

# Efficient, 62.5 Watts all-fiber single-mode 1091 nm MOPA laser

Jiangming XU, Xiaolin DONG, Jinyong LENG, Pu ZHOU, Jing HOU (✉)

College of Optoelectronic Science and Engineering, National University of Defense Technology, Changsha 410073, China

© Higher Education Press and Springer-Verlag Berlin Heidelberg 2011

**Abstract** A high power all-fiber single-mode 1091 nm laser is constructed in master oscillator power amplifier (MOPA) configuration. The home-made seed source is an  $\text{Yb}^{3+}$ -doped fiber ring laser with 22.5 mW maximal output power. A two-stage pre-amplification configuration is employed to boost seed power to 3 W. The ultimate output power of the main amplification stage is 62.5 W, corresponding to an optical-to-optical conversion efficiency of 78.1%. No residual pump light or amplified spontaneous emission (ASE) is observed under maximal output power. Because of the using of fiber Bragg grating (FBG) to select frequency in seed laser, the full width at half maximum (FWHM) linewidth of output light is narrower than 0.1 nm.

**Keywords** all-fiber, high efficiency, single-mode, master oscillator power amplifier (MOPA), fiber amplifier, 1091 nm

## 1 Introduction

High power  $\text{Yb}^{3+}$ -doped fiber lasers have attracted so much attention of researchers and manufacturers for their high beam quality, high stability, maintenance-free operation, and high conversion efficiency. Therefore, they are very attractive for various applications, especially in the fields of scientific research, medicine and industry producing, free space communication and security<sup>1)</sup> [1,2]. Meanwhile, the all-fiber construction of high power lasers is of many unique advantages, including low-loss, and good performance on anti-jamming.

The output power of  $\text{Yb}^{3+}$ -doped fiber lasers increased dramatically in the last decade for the rapid development of large mode area (LMA) dual-clad fibers and the availability of high brightness laser diodes (LD). IPG Photonics Corporation announced a successful test on a single-mode fiber laser operating at 1070 nm with 9.6 kW output power in 2009<sup>2)</sup>. Meanwhile, Chinese researchers have also obtained many progresses in high power fiber lasers<sup>3)</sup> [3–7].

1091 nm lasers can be utilized as pump light of cascaded Raman lasers and amplifiers to obtain special wavelength laser [8]. Single-frequency 1091 nm laser can be utilized to generate 545 nm green yellow light with frequency doubling crystal [9,10]. Consequently, it is significant to construct 1091 nm laser. In 2005, Ning et al. [11] reported a cladding pumped  $\text{Yb}^{3+}$ -doped fiber laser operating at 1090 nm with 196 W output power. Lou et al. [7] demonstrated a 1.75 kW bidirectional cladding pumped  $\text{Yb}^{3+}$ -doped fiber laser operating at 1097 nm with a broad bandwidth about 20 nm. Most of these high power fiber lasers operating near 1091 nm typically employed a length of dual-clad fiber as gain medium pumped via free-space coupling and bulk optics components as the cavity reflectors, which had big sizes, strict work conditions, low coupling efficiency of pump source, and broad bandwidth. The use of all-fiber based components can clearly simplify the laser configuration and make the laser more compact and efficient.

Here, we demonstrate a high power all-fiber single-mode 1091 nm master oscillator power amplifier (MOPA) laser based on  $\text{Yb}^{3+}$ -doped fiber, which is seeded by a home-made fiber ring laser. The maximal output power of this MOPA laser is 62.5 W, corresponding to an optical-to-optical conversion efficiency of 78.1%. The amplified spontaneous emission (ASE) suppression is higher than 27

Received June 16, 2011; accepted September 23, 2011

E-mail: houjing25@sina.com

- 1) FIBER AMPLIFIERS: High-power fiber amplifiers enable leading-edge scientific applications, <http://www.laserfocusworld.com/articles/print/volume-47/issue-2/features/fiber-amplifiers-high-power-fiber-amplifiers-enable-leading-edge-scientific-applications.html>
- 2) IPG photonics successfully tests world's first 10 kilowatt single-mode production laser, <http://www.ipgphotonics.com>
- 3) Xi'an Institute of Optics and fine Mechanics. [http://www.opt.ac.cn/xwzx/tpxw/200910/t20091026\\_2590079.html](http://www.opt.ac.cn/xwzx/tpxw/200910/t20091026_2590079.html)

dB, and the full width at half maximum (FWHM) linewidth of output laser is narrower than 0.1 nm. The gain fiber utilized in the main amplifier has an 11  $\mu\text{m}$  small core and a numerical aperture (NA) of 0.075, which is a single-mode fiber that produces pure single-mode radiation and can easily adopted in further laser system.

## 2 Experimental setup and results

MOPA system configuration we reported in this manuscript is schematically plotted in Fig. 1. Figure 2 shows the diagram of the experiment setup of the home-made seed laser, which is a standard fiber ring laser configuration. The seed laser is pumped through a wavelength division multiplexer (WDM) by a 500 mW level fiber-pigtailed 976 nm single-mode LD. Special attention is made to protect the LD from possible eventual return power, using a band-pass filter (BPF). Single-mode single-clad heavily  $\text{Yb}^{3+}$ -doped fiber is used as the laser gain medium, and the length of gain fiber is 20 cm. The NA of the core is 0.2, and the absorption coefficient of 976 nm pump wavelength is about 1200 dB/m. A fiber Brag grating (FBG) with a reflectivity greater than 99% at the central wavelength 1091.2 nm is located at the second arm of the circulator acting as total reflection cavity mirror. A 30/70 fiber coupler couples part of the circulating power out of the ring cavity. A fiber isolator (ISO) is spliced to output arm of the coupler to prevent seed laser apparatus from destruction by back scattering light.

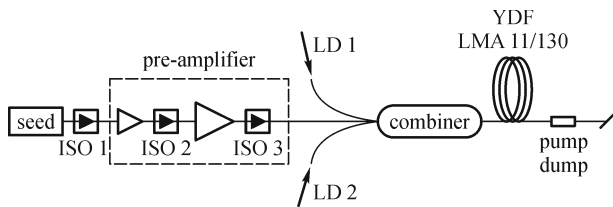


Fig. 1 Schematic of all-fiber 1091 nm MOPA laser

The dependence of output power of seed laser on the pump power is charted in Fig. 3(a). From Fig. 3(a) we can see that the pump threshold is about 100 mW and the output power of seed laser is linearly increased with the enhancing of pump power above the pump threshold. The maximal output power of seed laser is 22.5 mW with 428 mW pump power injected. The spectrum of the seed laser measured after the fiber ISO 1 at maximal output power is plotted in Fig. 3(b). It is shown that the remnant pump power is neglectable and the ASE is suppressed by over 50 dB. For the using of FBG to select frequency, the FWHM linewidth of output light is narrower than 0.1 nm (for the resolution limit of spectrometer).

To provide enough seed power for main amplification stage, two pre-amplifiers followed by fiber ISOs are employed. After the two-stage pre-amplification, the laser

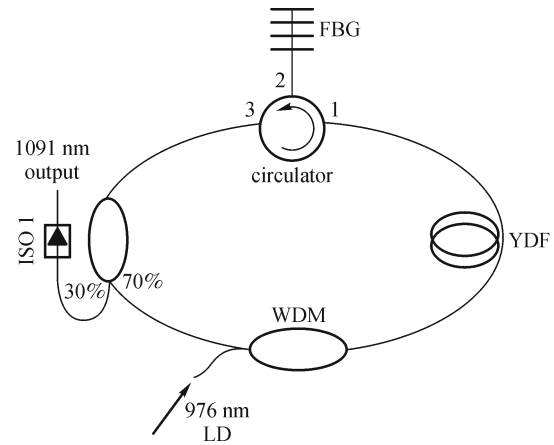
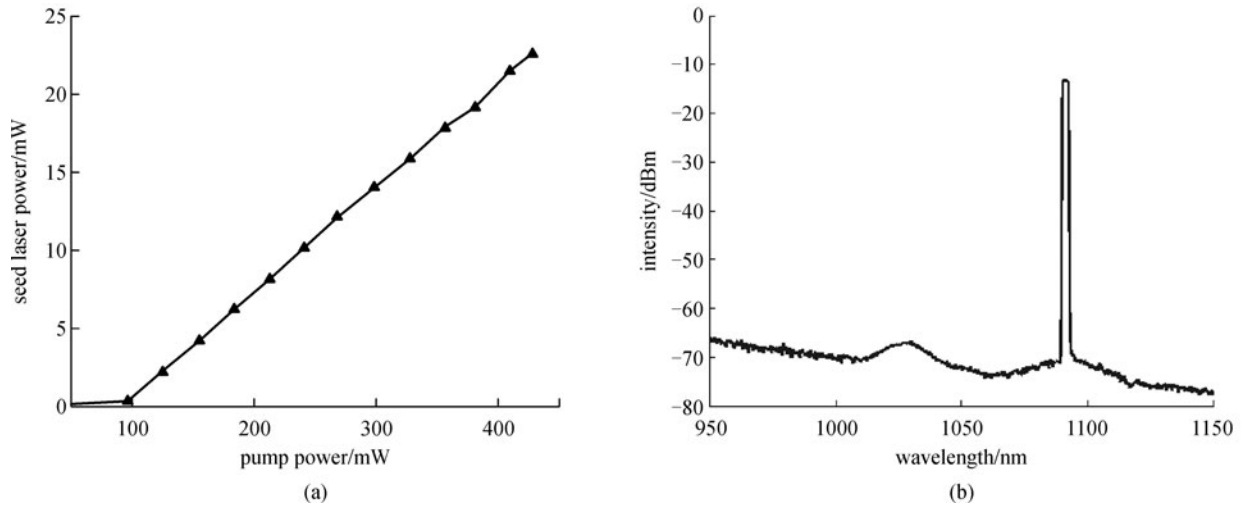


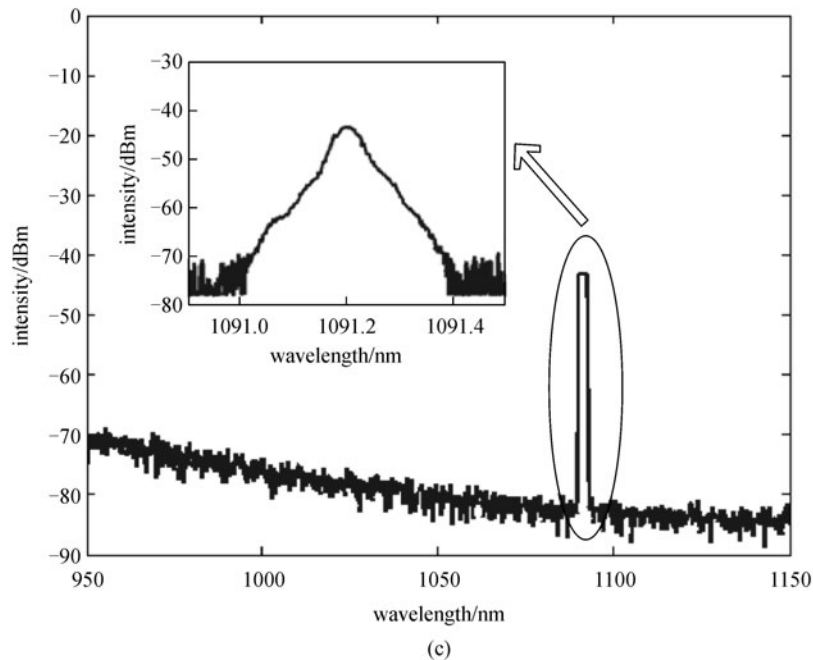
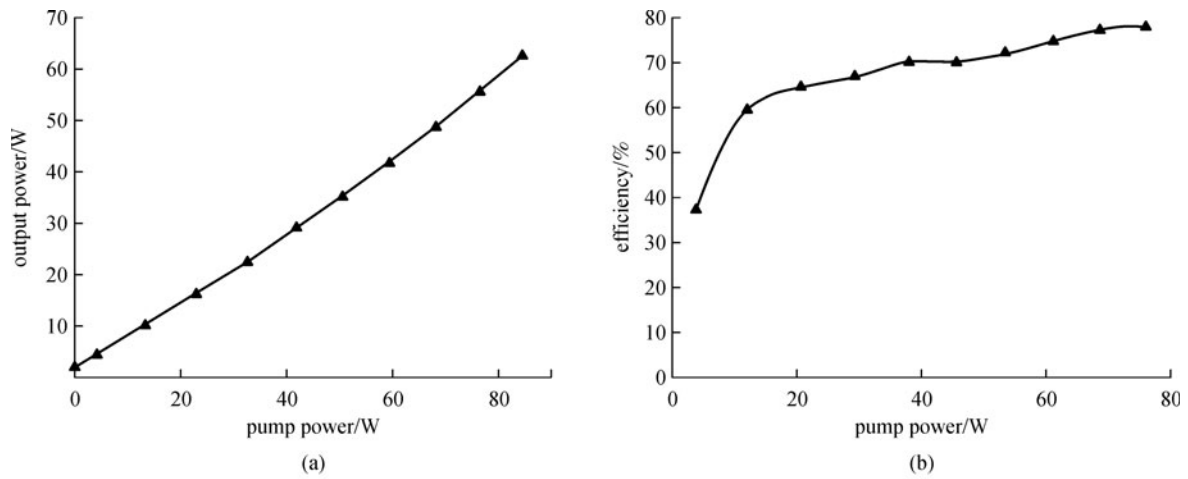
Fig. 2 Schematic of home-made 1091 nm seed laser

power is boosted to 3 W. The main amplification stage is a double clad  $\text{Yb}^{3+}$ -doped fiber amplifier (YDFA) pumped by two fiber-pigtailed 45 W-level LDs via a  $(2 + 1) \times 1$  pump combiner. The insertion loss of the pump combiner for the signal laser is 0.5 dB and the pump efficiency is 90%. The central wavelength of the pump LDs drifts from 970 to 976 nm with the enhancing of output power. A section of 5-m-long  $\text{Yb}^{3+}$ -doped LMA double clad fiber exhibiting 11/130  $\mu\text{m}$  core/inner clad diameter with 0.46 NA is adopted in this stage. The absorption coefficient of 976 nm pump laser is about 5.5 dB/m. All the components of the main amplification system and pump LDs are heat-sunk to aluminum baseplates with cold water circulating inside for stable high power operation. The temperature of the circulating water for the main amplification stage and LDs are controlled to be 20°C and 25°C, respectively using two independent cooling systems. A 0.5-m-long Ge-doped double-clad fiber with same core/inner cladding diameter and NA as the LMA YDF is spliced to the LMA fiber for power delivery. The spliced region is covered in high-index gel to strip the residual pump laser. To eliminate back reflection and prevent end facet damage, we cleave an angle of 8° at the output port of the power delivery fiber.

A pump power of up to 84.7 W at 976 nm was coupled into the pump combiner. Taking the pump efficiency of the pump combiner into account, the total pump power injected into the main amplification stage is about 76.2 W when the pump LDs are both turned on. And the ultimate output power of the main amplification stage is 62.5 W for given 3 W input seed power. The power property, optical-to-optical conversion efficiency variation and spectrum of the main amplification stage are depicted in Fig. 4. As shown in Fig. 4(a), the output power of the last amplification stage is enhanced monotonously with the increasing pump power till the maximal power level, indicating that the output power can still be increased with more powerful pump source. The optical-to-optical conversion efficiency of the main amplification stage, shown in the inset of Fig. 4(b), is about 37% with a pump power



**Fig. 3** Characters of seed laser. (a) Output power of seed laser vs pump power; (b) spectrum of the seed laser



**Fig. 4** Properties of the main amplification stage. (a) Output power of the amplified laser vs pump power; (b) optical-to-optical conversion efficiency of the amplified laser vs pump power; (c) spectrum of the amplified laser

of 3.78 W, and increases with the wavelength shifting of pump LDs. The highest optical-to-optical conversion efficiency is 78.1% corresponding to the pump power of 76.2 W. Figure 4(c) is the optical output spectrum when the seed laser is directly amplified to 62.5 W. As can be seen from the figure, the pump laser has been almost totally absorbed or dumped. The ASE is suppressed by a factor of 27 dB, and the FWHM linewidth of the output light is narrower than 0.1 nm. Remarkably, the power fluctuation of the main amplifier is less than 3% in 30 minutes continuous operating for the high stability of all-fiber construction.

### 3 Conclusions

High power all-fiber single-mode 1091 nm laser based on the MOPA configuration system is demonstrated. A home-made  $\text{Yb}^{3+}$ -doped fiber ring laser with 22.5 mW output power is utilized as the seed source. To provide enough power for main amplification stage, a two-stage pre-amplification configuration is employed to pre-amplify seed power to 3 W. At the main amplification configuration, a maximal output power of 62.5 W is obtained under 76.2 W pump power, giving an optical-to-optical conversion efficiency of 78.1%. The ASE is suppressed by a factor of greater than 27 dB, and the FWHM linewidth of the output light is narrower than 0.1 nm. For the high stability of all-fiber construction, the power fluctuation of the main amplifier is less than 3% in 30 minutes continuous operating. The output power is limited by the pump power, and it is believed that this MOPA laser can be further power scaled as long as higher pump power is available.

**Acknowledgements** This work was supported by the Program of China for New Century Excellent Talents in University (NO. NCET-08-142) and the National Natural Science Foundation of China (Grant NOs. 61077076, 10904173, 11004247).

### References

1. Arturo C P. Compact, highly coherent fiber lasers and amplifiers for sensing and oil and gas exploration. OSA/FILAS, 2011, JWA4
2. Saby J, Cocquelin B, Salin F, Falletto N. Photovoltaics applications of high power green and UV fiber lasers. OSA/FILAS, 2011, FThB5
3. Zhou J, Lou Q H, Zhu J Q, He B, Dong J X, Wei Y R, Zhang F P, Li J Y, Li S Y, Zhao H M, Wang Z J. A continuous-wave 714 W fiber laser with China-made large-mode-area double-clad fiber. *Acta Optica Sinica*, 2006, 26(7): 1119–1120 (in Chinese)
4. Li C, Yan P, Chen G, Gong M L. A continuous-wave 700 W fiber laser with China-made  $\text{Yb}^{3+}$ -doped double-clad fiber. *Chinese Journal of Lasers*, 2006, 33(6): 738 (in Chinese)
5. Li W, Wu Z C, Chen X, Shi J F, Chen Z, Dai M, Dong H Y, Guo S G. 1 kW high power fiber laser. *High Power Laser and Particle Beam*, 2006, 18(6): 890 (in Chinese)
6. Zhao H, Zhou S H, Zhu C, Li Y, Wu J. 1.2 kW high power fiber laser. *Laser & Infrared*, 2006, 36(10): 930 (in Chinese)
7. Lou Q H, He B, Xue Y H, Zhou J, Dong J X, Wei Y R, Wang W, Li Z, Qi Y F, Du S T, Zhao H M, Chen W B. 1.75 kW fiber laser with China-made double-clad fiber. *Chinese Journal of Lasers*, 2009, 36(5): 1277 (in Chinese)
8. Papernyi S B, Xvnnov V B, Koyano Y, Yamamoto H. Sixth-order cascaded Raman amplification. In: *OFC Proceeding, 2005, Post-deadline paper OThF4*
9. Lucas-Leclin G, Augé F, Auzanneau S C, Balembois F, Georges P, Brun A, Mougel F, Aka G, Vivien D. Diode-pumped self-frequency-doubling  $\text{Nd:GdCa}_4\text{O}(\text{BO}_3)_3$  lasers: toward green microchip lasers. *Journal of the Optical Society of America. B, Optical Physics*, 2000, 17(9): 1526–1530
10. Lupei V, Aka G, Petit J, Vivien D. Spectroscopic bases for efficiency enhancement and power scaling of self-frequency multiplication and self-sum-frequency mixing emission in Nd-doped nonlinear crystals. *Journal of the Optical Society of America. B, Optical Physics*, 2004, 21(9): 1620–1629
11. Ning Z Y, Ning T G, Jian S S. High power cladding pumped fiber laser with 196 W power output. *Study On Optical Communications*, 2005, (6): 50–52 (in Chinese)