plane parallel to the array by use of a telescope system consisting of cylindrical aspheric lenses, and then the collimated beams were cut with splitters. The beam parameter in the plane parallel to the array was optimized to 84 mm · mrad(BPP_x) after the reshaping, and a coupling efficiency of 70% was achieved by this means. A series connection structures consisting of two sections of Tm fiber with identical length were fabricated to increase available pump power and reduce the heat generation along the fiber ends, which achieved a total available pump power up to 580 W. With regard to the thermal management, each end section

---

Foundation item: "Hundreds of Talents Programs" of Chinese Academy of Sciences

First author: LONG Jing-yu (1979—), male, Ph. D. degree, mainly focuses on fiber laser technology. Email:jylong532@sina.com
Contact author(Corresponding author): SHEN De-yuan (1962—), male, research fellow, mainly focuses on fiber laser technology. Email: shendy@opt.ac.cn

Received: Mar. 11, 2013; **Accepted**: Jun. 17, 2013

(250 mm long) of fibers was embedded in a V groove in a water cooled aluminum heat sink. Based on this configuration a continuous-wave output power of up to 280 W operating at 2 015 nm was obtained for 6.4m-long gain fiber, corresponding to a slope efficiency of 55.6% with respect to the launched pump power. The experimental results indicate that the special reshaping and laser configuration can improve pump coupling efficiency, reduce thermal loading and give more even axial temperature distribution along the gain fibers.

Key words: Beam shaping; Tm-doped fiber laser; Distributed pump

0 Introduction

Tm doped fiber lasers emitting at 2 μm wavelength rang have attracted considerable research interests recently because of various potential applications for medicine, optical communications, eye-safe radar, remote sensing and military technology. The double-cladding Tm doped silica fiber lasers offer a route to very high power operation by pumped from the absorption band at about 800 nm with an improved efficiency by exploiting the "two-for-one" cross-relaxation process ($^3H_4 + ^3H_6 \rightarrow ^3F_4 + ^3F_4$). High power Tm doped silica fiber lasers operating at continuous-wave (cw), tunable and single frequency modes have been reported with ~790 nm high power diode pumping. T. Ehrenreich, *et al*. demonstrated a 1-kW, all-glass Tm fiber MOPA system with a slope efficiency of 53%[1]. W. A. Clarkson, *et al*. used a MOPA configuration to successfully obtain >100 W of cw output with a wavelength tuning range of 190 nm from 1 820 nm to 2 010 nm[2]. Gregory D, *et al*. reported a four-stage, Tm-doped fiber amplifier chain emitting 608 W of single-frequency (SF) output power with 53 dB gain, 54% slope efficiency, and $M^2 = 1.05$ beam quality[3]. Both experimental results and theoretical analysis indicate that below the 1 kW laser power region, the power limitation of Tm silica fiber laser is the available pump power for the common fiber length and core diameter[4]. Nonetheless, coupling high power laser diode light into the fiber cladding is always challenging due to the low brightness nature of laser diodes. To achieve efficient launching efficiency, one should employ the diode laser with a small beam parameter product (BPP) which is depend on the fill factor of diode emitters and beam shaping technique[5-8]. Compared to bulk solid state lasers, though, fiber lasers encounter less difficulty in thermal management by virtue of more favorable surface to volume ratios, but they are far from completely thermal immune. In fact, there is a temperature limit relating to the thermal degradation of double clad fiber coatings[9]. For scaling power to high level (normally 100 W or more), effective removal of the heat dissipated in the core is crucial to keep the coating temperature below the onset of damage. Using distributed pump configuration as a solution to facilitate heat dissipation and reduce the operating temperature has been proposed in numerical modeling work[10]. Side-pumping via imbedded v-grooves and pump couplers used in all-fiber lasers are well suited for coupling multiple pump beams into inner-cladding of the gain fiber[11-12]. For end-pumped fiber lasers, however, it is difficult to realize distributed pump scheme.

In this paper, we propose a Tm-doped double-cladding silica fiber laser distributed pumped by high power laser diodes at 790 nm. Benefiting from reduced thermal loading and improved uniformity of the axial temperature distribution along gain fibers, a continuous-wave power of up to 280 W operating at 2 015 nm was produced with a slope efficiency of 55.6% with respect to launched pump power.

1 Beam shaping design

The Tm doped silica fibers used in our experiment have an inner cladding of octagonal cross section and with flat to flat diameter of 400 μm which was coated with a low refractive index polymer outer cladding resulting in a numerical aperture of 0.46. At wavelength of 790 nm the measured absorption coefficient was 2.7 dB/m. The core diameter is 25 μm with a numerical aperture of 0.09, which constructs a so-called large mode area (LMA) fiber with advantages in terms of the ability to mitigate unwanted nonlinear processes and catastrophic damage. Two identical LD modules with center wavelength of 790 nm were employed as pump sources each providing up to 400 W power (provided by Xi′an Focuslight Technologies Co. Ltd. For effectively coupling the pump light into the fiber inner cladding, one should ensure its BPP fulfill the following condition[13]

$$\mathrm{BPP} \leqq D \cdot \arcsin(\mathrm{NA})/2 \qquad (1)$$

where D and NA are diameter and numerical aperture of inner cladding, respectively. The output beam of LDs have an approximate rectangular cross section with a beam width in the plane parallel to the array $d_x = 30$ mm and a beam width in the plane perpendicular to the array $d_y =$ 23mm, respectively. The beam parameter products in orthogonal planes were measured to be $\mathrm{BPP}_x =$ 168 mm • mrad (parallel to the array) and $\mathrm{BPP}_y =$ 96 mm • mrad (perpendicular to the array), respectively (NanoScan, Photon Inc), which indicated that the BPP_x significantly exceeded the limit calculated from the corresponding parameter product D • arcsin(NA)/2 of the Tm doped fiber used in our experiment (i. e. 95. 6 mm • mrad), and there was an asymmetric for either beam width or BPP along two orthogonal planes.

A poor beam quality of pump light does not merely mean a low launch efficiency, since the pump light can not be confined in inner-cladding completely. The escaped pump light heats the fluorinated polymer coating directly and the heat combined with the thermal loading from quantum defect heating in the core may damage the coating (with a low withstand temperatures up to 150℃～200℃). In our preliminary experiments, indeed, while we attempted to focus this pump light into the fiber inner-cladding, the concentrated heat dissipated at fiber end even ignited the coating and then fused the silica fiber itself, although the water cooled heat sinks were used to cool the fiber ends. Therefore, beam reshaping must be carried out for laser diodes to reduce the BPP_x to less than $\mathrm{BPP} \leqq \mathrm{D} \cdot \arcsin(\mathrm{NA})/2$ and then to produce a more symmetrical BPP along two orthogonal planes. The approach to reshape the beam of pump LDs is shown in Fig. 1.

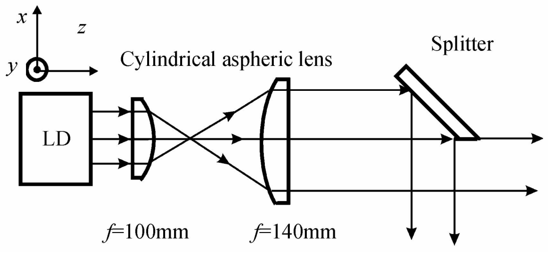

Fig. 1 Optical system for beam reshaping

For the first step, we employed two cylindrical aspheric lenses with the focal length of 100 mm and 140 mm, respectively, to construct a telescope system by which we compressed the far-field divergence angle and expanded the beam width in the plane parallel to the array by a factor of 1. 4. And then, for the second step, we inserted a mirror with high reflectivity at 790 nm (as a splitter) into the beam along the plane parallel to the array by 45° and positioned it where the beam width in the plane parallel to the array was split to half. By this means, we obtained two identical beams with mutually perpendicular propagation direction with improved beam quality (i. e. reduced BPP_x to 84 mm • mrad). Even the beam quality in the plane perpendicular to the array has not been improved yet, more symmetrical beam width(i. e. an approximate square cross section) and nearly equal BPP in orthogonal planes were achieved.

2 Laser setup with distributed pump

The Tm doped fiber laser with distributed pump configuration is shown schematically in Fig. 2. We used two sections of Tm fiber with identical length to build up a series connection structure. The optical connection was achieved by two uniform aspheric lenses ($f = 40$ mm) and mirrors with high reflectivity (>99%) at 1 850～2 100 nm (M_2 and M_3). One of fiber ends was perpendicularly-cleaved to provide the lasing feedback by the 3. 6% Fresnel reflection and as output coupler, which combined a mirror (M_1) with high reflectivity (>99%) at 1 850～2 100 nm locating behind one end of other fiber to make a (a simple Fabry-Perot) resonator configuration. The other three fiber ends were angle cleaved to suppress oscillation of each fiber independently. Aspheric lenses ($f = 26$mm) with antireflection coated at 650～1 050 nm were used as focal lens to couple the pump light into the inner-caldding of Tm doped fiber. The 2 μm laser was separated from unabsorbed pump light by use of dichroic mirrors (DMs) with a high reflectivity at 1 850～2 100 nm (>99%) and high transmission at the

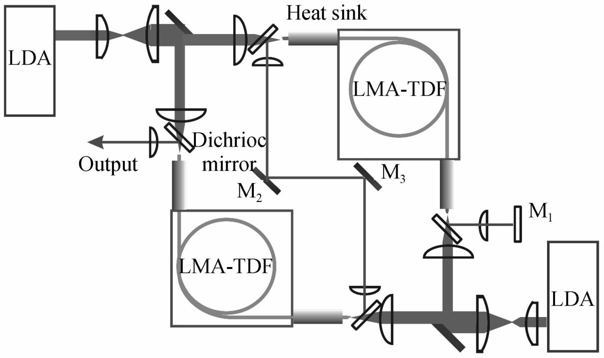

Fig. 2 Tm doped fiber laser with distributed pump configuration

pump wavelength (96%) orientated at 45° relative to the axis of the fiber. The laser output was collimated with an antireflection-coated 40 mm focal length lens. To facilitate heat removal and minimize the risk of thermally induced damage, each end section (250 mm long) of fibers was embedded in a V groove in a water cooled aluminum heat sink with the aid of thermally conducting grease and the remainder of fiber length immersed in room-temperature water.

3 Experimental results and discussion

After passing the beam reshaping optics, the focal lens and the DM, the maximum incident pump power of each reshaped beam was measured to be 188 W. The coupling efficiency was estimated to be about 0.7 from measurements of the transmitted power for a series of different short fiber lengths, which produced a maximum launched power of as much as 132 W for each fiber end. We focused the four beams into the four fiber ends respectively, without any observed fiber facet damage even at full power level, which we contributed to a improved coupling efficiency and a significant decline of thermal loading along the entire fiber length. The output power of the Tm-doped silica double-cladding fiber laser with total gain fiber length of 6.4m and 8m respectively as a function of the total launched pump power are shown in Fig. 3.

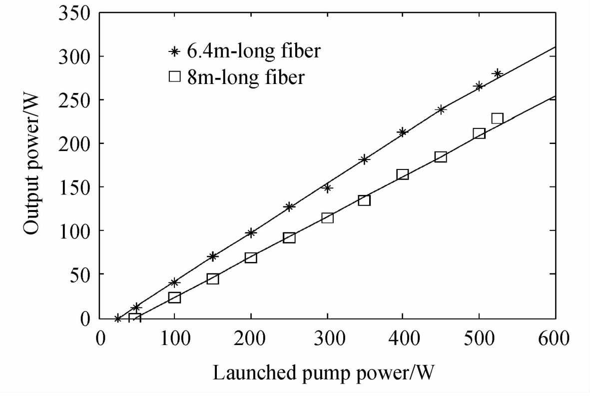

Fig. 3 Output laser power versus pump power

For 6.4-m-long fiber, the output power reached 280 W at the maximum launched pump power of 528 W and the threshold was 25 W, corresponding to a slope efficiency of 55.6%. In contrast, the laser performance was demonstrated be actually degraded for 8m-long fiber. This was, we believed, because of the characteristic three-level re-absorption effects[14]. The fiber with shorter length was not used in our experiments to prevent the increased unabsorbed pump light from damaging the opposite diode elements. It is worth pointing out that there was no rolloff in power (see Fig. 3) and no sign indicating that the power approached the damage threshold of the gain fiber. Thus, we expect that output power is scalable, given more incident pump power. Fig. 4 shows the spectra of laser output. The central wavelength was 2 015 nm at the maximum output power for 6.4-m-long fiber. Due to the re-absorption effects and different thermal loading in the core[15], the lasing wavelength red-shifted to 2 048 nm for the 8m-long fiber. In additional, the significant broad wavelength range with spectral linewidth exceeding 10 nm was always observed in these free-running operations because of the high multiple Stark levels and phonon broadening of Tm ion in silica glass[16].

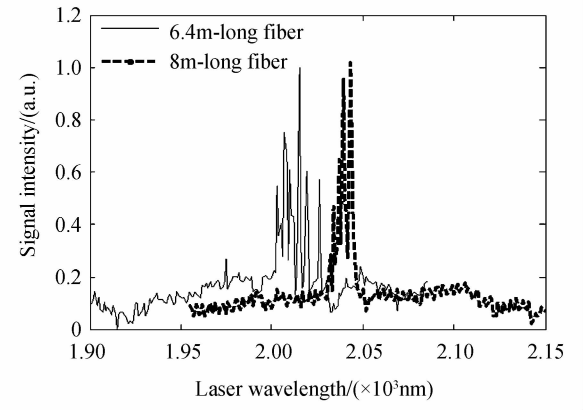

Fig. 4 Output spectra of the Tm doped fiber laser

4 Conclusion

In summary, we demonstrated a high-power Tm doped silica fiber laser operating at 2 015 nm that is capable of generating 280 W of output power, limited by available pump power, with a slope efficiency of 55.6% by using the beam reshaped high-power laser diodes operating at 790 nm. We have shown that even for moderate beam quality levels of pump light, by introducing beam reshaping technique and distributed pump scheme, high power output of Tm doped silica fiber laser can be achieved with improved pump coupling efficiency and more even axial temperature distribution along the gain fibers.

References

[1] EHRENREICH T, LEVEILLE R, MAJID I, *et al*. 1-kW, all-glass Tm: fibre laser [C]. LASE, Fibre Lasers VII: Technology, Sysltems and Applications, SPIE Phtonics West 2010, 2010: 7850-112.

[2] CLARKSON W A, PEARSON L, ZHANG Z, *et al*. High power thulium doped fiber lasers [C]. Optical Fiber Communication Conference, OSA Technical Digest (CD), 2009: paper OWT1.

[3] GOODNO G D, BOOK L D, ROTHENBERG J E. Low phase-noise, single-frequency, single-mode 608 W thulium fiber amplifier[J]. *Optics Letters*, 2009, **34**(8): 1204-1206.

[4] DAWSON J W, MESSERLY M J, BEACH R J, *et al*. Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power[J]. *Optics Express*, 2008, **16**(17): 13240-13266.

[5] CLARKSON W A, HANNA D C. Two-mirror beam-shaping technique for high-power diode bars[J]. *Optics Letters*, 1996, **21**(6): 375-377.

[6] TREUSCH H G, DU K, BAUMANN M, *et al*. Fiber-coupling technique for high-power diode laser arrays[C]. SPIE, 1998, **3267**: 98-106.

[7] WANG P Y, GHEEN A, WANG Z. Beam shaping technology for laser diode arrays[C]. SPIE , 2002, **4770**: 131-135.

[8] GAO X, OHASHI H, OKAMOTO H, *et al*. Beam-shaping technique for improving the beam quality of a high-power laser-diode stack[J]. *Optics Letters*, 2006, **31**(11): 1654-1656.

[9] LAPOINTE M A, CHATIGNY S, PICHE M, *et al*. Thermal effects in high-power CW fiber lasers[C]. SPIE, 2009, **7195**: 71951U.

[10] WANG Y, XU C, PO H. Thermal effects in Kilowatt fiber lasers[J]. *IEEE Photonics Technology Letters*, 2004 , **16**(1): 63-65.

[11] RIPIN D J, GOLDBERG L. High efficiency side-coupling of light into optical fibres using imbedded v-grooves[J]. *Electronics Letters*, 1995, **31**(25): 2204-2205.

[12] YAN P, GONG M, LI C, *et al*. Distributed pumping multifiber series fiber Laser[J]. *Optics Express*, 2005, **13**(7): 2699-2706.

[13] GRENIER P, TAILLON Y, WANG M, *et al*. Laser beam transformation technique for high-power laser diode linear arrays[C]. SPIE, 2006, **6104**: 61040R.

[14] JACKSON S D, KING T A. Theoretical modeling of Tm-dopedsilica fiber lasers[J]. *IEEE Journal of Lightwave Technology*, 1999, **17**(5): 948-956.

[15] FRITH G, LANCASTER D G, JACKSON S D. 85W Tm^{3+}-doped silica fibre laser[J]. *Electronics Letters*, 2005, **41**(12): 1207-1208.

[16] JACKSON S D. The spectroscopic and energy transfer characteristics of the rare earth ions used for silicate glass fibre lasers operating in the short wave infrared laser[J]. *Laser & Photonics Reviews*, 2009, **3**(5): 466-482.