90.4-W all-fiber single-frequency polarization-maintained 1 083-nm MOPA laser employing ring-cavity single-frequency seed oscillator

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Received July 22, 2011; accepted September 15, 2011; posted online November 18, 2011

A high-power all-fiber single-frequency polarization-maintained (PM) laser operating at 1 083 nm is demonstrated using a master oscillator power amplifier (MOPA) structure. The seed source of this MOPA laser system is an in-house-built ring-cavity fiber oscillator. Four-stage amplification configuration is employed, in which the maximal output power of the main amplifier is 90.4 W, corresponding to a conversion efficiency of 72.5%. The polarization extinction ratio of the output light is 13 dB. The amplified spontaneous emission is suppressed by a factor of over 25 dB, and no stimulated Brillouin scattering effect is observed when a large-mode-area and high absorption coefficient PM gain fiber is employed.

OCIS codes: 060.2320, 140.3560, 140.3615.

doi: 10.3788/COL201210.031402.

High-power fiber lasers are very important components of materials processing, industrial production, and remote sensing due to their high beam quality and conversion efficiency as well as maintenance-free operation[1−2]. Especially, many applications, such as atom trapping and cooling, nonlinear frequency conversion, coherent beam combination, and gravitational wave detection, require polarization-maintained (PM) laser sources[3−5]. High-power single-frequency PM fiber lasers have attracted increasing research attention in recent years, because the SBS threshold can be increased to a level that is greater than 100 W by enlarging the fiber core and the effective mode field can be scaled up by applying a temperature gradient along the fiber length; in addition, near-diffraction-limited beam quality can be obtained with modern fibers and techniques, such as coiling and mode matching[2,5−8]. Meanwhile, 1 083-nm laser sources with a narrow linewidth have found widespread applications in atomic/molecular spectroscopy, such as thermometric lidar and medical lung diagnostics[9,10].

There are many reports on high-power single-frequency PM fiber lasers in the last decade. Liem *et al.* demonstrated a 100-W-level single-frequency master oscillator power amplifier (MOPA) laser at 1 064 nm employing a Nd:YAG nonplanar ring oscillator (NPRO) seed source[6]. Gray *et al.* reported 264- and 402-W single-frequency single-mode plane-polarized MOPA sources at 1 060 nm, using a distributed-feedback (DFB) seed laser, respectively[2,7]. Qi *et al.* presented a 128-W class single-frequency line-polarized fiber amplifier at 1 064 nm with a DFB seed laser[8]. Most of these high-power single-frequency PM fiber lasers typically employ bulk optics configuration that have strict working conditions, large size, and low coupling efficiency. The use of all-fiber components can significantly make the laser more compact and reliable. Liu *et al.* reported an all-fiber single-frequency linearly polarized fiber amplifier with a maximal output power of 43.8 W at 1 064 nm employing a DFB seed laser[11]. With reference to the seed laser, most of these reports employed commercial DFB seed sources.

In this letter, we demonstrate a high-power all-fiber single-frequency PM MOPA laser. The seed source is an in-house-built ring-cavity single-frequency fiber oscillator utilizing a piece of saturable absorber (SA), two polarization controllers (PCs), and a polarization-dependent isolator (PD-ISO). The central wavelength of the seed oscillator is 1 083 nm, with a linewidth of 12 MHz. Four-stage amplification configuration is employed in our experiment, and the maximum output power of the main amplifier is 90.4 W, with a polarization extinction ratio (PER) of 13 dB. The corresponding optical-to-optical conversion efficiency is 72.5%. Although the SBS thresholds in the PM fibers are much lower than those in non-PM fibers[12], no SBS effect has been observed in using LMA and high absorption coefficient PM gain fiber. To the best of our knowledge, this is the highest power all-fiber single-frequency PM 1083-nm MOPA laser source ever reported.

In the proposed method, the seed oscillator was pumped by a fiber-pig-tailed 976-nm single-mode laser diode (LD) through a 976/1 080-nm wavelength division multiplexer (WDM). The insertion losses of WDM for the pump light and signal light were 0.09 and 0.06 dB, respectively. Single-mode single-clad heavily ytterbium (Yb)-doped fiber with a length of 25 cm was utilized as the laser gain medium. The gain fiber had a 6-μm/125 μm-core/cladding diameter, with a core numerical aperture

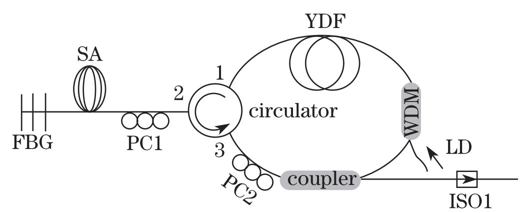

Fig. 1. Schematic diagram of the ring-cavity single-frequency seed oscillator.

(NA) of 0.15 and an average absorption coefficient of 1 200 dB/m for 976-nm pump wavelength. A circulator, with isolation ratios of 37 dB from port 2 to port 1 and 39 dB from port 3 to port 2, respectively, was applied in the ring-cavity fiber oscillator. A high reflectivity ($R \approx$97.8%) fiber Bragg grating (FBG) with a full-width at half-maximum (FWHM) linewidth of about 0.06 nm was placed at the second port of the circulator, which acted as the total reflection cavity mirror. An optimal un-pumped Yb-doped fiber with a length of 1.5 m and the same parameters as those of gain fiber was utilized as the SA to form a narrow self-written filter[13]. PC 1 was used to adjust the polarization states of the counter-propagating waves in the SA. A 1×2 3-dB fiber coupler was used to couple about 50% of the circulating power out of the cavity. PC 2 was adopted to control the wave polarization in the ring cavity. To prevent the destruction of the seed oscillator apparatus due to back scattering light, ISO 1 was spliced to the output port of the coupler. To make the seed source less sensitive to environment disturbance, the ring-cavity was placed in an acryl-glass box with special temperature and vibration control. The temperature was controlled to 20 °C using a thermostat, and the acryl-glass was placed on an air-cushioned vibration-isolated optical-table from the University of Shanghai for Science and Technology. The schematic diagram of the ring-cavity single-frequency seed oscillator is plotted in Fig. 1.

In our experiment, we first injected an appropriate power of pump light into the oscillator, after which we rotated PC1 and PC2 slightly. Single-frequency seed light can be obtained by rotating certain positions. The maximal injected pump power of the single-frequency operation was 87 mW, with a laser power of 2.8 mW. Spectrum analyzer (86142B Agilent) and scanning Fabry-Perot (F-P) interferometer (SFPI 100, fineness 400, free spectral range 4 GHz, Toptica Inc.) were utilized to measure the spectrum and frequency spectrum of the seed oscillator, respectively. As depicted in Fig. 2(a), the residual pump power and ASE of the output light can be neglected. The detailed frequency spectrum of the seed oscillator plotted in Fig. 2(b) indicates that the FWHM linewidth is about 12 MHz, which is slightly wider than that of a previously reported narrow-linewidth fiber laser[14]. This can be explained as follows. Since the reflectivity of the FBG is not high enough, the counter-propagating waves in the SA are inadequate, and the interference of the standing waves is limited to form a MHz-class dynamic absorption grating. The insert drawing of Fig. 2(b) shows a full scan over one free spectral range (FSR), confirming that only one laser mode oscillates. The PER of the seed oscillator was measured by an extinction ratio meter (ERM 100, THORLABS Inc). Although the oscillator had a non-PM structure, the PER of the seed light was still 13 dB due to the utilization of the two PCs. Since our focus is to protect the seed oscillator from environmental disturbance, the output power and single-mode-oscillating can be maintained in 60 min operation time without conspicuous variation.

The MOPA laser system we demonstrated in this manuscript is schematically plotted in Fig. 3. The seed laser and pump source were injected into the first stage non-PM pre-amplifier through a 976-nm/1 080-nm WDM with the same parameters as the WDM adopted in the oscillator. The gain fiber with a length of 30 cm and the fiber-pig-tailed LD are identical to those in the seed oscillator. To enhance the PER of the seed light, we employed a PD-ISO after the non-polarized pre-amplifier. Then, the 2.8 mW seed power was boosted to 12 mW using the non-polarized pre-amplifier. The output power from the PD-ISO was 7 mW with a PER of 22 dB. To provide enough power for main amplification stage, a 2-stage PM pre-amplifier followed by a couple of 3-W level PM-ISOs were utilized. The second stage PM pre-amplifier was a commercial fiber amplifier (YAD-1K-1083-LP-SF, IPG Inc) with an output power of 115 mW. The third PM-preamplifier used was a double-clad Yb-doped fiber amplifier (YDFA) pumped by a 9-W level fiber-pig-tailed LD. The 976-nm pump laser and signal light were launched into the gain fiber using a (2+1)×1 pump combiner. The active fiber in this stage was a section of the double-clad PM-YDF with a length of 4-m and 5-μm/130-μm core/inner clad diameter with 0.13/0.46 NA, respectively. The maximal output power of the third stage PM pre-amplifier was 2.2 W.

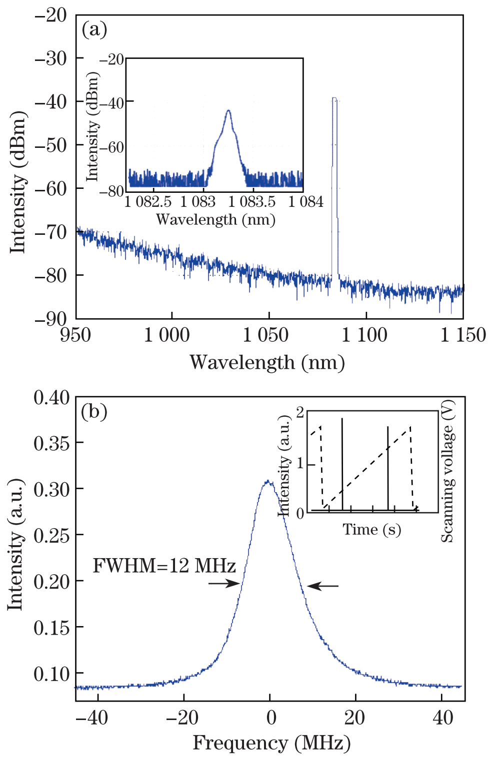

Fig. 2. Characteristics of the seed oscillator. (a) Wavelength spectrum and (b) frequency spectrum.

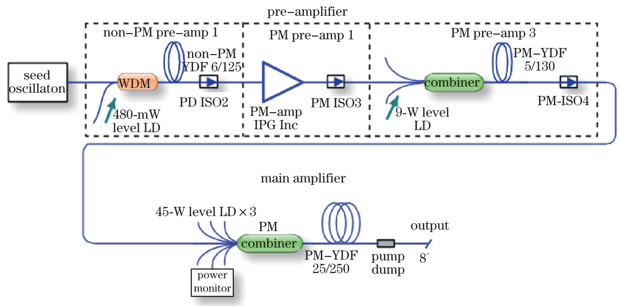

Fig. 3. Schematic diagram of the MOPA laser system.

The main amplification stage of the MOPA laser system was a PM double-clad LMA YDFA. The amplified seed light and the pump light were injected into the power scaling stage using a (6+1)×1 PM fiber combiner, whose signal input fiber exhibited 6-μm/125-μm core/inner clad diameter (NA=0.11). The pump delivery fibers of PM combiner and fiber-pig-tailed LDs were both 105 μm /125 μm (NA=0.22). Three 45-W class pump LDs were utilized with two independent drivers. The central wavelengths of the LDs drift from 972 to 976 nm with enhanced output power. The PM active fiber in this stage is a piece of PM double-clad LMA Yb-doped fiber with a length of 3.5 m, exhibiting 25-μm/250-μm core/inner clad diameter with 0.06/0.46 NA, respectively. The average absorption coefficient of the inner clad for 976-nm pump source is about 11.2 dB/m. The active fiber is few-modes fiber, thus, the gain fiber was coiled with a diameter of about 15 cm to strip the high order mode radiation. A section of Ge-doped double-clad passive fiber with a length of 0.4 m and the same core/inner clad diameter and NA as those of the LMA PM-YDF was spliced to the PM active fiber for power delivery. The spliced region was covered with high-index gel to strip the residual pump laser and high order mode laser in the inner clad of the active fiber. An 8° angle was cleaved at the output port of the power delivery fiber to suppress back reflection and prevent end facet damage. All the components of the power amplifier and pump LDs were heat-sunk to aluminum baseplates with cold water circulating inside for stable high power operation. The temperature of the circulating water for the main amplifier and the three pump LDs were then controlled to be 20 °C with an industrial cooling system. As our previous work verified that the back scattering power from idle pump ports of combiner is linear to the backward power of main amplifier[15], we employed a power monitor to detect the back scattering light for estimating the SBS effect.

The characteristics of the output and backward power of the main amplifier versus pump power are shown in Fig. 4(a). The absorption coefficients of the gain fiber for pump light at different wavelengths are not equivalent. As the driven currents of the three pump LDs are enhanced orderly, and the central wavelengths of LDs shift slightly, the optical-to-optical conversion efficiency differ. In addition, there are 2 inflexions on the curves LD2 and LD3 are turned on. The ultimate output power of the main amplifier is 90.4 W for given 121.7-W pump power. The corresponding optical-to-optical conversion efficiency is 72.5% under the maximum output power. The PER of the output light is 13 dB for temperature non-uniformity along the fiber and mechanical perturbations from the cooling system. Given that the backward power is enhanced monotonously with the increase in output power, it can be concluded that no SBS effect has been observed. The LMA and high absorption coefficient characteristics of the PM-YDF employed in our experiment is propitious to the suppression of SBS. The output power can still be increased with more powerful pump source. Figure 4(b) shows the optical spectrum of the main amplification stage at maximal output power. As can be seen from the spectrum, the ASE is suppressed by a factor of over 25 dB and the pump laser has

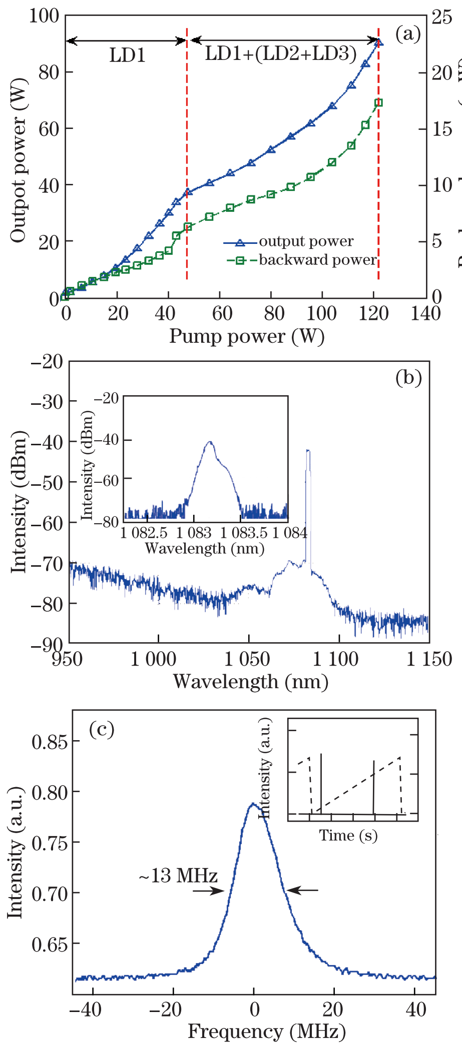

Fig. 4. Characteristics of (a) Output and backward powers of the main amplifier versus pump power; (b) spectrum; (c) frequency spectrum.

been almost totally absorbed or dumped. To study the frequency spectrum characteristic under maximal output power, ∼5 mW amplified laser was coupled into the scanning F-P interferometer using two 1/99 reflecting mirrors and a free-space to fiber coupling system. As depicted in Fig. 4(c), only a single laser mode oscillates, and the FWHM linewidth of the amplified laser is about 13 MHz, which is slightly wider than that of the seed laser. This is due to the temperature and doping non-uniformity along the fiber.

In conclusion, we demonstrate an all-fiber single-frequency PM 1 083-nm MOPA laser with 90.4-W output power. The seed source of this MOPA laser system is a home-made ring-cavity single-frequency fiber oscillator. The central wavelength of the seed oscillator is 1 083 nm, with a linewidth of 12 MHz. Stable single-frequency PM seed light is obtained by utilizing a piece of SA, two PCs, and a PD-ISO. Four-stage amplification configuration is employed in our experiment, and the maximal output power of the main amplifier is 90.4 W, with 13-dB PER corresponding to an optical-to-optical conversion efficiency of 72.5%. The ASE is suppressed by a factor of over 25 dB and no SBS effect is observed for the LMA and high absorption coefficient characteristics of the PM-YDF employed in our experiment. Furthermore, the output power is limited by the pump power, and further power scaling of this MOPA laser system is available.

This work was supported by the Program of China for the New Century Excellent Talents in University (No. NCET-08-142) and the National Natural Science Foundation of China (Nos. 61077076, 10904173, and 11004247). We are particularly grateful to J. Leng and X. Dong for their support in completing this work.

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