Linearly polarized operation of Yb-doped fiber laser by Brewster's angle-polished fiber end

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Received March 27, 2009

A new method to obtain linear polarization operation by Brewster's angle-polished fiber end is demonstrated. By using the special polarization operation technique together with introducing a narrow-linewidth fiber grating into the laser cavity, a cladding-pumped linear polarization and single-transverse-mode ($M^2 < 1.1$) Yb-doped fiber laser with narrow linewidth whose full-width at half-maximm (FWHM) is less than 0.2 nm, is obtained in a simple configuration. The output power is up to 10 W which is continuous-wave output at 1085 nm, and the slope efficiency is 63% with respect to the coupled pump power and 75% with respect to the absorbed pump power, respectively. The measured 21-dB polarization extinction ratio does not degrade with the output power. The simplicity of such an approach is highly beneficial for a number of applications, including the use of a fiber laser for the nonlinear wavelength conversion (especially for the intracavity frequency doubling) and for the coherent and spectral beam combination.

OCIS codes: 140.3510, 140.3615.

doi: 10.3788/COL20100802.0184.

During the last decade, fiber lasers have attracted great attention due to their compactness, high reliability, and high wall-plug efficiency. For many applications such as nonlinear frequency conversion[1,2] and coherent and spectrum beam combining[3−5], research on developing high quality fiber lasers in viewpoints of single polarization and narrow bandwidth is very important. So far, selecting and keeping a linear polarization have been based on the use of free-space or in-line polarization components[6−8] and the narrow linewidth laser output was usually achieved by complex master-oscillator-power-amplifier (MOPA) setups[9]. However, the use of bulk components involves problems such as sensitive alignment and instability. Besides, both free-space or in-line polarization components and MOPA setups involve disadvantages like increased costs, additional losses, and complexity of the system.

Here we demonstrate a new method to obtain linear polarization operation by Brewster's angle-polished fiber end instead of using any free-space or in-line polarization components or basing on the complicated MOPA setups in the demonstrated high-power polarization maintaining (PM) fiber laser designs. As far as we know, this is the first time to adopt this technique to obtain polarized output of a fiber laser and the polarization extinction ratio (PER) is better than 21 dB, which is higher than the typical value of 16−19 dB in the other reports[6−9]. The output power of the presented single-transverse mode continuous-wave (CW) fiber laser was exceeding 10 W with a 63% slope efficiency with respect to the coupled pump power at 1085 nm. Considering the leak pump power of about 3 W at the 10.1 W of the laser output, the actual slope efficiency was more than 75% with respect to the absorbed pump power. Additionally, the lasing spectrum at 1085 nm with a narrow-linewidth whose full-width at half-maximum (FWHM) was less than 0.2 nm, had been stabilized by a narrow linewidth fiber Bragg gratings (FBGs) which was spliced at one end of the active fiber. This simple technique together with the special linear polarization operation technique can make the design simple and robust. Furthermore, using the high-power large-mode-area (LMA) fiber as the active fiber together with the absence of polarizing components can significantly facilitate the power scalability of this approach. Therefore, although the maximum output power limited by the available pump power is only 10 W, the power scalability of this approach is indubitable. Finally, to achieve the single-transverse-mode operation, higher-order modes can be suppressed by using the conventional fiber-bending-induced differential loss between fundamental and higher-order modes in low numerical arperture (NA) LMA core fibers[10]. Undoubtedly, this simple and robust design is particularly attractive for coherent and spectral beam combining as well as for nonlinear wavelength conversion (especially for the intracavity frequency doubling where the MOPA scheme is unavailable), where single-polarization and narrow-spectrum output is critical.

The experimental setup is shown in Fig. 1. The gain fiber is a 10-m-long Yb-doped, panda-type, highly birefringent LMA double-clad fiber, whose cross section is shown in the inset of Fig. 1. It has a 20-μm core and 400-μm octagon-shaped pump cladding with NAs of 0.06 and 0.45 for the core and the cladding, respectively. One end of the Yb-doped fiber was spliced with a high reflectivity ($R = 97\%$) FBG at 1085 nm imprinted

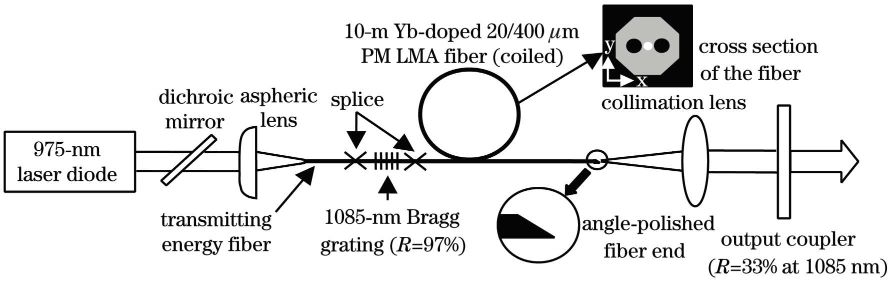

Fig. 1. Schematic of linearly polarized operation of Yb-doped fiber laser by Brewster's angle-polished fiber end.

into an identical 20-μm core LMA fiber with NA of 0.06 for the core, and the other end was Brewster's angle-polished (i.e., the normal of the output end at Brewster's angle with respect to the optical axis of the fiber was perpendicular to the slow axis of the fiber) which allowed us to achieve linear polarization at the output. Besides, to obtain output beam in a single-transverse mode, the Yb-doped fiber was coiled with a diameter of 7.5 cm. The pump laser operating at 975 nm was coupled by the aspheric lens with 80-mm focal length from the transmitting energy fiber which was spliced with the input end of the FBG. In order to form the laser cavity between the FBG and the output coupler, a 8-mm focal length lens used as a collimation lens was located 8 mm away from the output coupler ($R = 33\%$ at 1085 nm). Furthermore, a dichroic mirror was located between the pump laser and the aspheric lens to protect the pump laser because the reflectivity of the FBG for the 1085-nm laser was only 97%. Actually, an all-fiber pump configuration can be adopted if the reflectivity of more than 99% is available.

In the experiment, using the LMA fiber as the active fiber has allowed the laser power to be scalable. However, special operation to achieve single-transverse-mode should be adopted in such a highly birefringent LMA fiber. Therefore, we adopt the conventional approach in which the gain fiber is coiled to induce significant bend losses for all but the lowest-order mode to obtain single-transverse mode operation of a laser using LMA multimode fiber[11]. Besides, we can expect that the coiled gain fiber will further improve the polarization extinction ratio (PER) of the laser because of the bending-induced propagation-loss differentiation between different LP01-mode polarizations[12,13]. In Ref. [12], the x-polarized LP01 mode (i.e., polarized along the x axis in the fiber cross section picture shown in Fig. 1) can remain impervious to the bending, while higher-order modes and the y-polarized LP01 mode (i.e., polarized along the y axis) can experience bending-induced losses. Therefore, in our experiment, the normal of the output end of the fiber should be not only at Brewster's angle with respect to the optical axis of the fiber, but also perpendicular to the fast axis (i.e., the y-axis) of the fiber. Finally, we can expect that the fiber-bending will further improve the PER of the laser by this approach though the main purpose to coil the fiber is to obtain output beam in a single-transverse mode.

The output power of the laser as a function of pump power is plotted in Fig. 2 and up to 10 W of the laser output has been achieved with the slope efficiency of 63% which is respect to the coupled pump power. Considering the leak pump power of about 3 W at the 10.1 W of the laser output, the actual slope efficiency is more than 75% with respect to the absorbed pump power. As one can see from Fig. 2, the laser power increased linearly with the pump power and showed no evidence of roll-over even at the highest output power. The maximum output power was limited to the available pump power. Figure 3 shows the spectrum of the laser output at the maximum output power of 10.1 W, revealing a narrow

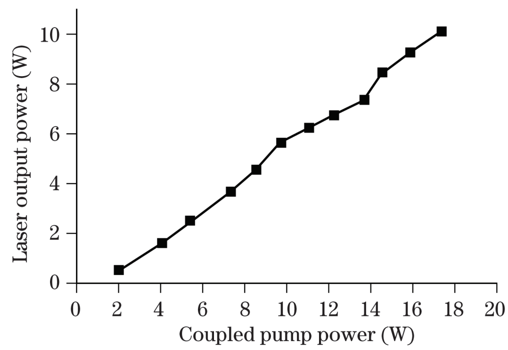

Fig. 2. Laser output power versus coupled pump power.

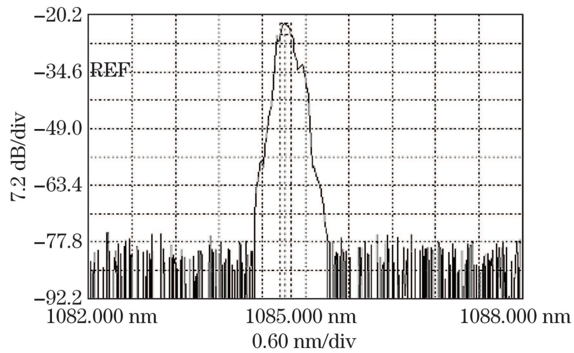

Fig. 3. Laser output spectrum.

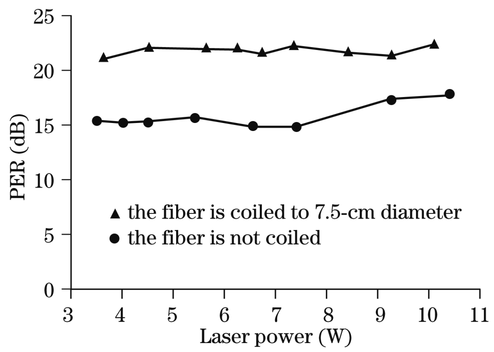

Fig. 4. PER at different laser output powers.

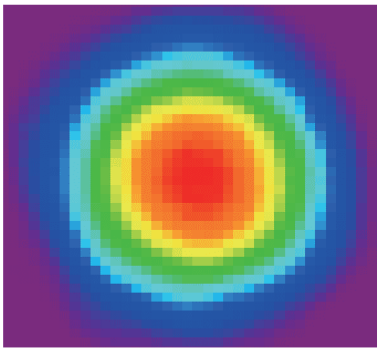

Fig. 5. Output laser beam profile.

linewidth (FWHM) of less than 0.2 nm.

The results of comparison of PER at different laser powers for the Yb-doped fiber coiled or not are shown in Fig. 4. Without the Yb-doped fiber coiled, the laser output was provided with the PER of more than 14.5 dB because of the special design of Brewster's angle-polished fiber end. While with the Yb-doped fiber coiled, the PER of the laser was improved to be better than 21 dB. It shows that the fiber-bending further improves the PER of the laser as predicted before though the main purpose to coil the fiber is to obtain output beam in a single-transverse mode. In our experiment, different coiled diameters was used and 7.5 cm was the optimum coiled diameter to obtain the optimum result of 21-dB PER when the fiber end was Brewster's angle-polished.

The measurements of the beam profile, as shown in Fig. 5, show excellent mode quality and demonstrate single-mode operation with beam quality factor (M^2) better than 1.1 at all powers.

In conclusion, a new method to obtain linear polarization operation by Brewster's angle-polished fiber end is demonstrated. The significance of such technique is that it avoids any free-space or in-line polarization components or MOPA scheme and provides a simple and robust design. By using this new linear polarization operation technique together with introducing a narrow-linewidth fiber grating into the laser cavity, a linear polarization and single-transverse-mode ($M^2 < 1.1$) CW Yb-doped LMA fiber laser with narrow spectrum has been developed in a simple configuration. Up to 10-W output power and 63%-slope efficiency with respect to the coupled pump power have been obtained. Considering the leak pump power of about 3 W at the 10.1 W of the laser output, the actual slope efficiency is more than 75% with respect to the absorbed pump power. The measured 21-dB PER does not degrade with the output power. Besides, the laser provides a narrow-linewidth of less than 0.2 nm by including a narrow-linewidth fiber grating into the laser cavity. What's worth of mentioning is that if the reflectivity of FBG more than 99% is available, an all-fiber pump configuration is capable to enhance the simplicity. Such PM and narrow-linewidth design is particularly valuable for beam combining, and other applications, for example, nonlinear wavelength conversion. Particularly, this simple and robust design of PM and narrow-linewidth operation will make the intracavity frequency doubling available for fiber laser, which will be a more efficient method than the usual single-pass frequency doubling method.

This work was supported by the National High Technology Research and Development Program of China (No. 2008AA03Z405) and the Shanghai Natural Science Foundation (No. 10ZR1433600).

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