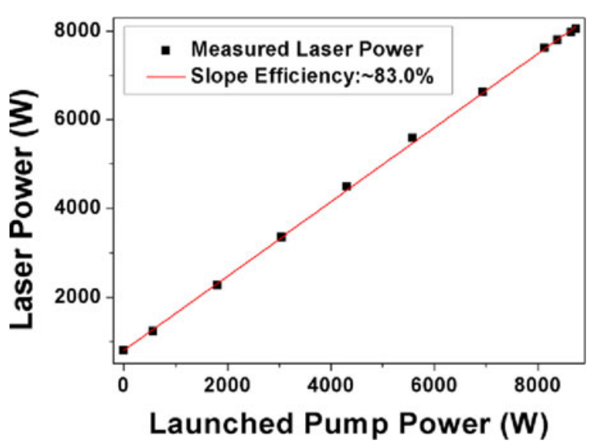
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

5 kW Near-Diffraction-Limited and 8 kW High-Brightness Monolithic Continuous Wave Fiber Lasers Directly Pumped by Laser Diodes

Volume 9, Number 5, October 2017

Qiang Fang
Jinhui Li
Wei Shi
Yuguo Qin
Yang Xu
Xiangjie Meng
Robert A. Norwood
Nasser Peyghambarian



DOI: 10.1109/JPHOT.2017.2744803
1943-0655

IEEE photonics SOCIETY
IEEE

5 kW Near-Diffraction-Limited and 8 kW High-Brightness Monolithic Continuous Wave Fiber Lasers Directly Pumped by Laser Diodes

Qiang Fang,[1,2] Jinhui Li,[1,4] Wei Shi,[1,3] Yuguo Qin,[2] Yang Xu,[2] Xiangjie Meng,[4] Robert A. Norwood,[5] and Nasser Peyghambarian[5]

[1]College of Precision Instrument and Optoelectronics Engineering, Tianjin University, Tianjin 300070, China
[2]HFB Photonics Co., Ltd., Shandong 264209, China
[3]Tianjin Institute of Modern Laser and Optics Technology, Tianjin 300384, China
[4]Tianjin Optera Laser Technology Co., Ltd., Tianjin 300384, China
[5]College of Optical Sciences, University of Arizona, Tucson, AZ 85721 USA

DOI:10.1109/JPHOT.2017.2744803

Manuscript received May 7, 2017; accepted August 22, 2017. Date of publication September 4, 2017; date of current version October 17, 2017. This work was supported in part by the National High Technology Research and Development Program under Grant 2014AA041901, in part by the Shandong Province Independent Innovation and Achievement Transformation Project under Grant 2014ZZCX04212, in part by the Science and Technology Support Program of Tianjin under Grant 15ZCZDGX00970, in part by the National Natural Science Foundation of China under Grants 61335013 and 61275102, and in part by the Natural Science Foundation of Shandong under Grant ZR2014FP015. Corresponding author: Wei Shi (e-mail: shiwei@tju.edu.cn).

Abstract: Tandem pumping technique are traditionally adopted to develop >3-kW continuous-wave (cw) Yb^{3+}-doped fiber lasers, which are usually pumped by other fiber lasers at shorter wavelengths (1018 nm e.g.). Fiber lasers directly pumped by laser diodes have higher wall-plug efficiency and are more compact. Here we report two high brightness monolithic cw fiber laser sources at 1080 nm. Both lasers consist of a cw fiber laser oscillator and one laser-diode pumped double cladding fiber amplifier in the master oscillator-power amplifier configuration. One laser, using 30-μm-core Yb^{3+}-doped fiber as the gain medium, can produce >5-kW average laser power with near diffraction-limited beam quality ($M^2<1.8$). The slope efficiency of the fiber amplifier with respect to the launched pump power reached 86.5%. The other laser utilized 50-μm-core Yb^{3+}-doped fiber as the gain medium and produced >8-kW average laser power with high beam quality (M^2: ~ 4). The slope efficiency of the fiber amplifier with respect to the launched pump power reach 83%. To the best of our knowledge, this is the first detailed report for >5-kW near-diffraction-limited and >8-kW high-brightness monolithic fiber lasers directly pumped by laser diodes.

Index Terms: Diode-pumped lasers, fiber lasers, high power, near-diffraction-limited, ytterbium-doped.

1. Introduction

High power ytterbium-doped glass fiber lasers and amplifiers are emerging as the workhorse for providing multi-kilowatts and even tens of kilowatts high-brightness laser emission, benefiting from the development of high-brightness semiconductor laser diodes, novel fiber designs, new pumping

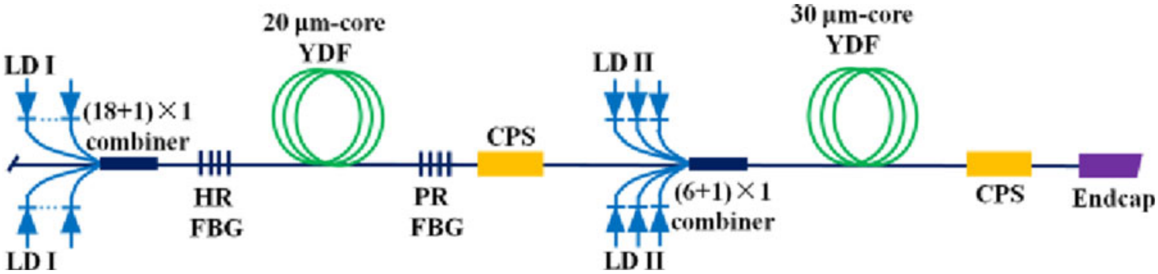


Fig. 1. Schematic configuration of the 5 kW near-diffraction-limited cw monolithic fiber laser.

schemes, and high-power fiber components over the past decade [1], [2]. Conventionally, high power glass fiber lasers and amplifiers are directly pumped by laser diodes. Several laser-diode-pumped multi-kilowatts fiber lasers with near diffraction-limited beam quality have been reported [3]–[7]. NLIGHT Inc. reported a laser-diode-pumped fiber laser in master oscillator-power amplifier (MOPA) configuration, which can produce 4 kW laser power with beam parameter product (BPP) of 1.1 mm-mrad [8]. Tandem pumping, in which fiber lasers operating at shorter wavelengths are utilized as high-brightness pumping sources for another fiber laser or fiber amplifier, are usually adopted to develop high power continuous wave (cw) fiber laser sources [9]. IPG's 10 kW single mode fiber laser with a wavelength of 1070 nm was tandem-pumped by a number of fiber lasers operating at 1018 nm [10]. In contrast to tandem pumped fiber lasers, laser-diode-pumped fiber lasers have higher wall-plug efficiency and can be packaged more compactly. With the increased brightness of pump laser diodes and the development of high-power fiber combiner, it is possible for the laser-diode-pumped fiber lasers to produce more laser power.

In this paper, we report two laser-diode-pumped high brightness monolithic cw fiber laser sources at 1080 nm. One laser can produce $>$5 kW average laser power with near diffraction-limited beam quality ($M^2 < 1.8$). The other laser can produced $>$8 kW average laser power with high beam quality (M^2 :$\sim$ 4). The technical details for both high power fiber laser systems are addressed in the paper. To the best of our knowledge, this is the first detailed report for $>$5 kW near-diffraction-limited and $>$8 kW high-brightness monolithic fiber lasers directly pumped by laser diodes.

2. 5-kW Near-Diffraction-Limited CW Monolithic Fiber Laser

Fig. 1 shows the schematic configuration of the 5 kW near-diffraction-limited CW monolithic fiber laser, consisting of a master oscillator and one power amplifier in MOPA configuration. The laser cavity of the oscillator consists of a pair of fiber Bragg gratings (FBG, from ITF Technologies Inc.) centered at the wavelength of $\sim$1080 nm and $\sim$20 meters 20/400 μm (diameter of the core/inner cladding) double cladding ytterbium-doped fiber (YDF, from Nufern Inc.). The reflectivity of the high reflection (HR) FBG and the partial reflection (PR) FBG at 1080 nm is 99.8%, 10.5%, respectively. The 3 dB reflection bandwidths for the HR FBG and the PR FBG are 2 nm and 1 nm, respectively. The numerical aperture (NA) for the core of the YDF is 0.06. Thirteen fiber coupled multimode laser diodes (LD I shown in Fig. 1, from BWT Inc.) were coupled through a home-made $(18 + 1) \times 1$ fiber based pump & signal combiner to end-pump the YDF in the oscillator. Each LD can provide up to 50 W laser power near 976 nm. The cladding absorption coefficient at 976 nm of the 20 μm-core YDF is $\sim$1.2 dB/m. The laser power propagating in the fiber cladding was eliminated by one home-made cladding power stripper (CPS). This oscillator can produce up to $\sim$475 W cw laser power at 1080 nm with launched pump power of $\sim$650 W. All the components, including LDs, YDF, FBGs, the combiner and the CPS, are actively cooled by a heat sink.

In order to boost the average power of the oscillator, one fiber amplifier was built, which consists of six state-of-the-art high-brightness fiber-coupled LDs at 976 +/− 2 nm (from DILAS), one home-made $(6 + 1) \times 1$ pump & signal fiber combiner, $\sim$23 meters 30/600 μm (diameter of the core/inner cladding) double cladding YDF (from Nufern Inc.), and one home-made CPS. The input fiber and

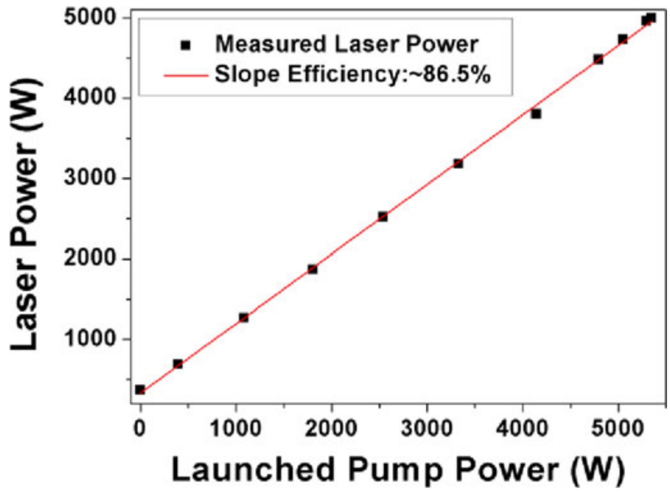


Fig. 2. The laser power output from the amplifier vs. launched pump power.

the output fiber for the combiner is 20/400 μm fiber and 30/600 μm fiber, respectively. The numerical aperture (NA) for the core of the YDF is 0.06. The cladding absorption coefficient at 976 nm of this active fiber is $\sim$1.2 dB/m. Each LD is able to provide up to $\sim$900 W laser power in the 200 μm core of the fiber (NA = 0.22). These diodes were connected by the $(6 + 1) \times 1$ fiber combiner to forwardly end-pump the 30 μm-core YDF in the amplifier. The coupling efficiency of these pumps into the combiner is >98%. The residual pump and the laser power propagating in the fiber cladding were stripped out by the CPS, which was tested to have the capability of clearing up to 500W laser power. Note that all the components are actively cooled by a heat sink. One home-made endcap was utilized as the output end of the whole laser system to avoid any end-face-reflection.

For the laser system shown in Fig. 1, all the fiber components are spliced together to make the entire laser system fiber-integrated. The optical fiber fusion splice is a permanent joint between two fibers, enabling optical signal to pass from one fiber to the other. However, at any fiber fusion splice joint, some of the optical signal may be radiated out of the fiber. Therefore the optical fiber splice joints have significant influence on the performance of the high power fiber laser system [11], [12]. Each fiber splice in the laser system was carefully done using the commercial fiber splicer. Each fiber splice joint, especially the one between the output fiber of the $(6 + 1) \times 1$ combiner and the YDF, was well packaged and cooled to avoid thermal accumulation and damage.

Fig. 2 shows the laser power output from the endcap as a function of the pump power launched into the amplifier through the $(6 + 1) \times 1$ combiner. The laser power was measured by a water cooled power meter from Ophir Inc., which can measure up to 10 kW laser power. When $\sim$475 W seed power was launched into the fiber amplifier, $\sim$380 W laser power could be measured as output from the endcap. The maximum cw laser power, produced by this monolithic fiber laser system, reached 5010 W when $\sim$5350 W pump power was launched into the fiber amplifier. The slope efficiency for the fiber amplifier reaches 86.5%.

The spectrum of the amplified laser with 5010 W laser power was measured using an optical spectrum analyzer (OSA) (AQ6370C from Yokogawa Inc.) with 0.1 nm resolution. Fig. 3 demonstrates the spectrum in both decibel scale and linear scale. In addition to the main laser peak at 1080 nm and the residual pump near 976 nm ($\sim$30 dB less than the main laser peak), there are two peaks around 1060 nm and 1100 nm, respectively. The two peaks result from four wave mixing in the fiber amplifier. This laser is not strictly diffraction limited and the strong four wave mixing, to some extent, results from the phase matching between the fundamental mode and the high-order-mode [13]. The laser peak at 1100 nm is higher due to the fact that it receives more gain from the fiber amplifier. Note that stimulated Raman emission around 1130 nm also starts to appear. The

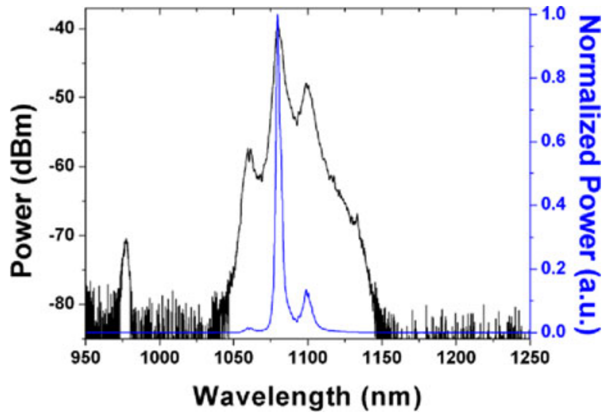


Fig. 3. The output spectrum for the amplified laser with a power of 5010 W.

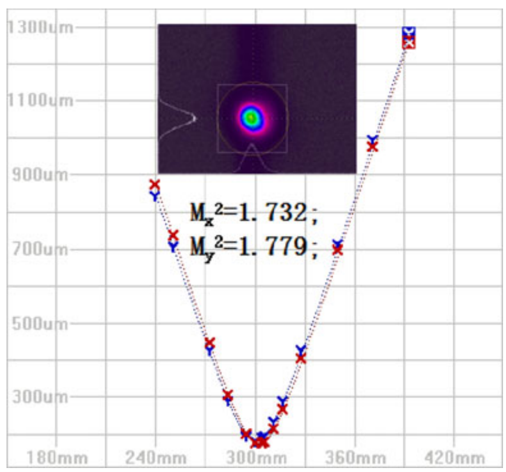


Fig. 4. The beam quality factor (M^2) for the laser with 5010 W laser power. Inset: the typical laser beam profile.

maximum laser power output from this laser system was limited by both the available pump power and conversion to stimulated Raman.

For the YDF utilized in the fiber amplifier, the core diameter and the NA are 30 μm and 0.06, respectively. The V-number of the fiber was about 5.236 and thus the fiber core supported several propagating modes. Higher order modes can be effectively suppressed by coiling the active fiber tightly [14], [15]. The method was also adopted in our laser system to suppress the high-order modes to improve the beam quality. The smallest coiling radius of the active fiber in our laser amplifier was about 6.5 cm.

As Fig. 4 shown, the beam quality factor was measured to be $\sim$1.732 and $\sim$1.779 in the x and y directions, respectively, for the laser beam with $>$5000 W laser power using a beam profile analyzer (M2-200S, Ophir Photonics) based on 4-sigma method; near diffraction-limited beam quality was achieved. Mode instability is a phenomenon of beam quality degradation for high power fiber laser systems [16], [17]. The $>$5000 W laser beam was monitored and no mode instability was observed. The laser power was simultaneously monitored and no power roll-off was observed.

3. 8-kW High Brightness CW Monolithic Fiber Laser

A schematic diagram of the 8 kW high-brightness CW monolithic fiber laser is shown in Fig. 5. It also consists of a master oscillator and one power amplifier in the MOPA configuration. The oscillator

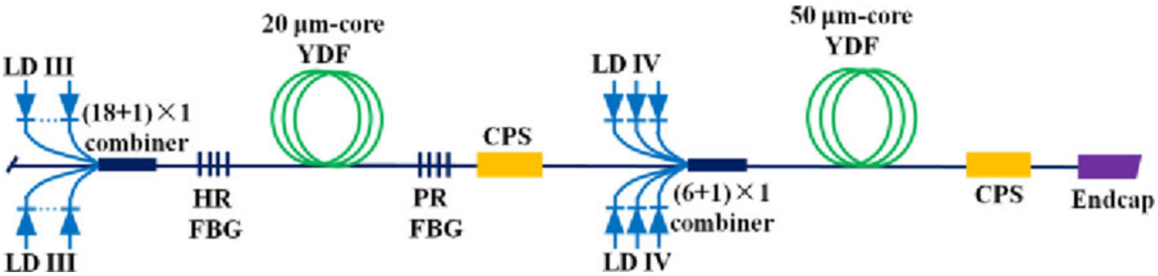


Fig. 5. Schematic configuration of the 8 kW high-brightness CW monolithic fiber laser.

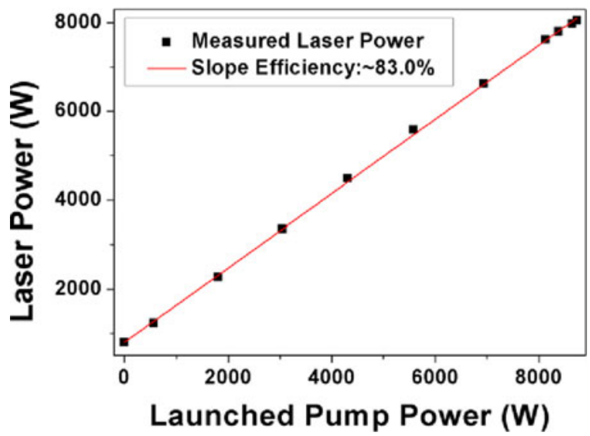


Fig. 6. The laser power output from the amplifier vs. launched pump power.

was same as that for the 5 kW laser (see Fig. 1), with the only difference being that thirteen 105 W fiber coupled multimode laser diodes (105/125 μm, 0.22 NA; LD III shown in Fig. 5, from BWT Inc.), instead of the 50 W laser diodes, were coupled through the (18 + 1) $\times$ 1 fiber pump & signal combiner to pump the YDF in the oscillator. The oscillator can produce up to $\sim$1000 W laser power at $\sim$1080 nm with launched pump power of $\sim$1350 W.

One fiber amplifier was built to boost the average power of the seed laser output from the oscillator. The fiber amplifier consists of six fiber coupled LDs at 976 +/− 2 nm (from DILAS), one home-made (6 + 1) $\times$ 1 pump & signal fiber combiner, $\sim$17 meters 50/800 μm (diameter of the core/inner cladding) double cladding YDF (from Nufern Inc.), and one home-made CPS. The input fiber and the output fiber for the combiner is 20/400 μm fiber and 50/800 μm fiber, respectively. The NA for the core of the YDF is 0.06. The cladding absorption coefficient at 976 nm of this active fiber is $\sim$1.6 dB/m. The smallest coiling radius of the active fiber in the laser amplifier was about 11 cm. Each of the six state-of-the-art high-brightness fiber coupled laser diodes can provide up to $\sim$1500 W laser power in the 300 μm-core of the fiber (0.22 NA). These diodes were connected by the (6 + 1) $\times$ 1 fiber combiner to forwardly end-pump the 50 μm-core YDF in the amplifier.The coupling efficiency of these pumps into the combiner is >98%. The CPS was utilized to strip out the residual pump and the laser power propagating in the fiber cladding. One endcap (from Optoskand Inc.) was utilized as the output end of the whole laser system. Similarly, this laser system are also all fiber-integrated. Each fiber splice in the laser system was carefully done using the commercial fiber splicer. Each fiber splice joint, especially the one between the output fiber of the (6 + 1) $\times$ 1 combiner and the YDF, was well packaged and cooled to avoid thermal accumulation and damage.

When $\sim$1000 W seed power was launched into the fiber amplifier, $\sim$800 W laser power could be measured from the endcap. About 200 W laser power was absorbed by the 50 μm-core YDF and lost in the components and splice joints in the fiber amplifier. Fig. 6 shows the output power versus pump power launched into the fiber amplifier. The maximum laser power of $\sim$8050 W was achieved

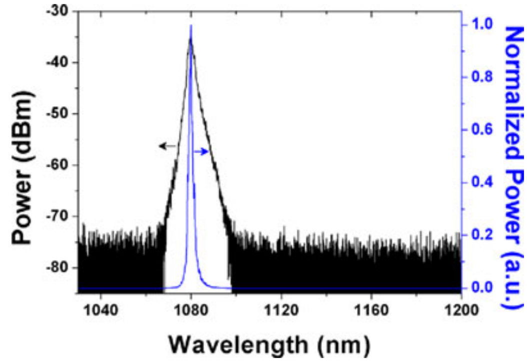


Fig. 7. The output spectrum for the amplified laser with a power of 8050 W.

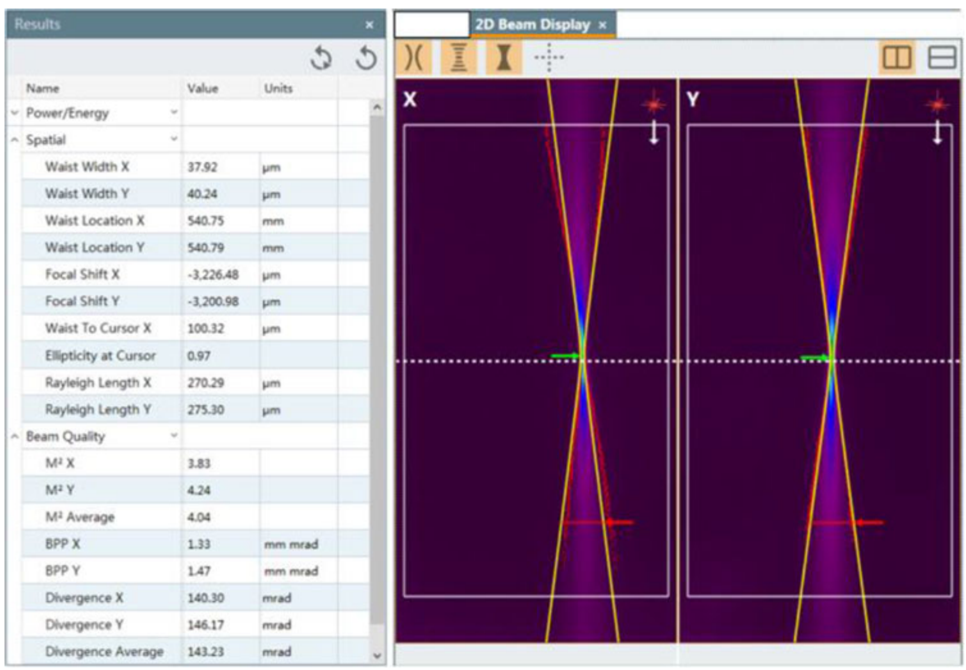


Fig. 8. The beam quality factor (M^2) of the laser beam with 8050 W laser power.

when ~8730 W pump power was launched into the fiber amplifier. The slope efficiency for the fiber amplifier reached 83%.

The spectrum of the amplified laser with 8050 W laser power was measured using an optical spectrum analyzer (OSA) (AQ6370C from Yokogawa Inc.) with 0.02 nm resolution. Fig. 7 shows the spectrum in both decibel scale and linear scale. The laser centered at 1080 nm and the 3 dB spectral linewidth (full width at half maximum, FWHM) was measured to be ~1.85 nm. Compared with the spectrum of the 5 kW laser (see Fig. 3), the spectrum of the 8 kW laser has narrower spectral linewidth, without four wave mixing or Raman. The larger core of the fiber utilized in this amplifier enabled a reduced laser power density in the fiber core and accordingly the threshold powers for nonlinear effects including the four wave mixing, Raman, etc. were raised. Therefore, the maximum laser power output from this laser system was only limited by the available pump power rather than any nonlinear effect.

The larger core fiber utilized in the amplifier is likely to degrade the laser beam quality. In order to evaluate the beam quality of the 8000 W laser beam, a commercial beam profile analyzer called

Beam Watch (from Ophir Photonics), was used. For Beam Watch, the measurement is made by imaging the Rayleigh scatter of the beam from the side using cameras.

The laser beam with $>$8000 W laser power, output from the endcap, was firstly collimated and then focused into the Beam Watch. As Fig. 8 shows, the beam quality factor (M^2) was measured to be $\sim$3.83 and $\sim$4.24 in the x and y directions, respectively. The beam product parameter (BPP) and some other parameters were also measured and shown in Fig. 8. The laser beam was also monitored using Beam Watch and no mode instability was observed.

4. Conclusion

We report two all-fiber-integrated high brightness CW fiber laser sources at 1080 nm, directly pumped by the state-of-the-art high-brightness fiber coupled laser diodes. One laser can produce $>$5 kW laser power with near diffraction-limited beam quality ($M^2 < 1.8$). The other laser can produce $>$8 kW average laser power with high beam quality ($M^2 :\sim 4$). The all-fiber construction of the laser systems enables compact size as well as maintenance-free, robust operation and thus allows various practical applications in laser cutting, laser welding, etc.

References

[1] W. Shi, Q. Fang, X. Zhu, R. A. Norwood, and N. Peyghambarian, “Fiber lasers and their applications,” *Appl. Opt.*, vol. 53, no. 28, pp. 6554–6568, 2014.
[2] M. N. Zervas and C. A. Codemard, “High power fiber lasers: A review,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 20, no. 5, pp. 1–23, Sep./Oct. 2014.
[3] Y. Jeong, J. K. Sahu, D. N. Payne, and J. Nilsson, “Ytterbium-doped large-core fiber laser with 1.36 kW continuous-wave output power,” *Opt. Exp.*, vol. 12, no. 25, pp. 6088–6092, 2004.
[4] V. Gapontsev *et al.*, “2 kW CW ytterbium fiber laser with record diffraction-limited brightness,” in *Proc. Eur. Conf. Lasers Electro-Opt.*, 2005, p. CJ1-1-THU.
[5] Q. Fang, W. Shi, Y. Qin, X. Meng, and Q. Zhang, “2.5 kW monolithic continuous wave (CW) near diffraction-limited fiber laser at 1080 nm,” *Laser Phys. Lett.*, vol. 11, 2014, Art. no. 105102.
[6] V. Khitrov, J. D. Minelly, and R. Tumminelli, “3 kW single-mode direct diode-pumped fiber laser,” in *Proc. SPIE*, 2014, Art. no. 89610V-1.
[7] H. Yu *et al.*, “3.15 kW direct diode-pumped near diffraction-limited all-fiber-integrated fiber laser,” *Appl. Opt.*, vol. 54, no. 14, pp. 4556–4560, 2015.
[8] D. A.V. Kliner, “nLIGHT alta: A versatile, next-generation fiber laser platform for kW materials processing,” in *Proc. 84th Int. Conf. Laser Mater. Process.*, 2016, pp. 1–7.
[9] D. J. Richardson, J. Nilsson, and W. A. Clarkson, “High power fiber lasers: Current status and future perspectives,” *J. Opt. Soc. Amer. B*, vol. 27, no. 11, pp. B63–B92, 2010.
[10] E. Stiles, “New developments in IPG fiber laser technology,” in *Proc. 5th Int. Workshop Fiber Lasers*, Dresden, Germany, Sep. 30, 2009.
[11] S. Yin, P. Yan, and M. Gong, “Influence of fusion splice on high power ytterbium-doped fiber laser with master oscillator multi-stage power amplifiers structure,” *Opt. Lasers Eng.*, vol. 49, no. 11, pp. 1054–1059, 2011.
[12] Z. Huang, T. Ng, C. Seah, S. Lim, and R. Wu, “Thermal modeling of active fiber and splice points in high power fiber laser,” in *Proc. SPIE*, 2011, Art. no. 79142W-1.
[13] G. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. San Diego, CA, USA: Academic, 2001.
[14] J. P. Koplow, D. A. V. Kliner, and L. Goldberg, “Single-mode operation of a coiled multimode fiber amplifier,” *Opt. Lett.*, vol. 25, no. 7, pp. 442–444, 2000.
[15] L. Huang, W. Wang, J. Leng, S. Guo, X. Xu, and X. Cheng, “Experimental investigation on evolution of the beam quality in a 2 kW high power fiber amplifier,” *IEEE Photon. Technol. Lett.*, vol. 26, no. 1, pp. 33–36, Jan. 2014.
[16] T. Eidam *et al.*, “Experimental observations of the threshold-like onset of mode instabilities in high power fiber amplifiers,” *Opt. Exp.*, vol. 19, no. 14, pp. 13218–13244, 2011.
[17] N. Haarlammert *et al.*, “Build up and decay of mode instability in a high power fiber amplifier,” *Opt. Exp.*, vol. 20, no. 12, pp. 13274–13283, 2012.