7.3-W single-frequency master-oscillator fiber power amplifier with China-made double-clad fiber

Fangpei Zhang (张芳沛)[1], Qihong Lou (楼祺洪)[1], Jun Zhou (周 军)[1], Hongming Zhao (赵宏明)[1], Jingxing Dong (董景星)[1], Yunrong Wei (魏运荣)[1], Bing He (何 兵)[1], Jinyan Li (李进延)[2], Weibiao Chen (陈卫标)[1], Jianqiang Zhu (朱健强)[1], and Zhijiang Wang (王之江)[1]

[1]*Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800*

[2]*Fiberhome Telecommunication Tech Co., Ltd., Wuhan 430073*

Received January 9, 2007

A narrow-linewidth master-oscillator fiber power amplifier system was presented, in which an ultrastable, continuous-wave, single-frequency laser was adopted as the master oscillator and a China-made Yb-doped large-mode-area fiber was used as the power amplifier medium. The system generates single-frequency radiation up to 7.3 W at 1064-nm wavelength with 39% slope efficiency and 26% optical-optical power conversion efficiency. The spectral characteristics as well as the suppression of amplified spontaneous emission were discussed in detail.

OCIS codes: 060.2320, 140.3280.

High-power, low-noise, single-frequency laser sources with very narrow-linewidths are of great interest in many scientific and engineering applications, such as spectral beam combination[1], gravitational-wave detection, wavelength conversion, and optical fiber communication. However, high-power operation of single-frequency oscillator is achieved difficultly. Therefore, the so-called master-oscillator power amplifier (MOPA) architecture which uses a low-power single-frequency seed source followed by high-power amplification is often adopted. In the past several years some experimental studies on the single-frequency master-oscillator fiber power amplifier (MOFPA) have been conducted. For example, using a 30-m-long Nd-doped single-mode double-clad fiber, Zawischa *et al.* described a Nd-based MOFPA that was capable of generating single-frequency radiation up to 5.5 W at 1064 nm with an approximately 27% slope efficiency with respect to the launched pump power[2]. Hildebrandt *et al.* reported on a MOFPA system consisting of a diode-pumped Yb:YAG monolithic nonplanar ring oscillator (NPRO) as the master oscillator and a large-mode-area (LMA) double-clad fiber as the power amplifier[3]. The system emitted single-frequency radiation up to 7.8 W at 1030 nm with a slope efficiency of 36% and an optical-optical power conversion efficiency of 26%. In 2003, Liem *et al.* presented a MOFPA system emitting narrow-linewidth single-frequency radiation of 108 W at 1064 nm with low noise and excellent spectral properties by use of a 9.4-m-long Yb-doped LMA fiber[4]. In addition, a narrow-linewidth distributed feedback laser source was even amplified to 264 W without a sign of stimulated Brillouin scattering (SBS) owing to a specific thermal fiber management[5]. In China, Wang *et al.* analyzed and simulated the suppression condition of SBS in high-power single-frequency fiber amplifier in 2006[6]. At the same time, a single-frequency fiber amplifier with 6.65-W continuous-wave (CW) output power was demonstrated by use of a 4.4-m-long Yb-doped double-clad fiber[7]. The overall slope efficiency with respect to the launched pump power is 30.6%. It is noted that the fibers adopted in their MOFPA systems are all oversea. In this paper, using a China-made LMA fiber (fabricated by Fiberhome Telecommunication Tech Co. Ltd., China) as the power amplifier, we obtain a 7.3-W narrow-linewidth single-frequency output with a slope efficiency of 39%. The optical emission spectrum is investigated with respect to the suppression of amplified spontaneous emission (ASE).

The double-clad Yb-doped LMA fiber used in the experiment was designed by our independent technology and fabricated by standard modified chemical-vapor deposition (MCVD). Figures 1(a) and (b) show

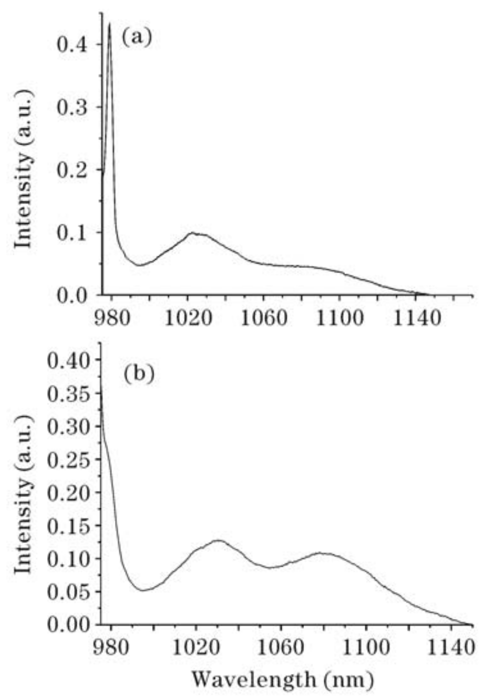

Fig. 1. Fluorescence spectra of (a) the China-made double-clad Yb-doped fiber and (b) the JDSU double-clad Yb-doped fiber.

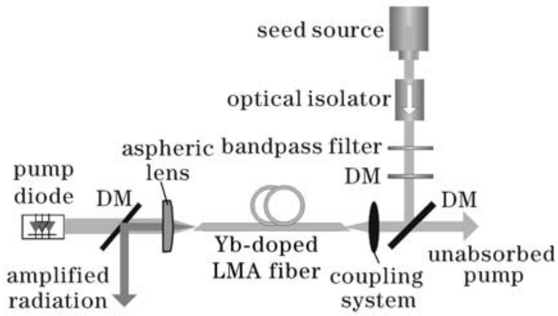

Fig. 2. Schematic setup of the single-frequency MOFPA. DM: dichroic mirror.

the fluorescence spectra of the China-made double-clad Yb-doped fiber and the JDSU (America) double-clad Yb-doped fiber, respectively. Obviously, the two fluorescence spectra are almost same. Recently, Adopting the China-made double-clad Yb-doped fiber, we have made some important progresses on high-power CW fiber lasers and pulsed fiber amplifiers. For example, a CW fiber laser with 714-W output power has been obtained from a 21-m-long China-made Yb-doped LMA double-clad fiber[8]. In 2006, we reported a MOFPA system with a 4-m-long Yb-doped China-made LMA double-clad fiber[9]. The system emitted amplified radiation up to 133 W at a wavelength of 1064 nm and a repetition of 100 kHz.

The experimental setup consists of an ultrastable, CW, single-frequency laser (Mephisto 200 OEM) as the master oscillator and a China-made double-clad Yb-doped LMA fiber as the power amplifier, as shown in Fig. 2. The Mephisto OEM (supplied by Innolight GmbH, Hannover, Germany) was used as the seed source for this experiment, which emitted single-frequency radiation as much as 200 mW at 1064-nm wavelength. It has built-in electronics for either suppression of the resonant relaxation oscillations or generation of defined amplitude modulation by pump-diode current modulation. The linewidth of the Mephisto OEM is specified to be less than 1 kHz. A dual-stage Faraday isolator is employed to protect the seed source against back-reflections or counter directionally running beams from the amplifier.

The fiber power amplifier is composed of a 5.3-m-long fiber with a 39-μm-diameter step-index Yb-doped core (numerical aperture (NA), 0.09) and a 650/600-μm D-shaped inner cladding with a NA of 0.48. The Yb doping concentration is evaluated to be 6000 mol-ppm. Both ends of the fiber are polished at an angle of 8° to suppress ASE or even spurious lasing in the fiber power amplifier. An optical coupling system is designed for coupling the narrow-linewidth seed beams into the active core of the LMA fiber with the coupling efficiency of about 80%.

The fiber amplifier is pumped by a 40-W output-collimated laser diode at 975 nm. An aspheric lens is designed for coupling the pump beams into the inner cladding of double-clad fiber with high coupling efficiency. A 45° dichroic mirror with high transmission coating at the pump wavelength and high reflection at the lasing wavelength (1064 nm) is used to separate the pump light from the amplified radiation. Furthermore, to avoid the potential endangerment of the possible spurious lasing or reflectively unabsorbed pump light towards the seed source, both a 1064-nm bandpass filter (transmission 80%) and a 0° dichroic mirror (high transmission at 1064 nm and high reflection at 975 nm) are inserted between the dual-stage Faraday isolator and a 45° dichroic mirror.

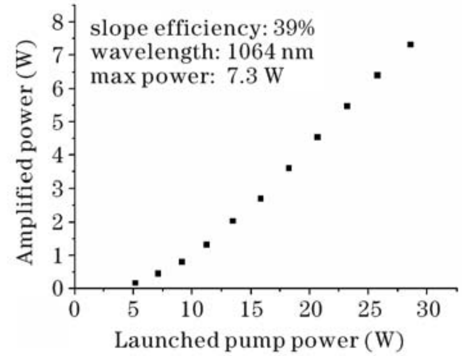

Fig. 3. Output power characteristic of the single-frequency MOFPA.

By careful adjustment we can successfully couple 104-mW master emission (of 141 mW after the isolator and the 1064-nm bandpass filter) into the active fiber core, which is propagating almost entirely in the fundamental mode. More than 90% of the pump power could be coupled into the fiber and about 36% is unabsorbed. The output power characteristic of the presented single-frequency MOFPA system is shown in Fig. 3. With a launched pump power of $\sim$ 28 W an amplified power of 7.3 W is obtained. The overall slope efficiency with respect to the launched pump power is about 39%, and the overall optical-optical power conversion efficiency is 26%. The reason for this relative low slope efficiency can be attributed to the shorter fiber length, which results in the insufficiency of pump-light absorption. Taking into account this factor, the slope efficiency with respect to the absorbed pump power is over 72%. The slightly increasing slope efficiency at higher pump power levels is caused by thermal tuning of the pump diode, which affects the overlap of the diode emission spectrum and the Yb^{3+} absorption band. Maximum absorption efficiency occurred at the highest pump power. The output power increases almost linearly over the whole pump power range and no roll-off due to undesirable nonlinear scattering (such as SBS) or indeed any other effect is observed. This suggests that it is possible to improve the amplified power level further if increasing the pump power. We believe that the large-core diameter (39 μm) is helpful to reduce the optical nonlinear effects like SBS often limiting single-frequency fiber amplifier systems.

The spectral properties of the output are investigated with an Anritsu optical spectrum analyzer (MS9710B) with a resolution of 0.07 nm. Figure 4 shows the emitted spectrum at the maximum output power of 7.3 W. Although magnitude orders of the linewidth of this single-frequency fiber power amplifier are far smaller than the spectrometer resolution, such a measurement can be used to explore the suppression of ASE. By integrating the measured optical spectrum, the suppression of the ASE is estimated to be better than 40 dB, corresponding to a ratio of ASE to amplified radiation of $\sim 8\times10^{-5}$.

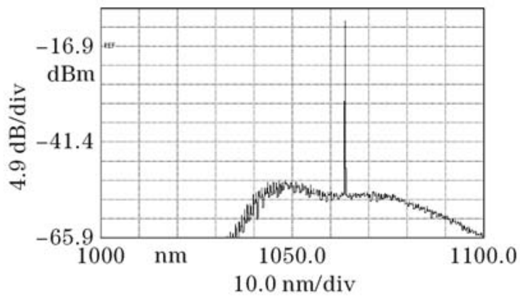

Fig. 4. Optical spectrum of the single-frequency MOFPA at the maximum output power of 7.3 W.

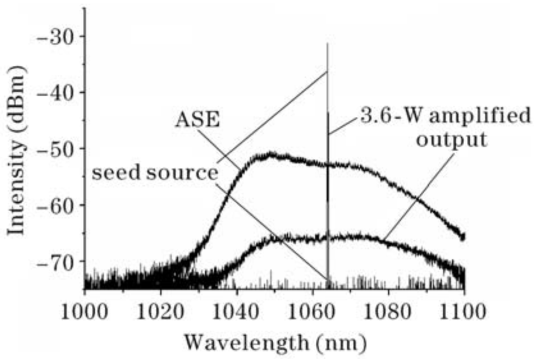

Fig. 5. Spectra of 3.6-W amplified output emission and ASE at the 18-W pump power, as well as the seed source.

Figure 5 shows the optical emission spectrum of the 3.6-W amplified output power at the pump power of 18 W, together with the seed source and ASE spectrum on a logarithmic scale. Obviously, the spectrum of the 3.6-W amplified power is almost the same as that of the seed radiation except that the appearance of ASE, whose range is from 1010 to 1100 nm. While pumping the fiber without injecting the seed radiation, we obtain the ASE at the pump power of 18 W, which centers in 1045 nm with a bandwidth of 90 nm. Nevertheless, while coupling the seed radiation into the core with high efficiency, we notice that the gain of ASE decreases and the peak of spectrum shifts to 1064 nm immediately, which is a result of mode competition.

In summary, a single-frequency MOFPA system using a 5.3-m China-made Yb-doped LMA fiber is demonstrated. A maximum CW output power of 7.3 W at 1064 nm with low noise and narrow-linewidth radiation is achieved, and the overall slope efficiency with respect to the launched pump power is maintained by 39%. Furthermore, the spectral characteristics of the single-frequency fiber power amplifier are investigated, and the suppression of the ASE at the maximum output power of 7.3 W is estimated to be better than 40 dB. Further power scaling and optimization of this MOFPA system are planned to be investigated in the future as no limitation by nonlinear scattering processes is observed.

This work was supported by the 863 Key Program Foundation of China and the Shanghai Commission of Science and Technology (No. 05DZ22001). Q. Lou is the author to whom the correspondence should be addressed, his e-mail address is qhlou@mail.shcnc.ac.cn.

References

1. S. J. Augst, A. K. Goyal, R. L. Aggarwal, T. Y. Fan, and A. Sanchez, Opt. Lett. **28,** 331 (2003).
2. I. Zawischa, K. Plamann, C. Fallnich, H. Welling, H. Zellmer, and A. Tünnermann, Opt. Lett. **24,** 469 (1999).
3. M. Hildebrandt, M. Frede, D. Kracht, I. Freitag, and P. Weßels, in *Proceedings of ASSP'2006* MB6 (2006).
4. A. Liem, J. Limpert, H. Zellmer, and A. Tünnermann, Opt. Lett. **28,** 1537 (2003).
5. Y. Jeong, J. Nilsson, J. K. Sahu, D. B. S. Soh, C. Alegria, P. Dupriez, C. A. Codemard, D. N. Payne, R. Horley, L. M. B. Hickey, L. Wanzcyk, C. E. Chryssou, J. A. Alvarez-Chavez, and P. W. Turner, Opt. Lett. **30,** 459 (2005).
6. C. Wang, F. Zhang, Y. Lu, R. Geng, Z. Tong, T. Ning, and S. Jian, Chin. J. Lasers (in Chinese) **33,** 1630 (2006).
7. W. Sun, C. Zhao, S. Yang, and L. Li, Transactions of Beijing Institute of Technology (in Chinese) **26,** 60 (2006).
8. J. Zhou, Q. Lou, J. Zhu, B. He, J. Dong, Y. Wei, F. Zhang, J. Li, S. Li, H. Zhao, and Z. Wang, Acta Opt. Sin. (in Chinese) **26,** 1119 (2006).
9. F. Kong, Q. Lou, J. Zhou, D. Xue, and Z. Wang, Opt. Eng. **45,** 010502 (2006).