All-fiber, high power single-frequency linearly polarized ytterbium-doped fiber amplifier

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We report an all-fiber high power, single frequency large-mode area (LMA) linearly polarized ytterbium-doped fiber amplifiers (YDFA) module, which is based on the master oscillator multi-stage power amplifiers (MOPA). The maximum output power is 43.8 W at a wavelength of 1064 nm when 60-W launched pump light is coupled, with high slope efficiency of 88%, polarization extinction rate (PER) >17.2 dB and nearly diffraction-limited beam quality (M^2 <1.1).

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High-power, single-frequency linearly polarized lasers and amplifiers with nearly diffraction limit beam quality have widespread applications in science, industry, and defense, such as gravitational wave detection, coherent and spectrum beam combining, range finding, and lidar[1,2]. Especially, linear polarization is required for many of these applications, including fiber-optic gyroscopes, interferometric fiber sensors, optical parametric oscillators/amplifiers, and nonlinear frequency conversion[3,4]. There are many reports on high-power single-frequency, linearly polarized fiber amplifiers in recent years[5,6]. However, with the onset of stimulated Brillouin scattering (SBS), the output power of a single master oscillator multi-stage power fiber amplifiers (MOPFA) chain at narrow linewidth has been severely limited[7,8].

The high power fiber amplifiers mentioned above all are pumped with conventional free space coupling. Few reports about the high power, single-frequency, linearly polarized fiber amplifiers have been based on all-fiber system configurations. An all-fiber amplifier employs all-fiber components to replace the bulk-optic interface and consequently becomes compact, rugged, and reliable[9]. In the all-fiber pump configuration, the N-pumped laser diodes (LD) with pig fiber are spliced to an $(N+1)\times 1$ end-pumped combiner with signal feed-through. With the MOPFA configuration, single-frequency, linearly polarized fiber amplifiers approaching higher power levels are possible[10].

In this letter, we report a set of all-fiber, high power, single frequency, and large-mode area linearly polarized ytterbium-doped fiber amplifiers (YDFA) module chain, which comprises of a three-stage master oscillator power amplifier (MOPA) with co-propagating signal and pump light. The maximum output power is 43.8 W with high slope efficiency of 88%, polarization extinction rate (PER) >17.2 dB. A pump stripper was spliced to the end of the gain fiber to strip unwanted light in fiber amplifiers. An angled polished coreless fiber end cap was spliced and cleaved with an angle of 8° to minimize the back-reflection into the amplifier and avoid the surface damage.

The fiber amplifier configuration consisted of three stages: two pre-amplifier stages and one power scaling stage, both of which were built up by fusion splice. Thus, the all-fiber laser system required less maintenance and further alignments. The all-fiber experimental setup is illustrated in Fig. 1. The signal source is a commercially available single frequency, linearly polarized distributed feedback (DFB) fiber laser with an approximately 10-mW output power at a wavelength of 1064 nm; the linewidth below 20 kHz and PER is approximately 20 dB. Then, the signal from the fiber laser was amplified to a power level of 1 W by two pre-amplifiers with 5/130-μm polarization maintaining ytterbium-doped fiber (YDF) as gain media. Each stage of amplification was separated by >50 dB of isolation with a polarization maintaining isolator. It is necessary to suppress parasitic oscillations in the amplifier system, which was capable of damaging the pre-amplifier stage, even the signal source.

In the power scaling stage, the amplified signal light from the pre-amplifier and the pump light coupled by a $(6+1)\times 1$ polarization maintaining (PM) pump and signal combiners (PMC06113521, ITF Labs, Canada), six pump delivery fibers, and one signal input fiber were coupled to the inner cladding and the core of the double clad output fiber, respectively. Both signal input fiber and double clad output fiber were PANDA polarization maintaining double clad germanium doped fiber (GDF) with a core diameter of 20 μm (numerical aperture (NA) = 0.06) and circle inner cladding diameter of 400 μm (NA = 0.46), which were compatible with the gain fiber. Six single emitters of 10-W output at 976 nm, wavelength-stabilized, commercially available diode laser (L4-9897603, JDSU, USA) pump the power scaling amplifier. The diode laser pigtail fibers were standard 105/125-μm fibers (NA = 0.22), which were compatible with the pump delivery fibers of the $(6+1)\times 1$ PM pump and signal combiners.

A PANDA polarization maintaining double clad YDF (PLMA-YDF-20/400, Nufern, USA) was employed as

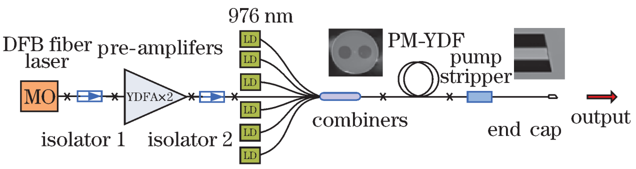

Fig. 1. Configuration of single frequency and linearly polarized YDFA.

gain fiber, with a core diameter of 20 μm (NA = 0.06) and clad diameter of 400 μm (NA =0.46). A microscope image of the inner cladding shape is shown in Fig. 1. The absorption of YDF at 975 nm was 1.7 dB/m, and the gain fiber length was 9 m.

An inline pump stripper was follow spliced to the end of the gain fiber, which was meant to strip the unwanted light in fiber amplifiers. The unwanted lights including amplified spontaneous emission (ASE), residual pump light at the end of the gain fiber, and core light leaking into the cladding or being reflected into the cladding, spread along the chain of components. By locally changing NA of the lights to strip this unwanted lights, it is possible to improve the quality of the fiber amplifier system and the output beam.

To avoid the fiber output facet damage, we spliced a 400-μm coreless end cap on the output end of the fiber amplifier. The maximum length of the end cap was determined by the equation $L_{\max} = d/(2n{\cdot}\mathrm{NA})$, where d is the diameter of the end cap, NA is the numerical aperture of the amplifier fiber core, and n is the refractive index of the end cap. In the experiment, the length of the end cap was set to 1.5 mm, which stretched the mode field to approximately 3/4 of the diameter of the end cap. The end cap was also cleaved with an angle of 8° to minimize back-reflection into the amplifier.

We have demonstrated that the maximum continuous wave (CW) output power of the MOPA is 43.8 W at 1064 nm which is limited by the available launched pump power of 60 W. The tolerance of wavelength of all the pump laser diodes is ±2 nm, and the pump spectral width is approximately 3 nm. Given that the absorption of ytterbium around 976 nm is extremely wavelength dependant, a precise temperature control has been adopted to control the central wavelength of all pump laser diodes at 976 nm. The amplified output power as a function of total launched pump power is plotted in Fig. 2. It shows that the slope efficiency with respect to the launched pump power is about 88%, and the optical-to-optical efficiency is around 73%. This proves that the maximum power is still limited by the available pump power. The substitution of the pump source with the more powerful one will enable further power scaling.

Due to the unwanted lights traveling in the cladding have been stripped by the pump stripper, the stability of the output power is less than ±1% within around 1 h measuring time. We employed the pump stripper although the maximum output power is not comparable to what has been demonstrated in Ref. [11]. Moreover, the angled polished coreless fiber end cap ensured the high power single-frequency amplifier long term operate reliably in practical applications.

The output spectra of the system were measured using an optical analyzer with a resolution of 0.02 nm for the maximum output power (Fig. 3). The spectrum shows no signs of parasitic lasing or significant levels of ASE. The signal-to-noise ratio of assembly presented in the spectra is more than 35 dB. Due to the pump stripper followed spliced to the end of the gain fiber, the residual pump light traveling in the cladding has also been stripped. Therefore, pump light spectrum does not appear in the output spectra, and the output amplified signal light has been further cleaned. Although the total fiber length of the power scaling amplifier is 9 m, we have not observed any non-linear signature on the output spectra.

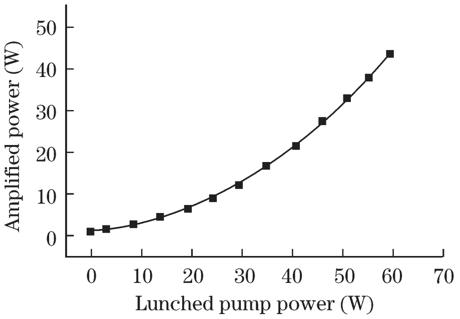

Fig. 2. Amplified output power as a function of total launched pump power.

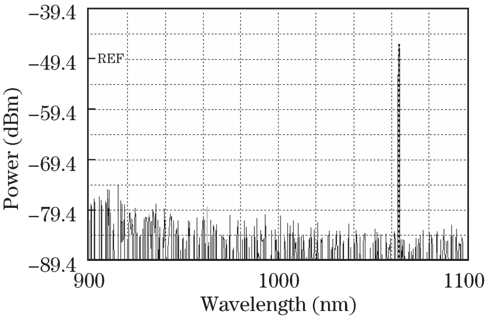

Fig. 3. Output spectra of the MOPA at the maximum output power.

Linear polarization from a fiber laser or amplifier is traditionally done with the use of an external polarizing element (e.g., polarizing beam splitter or Brewster-angle glass windows) in conjunction with the birefringence axis of the PM fiber[11,12], or with the use of fiber Bragg gratings (FBGs) written into the PM fiber acting as the polarization selective element[13,14]. Although the latter approach has an advantage in removing the need for external components to select polarization, it is most often used in low power applications and may not be applicable in high power levels. Due to the lower effective index of refraction, light polarized along the fast axis of the high birefringence PM fiber can have a higher macro-bend loss when the fiber is coiled; meanwhile, bend loss can effectively suppress light in the fast axis and prevent lasing along the fast polarization. Large mode area fibers are often coiled to specific diameters in order to strip out the higher order modes and also be used to control the polarization state.

In our amplifier system, the large mode area gain fiber has been used to spiral-wound coiled to a diameter of

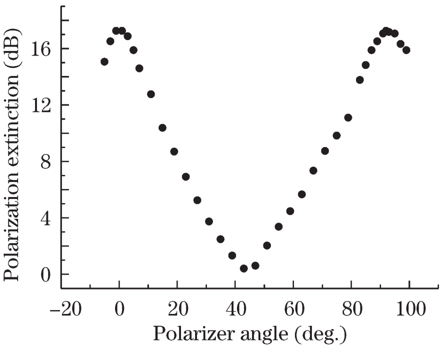

Fig. 4. Polarization extinction ratio versus polarizer angle at the maximum output power.

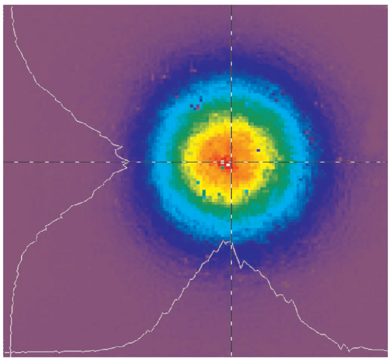

Fig. 5. Two-dimensional beam profile of the power scaling amplifier output at the maximum output power.

9−15 cm and placed on a water-cooled aluminum plate. The optimum coil diameter for effective higher order mode filtering in LMA fibers can also be used to control the polarization state of the fiber amplifier.

In this letter, the PER of the output was measured with a half-wave plate and a polarizer. Turning the polarization angle of the seed beam with a half-wave plate, strong changes of the PER were observed. In Fig. 4, the PER curve is plotted with the polarizer angle at maximum output power (43.8 W), and the PER of the amplified signal light is 17.2 dB. In this MOPA system, the PER has been partly limited by the intrinsic PER of the PM pump and signal combiners (20 dB), and the precise aligned to the birefringence axis of PM fiber in the course of PM fiber fusion splice. We also introduced an active rotational alignment system to achieve the best quality PM fiber splice. In an active rotational alignment system, the two PM fiber tips are laterally aligned to each other and separated by a small air gap. A polarized source launches light with a known polarization state into one of the fibers, while a polarization analyzer monitors the polarization state of the light emerging from the other fiber. The rotational alignment of the two fiber tips is adjusted to yield the best polarization, after which the fibers are fusion spliced together.

Measurements of two-dimensional beam profiles at a maximum output power of 43.8 W from a charge-coupled device are shown in Fig. 5. The output beam has excellent mode quality and demonstrates single-mode operation with M^2 <1.1. The higher order modes can be suppressed by using fiber-bending-induced differential loss between fundamental and higher-order modes in low-NA LMA core fibers.

In conclusion, we report the detailed characteristics of a scalable master oscillator fiber power amplifier system at a wavelength of 1064 nm with 43.8-W maximum output power with a corresponding high slope efficiency of 88% that has been linearly polarized with 17.2-dB PER, and nearly diffraction-limited beam quality and single-mode operation with M^2 <1.1. A pump stripper has been employed to strip unwanted light in fiber amplifiers and an angled cleaved end cap has been spliced to minimize back-reflection into the amplifier and to avoid the fiber output facet damage, ensuring high-power all-fiber amplifiers operating reliably.

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References

1. B. He, Q. Lou, J. Zhou, J. Dong, Y. Wei, D. Xue, Y. Qi, Z. Su, L. Li, and F. Zhang, Opt. Express **14,** 2721 (2006).
2. S. Saraf, S. Sinha, A. K. Sridharan, and R. L. Byer, in *Proceedings of Advanced Solid-State Photonics* (*OSA*) **83,** 426 (2003).
3. X. Liu, S. Du, J. Zhou, J. Dong, Y. Wei, Z. Yuan, W. Wang, Z. Su, and Q. Lou, Chin. Opt. Lett. **8,** 184 (2010).
4. J. Wang, J. Zhou, H. Zang, X. Zhu, and W. Chen, Chin. Opt. Lett. **8,** 670 (2010).
5. A. Liem, J. Limpert, H. Zellmer, and T. Tünnermann, Opt. Lett. **28,** 1537 (2003).
6. Y. Jeong, J. Nilsson, J. K. Sahu, D. N. Payne, R. Horley, L. M. B. Hickey, and P. W. Turner, IEEE Sel. Top. Quantum Electron. **13,** 546 (2007).
7. N. A. Brilliant, J. Opt. Soc. Am. B **19,** 2551 (2002).
8. A. Liu, Opt. Express **17,** 15201 (2009).
9. A. Kosterin, V. Temyanko, M. Fallahi, and M. Mansuripur, Appl. Opt. **43,** 3893 (2004).
10. D. Machewirth, F. Corbin, K. Tankala, M. O'Conner, B. Samson, and M. Alam, in *Proceedings of 19th Solid State and Diode Laser Technology Review* FIBER2-2 (2006).
11. Y. Jeong, J. Nilsson, J. K. Sahu, D. B. Soh, P. Dupriez, C. A. Codemard, S. Baek, D. N. Payne, R. Horley, J. A. Alvarez-Chavez, and P. W. Turner, Opt. Lett. **30,** 955 (2005).
12. Y. A. Barannikov, A. I. Oussov, F. V. Shcherbina, and N. S. Platonov, in *Conference on Lasers and Electro-Optics/International Quantum Electronics Conference and Photonic Applications Systems Technologies* (*OSA*) CMS3 (2004).
13. W. H. Loh, B. N. Samson, L. Dong, G. J. Cowle, and K. Hsu, J. Lightwave Technol. **16,** 114 (1998).
14. M. Leigh, W. Shi, J. Zong, J. Wang, S. Jiang, and N. Peyghambarian, Opt. Lett. **32,** 897 (2007).