

Experimental study on high power all-fiber laser

Baoyin Zhao (赵保银)^{1,2}, Kailang Duan (段开棕)^{1*}, Wei Zhao (赵卫)¹,
Cheng Li (李成)¹, and Yishan Wang (王屹山)¹

¹State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics,
Chinese Academy of Sciences, Xi'an 710119, China

²Graduate University of Chinese Academy of Sciences, Beijing 100049, China

*E-mail: kl.duan@tom.com

Received August 12, 2009

A high power all-fiber laser is experimentally studied. A monolithic fiber laser system with only one stage of resonator cavity is constructed and 404-W continuous wave (CW) output power is obtained. Its optical-to-optical conversion efficiency is up to 64%. The laser central wavelength is at 1081 nm with the spectral full-width at half-maximum (FWHM) of 2 nm. The laser setup can work with excellent stability; in the long time of high power operation, no thermal distortions or damages are observed.

OCIS codes: 140.3510, 140.3480.

doi: 10.3788/COL20100804.0404.

High power fiber lasers are of many unique advantages, including small size, easy cooling, high efficiency, and outstanding beam quality, which have made fiber lasers become very competitive in many applications such as material processing, marking, medicine, range finding, free space communication, and security^[1-4]. Fueled both by the rapid development of the fibers to carry high optical power and the availability of powerful diode lasers to use as pump sources, the output power of Yb-doped single-fiber laser has grown dramatically. In 2004, Jeong *et al.* reported an Yb-doped large-core fiber laser with 1.36-kW continuous wave (CW) output power^[4]. In 2005, Bonati *et al.* demonstrated a 1.53-kW large-mode-area (LMA) photonic crystal fiber (PCF) based fiber laser^[5]. Recently, IPG Photonics corporation announced a successful test of a single-mode fiber laser, which produced 9.6-kW laser power through a single fiber^[6]. Meanwhile, Chinese researchers have also accomplished many studies on high power fiber lasers. In 2006, Zhou *et al.* demonstrated a 714-W CW fiber laser, which was based on China-made LMA double-clad fiber^[7]. Zhao *et al.* reported a high power fiber laser with output power of 1.2 kW^[8]. Recently, Lou *et al.* obtained 1.75-kW laser output power with a fiber laser using China-made Yb-doped double-clad fiber as the gain medium^[9]. However, many of these experiments typically employed a length of gain fiber pumped via free-space coupling and bulk optical components as the cavity reflectors. This kind of fiber lasers occupy large space and require strict work conditions, such as humidity and air cleanliness. Compared with such type of fiber lasers, all-fiber lasers only employ fiber components, such as fiber combiners and fiber gratings, to replace the bulk optical components such as coupling lens and feed back mirrors. Thus the all-fiber lasers are more compact and reliable. Recently, great attention has been paid to all-fiber lasers in China. Gong *et al.* demonstrated a 300-W CW end-pumped Yb-doped all-fiber laser with structure of master oscillator multi-stage power amplifiers^[1]. In this letter, we report the experiment of an Yb-doped all-fiber laser with double-end-pumped structure, which is only one stage of

resonator cavity. The monolithic fiber laser generates 404-W CW laser output power under the pump power of 628 W.

The experimental setup is shown in Fig. 1. The fiber laser consisted of double-clad Yb-doped fiber (YDF), two (6+1) × 1 multimode combiners (C1 and C2), six diode modules (LD1 × 3 and LD2 × 3), and a pair of fiber Bragg gratings (FBG1 and FBG2). Optical collimator (OC) was the fiber end cap. The gain fiber was a 40-m-long YDF (LMA-YDF-20/400, Nufern, America), whose core and inner cladding diameters were 20 and 400 μm, respectively, and the core numerical aperture (NA) was 0.06. The specific absorption coefficient of the YDF was 0.55 dB/m at 915 nm. Both ends of the YDF were spliced with the signal delivery fibers of the combiners C1 and C2 made by ITF Labs. The dimensions of the signal delivery fibers of C1 and C2 were the same as that of the double-clad gain fiber. Both C1 and C2 had six pump delivery fibers whose core diameter was 200 μm and NA was 0.22. Six diode modules, each of which could provide the maximum pump power of 110 W at 915 nm via multimode pump delivery fibers, were divided into two groups LD1 × 3 and LD2 × 3. Their pump delivery fibers were spliced with the pump delivery fibers of combiners C1 and C2. FBG1 which had a reflectivity of 99.9% at 1080 nm was spliced with the signal fiber of C1. FBG2 with a reflectivity of 10% at 1080 nm used as the output coupler and was spliced with the signal fiber of C2. The other end of FBG1 was cleaved at an angle of about 8° to avoid back reflection and the other end of FBG2 was spliced with the end cap OC to avoid optical damages. In this configuration, the two FBGs were assembled on the outsides of C1 and C2 to beneficially avoid the pump

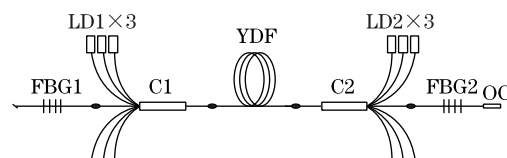


Fig. 1. Schematic diagram of the experimental setup of all-fiber laser.

power passing through the fiber gratings, thus to protect the fiber gratings from thermal damages.

Since splice loss has a significant impact on the performance of fiber laser, we paid great efforts to reduce the splice loss. In the experiment, insertion loss method was adopted to measure the splice loss^[10]. To have good splice results, the fibers have to be well prepared by cleaning and stripping carefully, and then cleaved with high quality of small cleave angle and smooth-end faces of the fiber tips. Cleave quality, particularly cleave angle, is an important factor affecting fusion splice loss^[10]. A poor cleave quality with an end angle more than about 1.5° can lead to a failure splice with bubbles at the splice joint. We cleaved the LMA fibers with cladding diameters of 200 or 400 μm with a large diameter fiber cleaver. Among many parameters needed to be set for the fiber cleaver, the cleaving tension is the most important one. Many failure tries were conducted to find appropriate cleaving tensions for different diameters of fibers. When the fiber preparation was finished, the fibers were arranged into the fiber splicer, for which there were also many parameters needed to be well selected. The four most important parameters are arc power, arc time, overlap, and pre-fusion time. The best splice results can only be obtained by an optimum combination of the splice parameter values. We spliced the fibers of 200- μm diameter pump delivery fibers with splice loss of about 0.03 dB, and splice loss for the double-clad fibers was no more than 0.05 dB.

The change of output power versus pump power is presented in Fig. 2. The fiber laser is found having a threshold power around 5 W. When the pump power is 628 W, the fiber laser generates a CW output power of 404 W. At this high output power level, the fiber gratings, splice joints, combiners, and the gain fibers needed to be cooled by mounting them on thermal sinks. With this measure, the all-fiber laser works well with stable output during long-time work in the experiment. Figure 3 shows the optical-to-optical conversion efficiency of the all-fiber laser. It can be seen that the optical-to-optical conversion efficiency is about 42% with a pump power near the threshold value and increases with increasing the pump power. The high optical-to-optical conversion efficiency of 64% is obtained corresponding to the pump power of 628 W. The output spectrum, which depends on reflection characteristic of the fiber gratings (shown in Fig. 4), is centered at 1081 nm, and the full-width at half-maximum (FWHM) of the outputs spectrum is 2 nm. We have also measured the beam

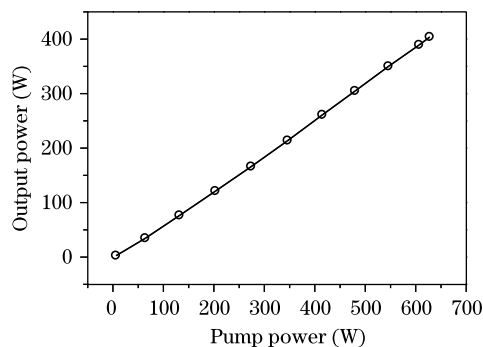


Fig. 2. Output optical power versus pump power.

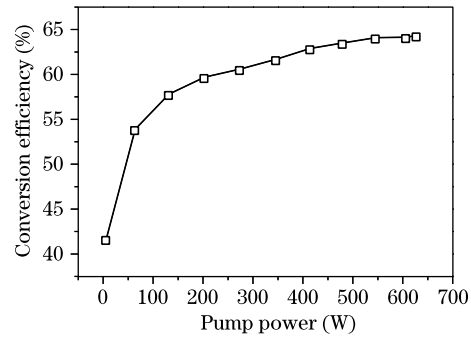


Fig. 3. Optical-to-optical efficiency of the fiber laser versus pump power.

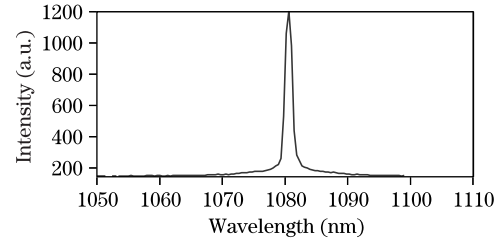


Fig. 4. Output spectrum of the fiber laser at output power of 404 W.

quality factor M^2 using the analyzer M2-200-FW-NIR. The M^2 factor of the beam is 1.3.

In conclusion, we demonstrate a double-end-pumped all-fiber laser. It consists of only fibers and fiber components, which are integrated by fiber fusion splice techniques. The fiber laser generates 404-W CW output power which is, to our knowledge, the highest level obtained for all-fiber laser to date in China. The optical-to-optical conversion is up to 64%. The laser system works stably with high power output, and there are no thermal distortions and fiber damages observed. So this power level can be updated soon when we have enough pump sources because there are still six pump delivery fibers of the combiners C1 and C2 left unused. Furthermore, the all-fiber laser reported here can be used as a laser source to drive an all-fiber structure master oscillator power-amplifier (MOPA).

This work was supported by the Chinese Academy of Sciences (No. 2006LH02) and the National Key Natural Science Foundation of China (No. 60537060).

References

1. S. Yin, P. Yan, and M. Gong, *Opt. Express* **16**, 17864 (2008).
2. V. P. Gapontsev and I. E. Samartsev, *OSA Proceedings on Advanced Solid-State Lasers* **6**, 258 (1990).
3. G. Hu, C. Shan, X. Deng, J. Zhan, Y. Pan, and L. Wang, *Opt. Laser Technol.* **37**, 3 (2004).
4. Y. Jeong, J. K. Sahu, D. N. Payne, and J. Nilsson, *Opt. Express* **12**, 6088 (2004).
5. G. Bonati, H. Voelckel, T. Gabler, U. Krause, A. Tünnermann, J. Limpert, A. Liem, T. Schreiber, S. Nolte, and H. Zellmer, "1.53 kW from a single Yb-doped photonic crystal fiber laser", presented at the Photonics Conf. West 2005 Session 5709-2a (2005).

6. IPG Photonics Corporation, "IPG Photonics successfully tests world's first 10 kilowatt single-mode production laser" <http://www.ipgphotonics.com/newsproduct.htm> (June 15, 2009).
7. Q. Lou, B. He, Y. Xue, J. Zhou, J. Dong, Y. Wei, W. Wang, Z. Li, Y. Qi, S. Du, H. Zhao, and W. Chen, *Acta Opt. Sin.* (in Chinese) **26**, 1119 (2006).
8. H. Zhao, S. Zhou, C. Zhu, Y. Li, and J. Wu, *Laser Infrared* (in Chinese) **36**, 930 (2006).
9. Q. Lou, B. He, Y. Xue, J. Zhou, J. Dong, Y. Wei, W. Wang, Z. Li, Y. Qi, S. Du, H. Zhao, and W. Chen, *Chinese J. Lasers* (in Chinese) **36**, 1277 (2009).
10. A. D. Yablon, *Optical Fiber Fusion Splicing* (Springer, Berlin, 2005).