High power single-mode large-mode-area photonic crystal fiber laser with improved Fabry-Perot cavity

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Received April 26, 2006

An Yb^{3+}-doped double-clad large-mode-area photonic crystal fiber (LMA PCF) laser with 103-W single-mode continuous-wave output power is demonstrated using an improved Fabry-Perot (F-P) configuration. The slope efficiency of 83.2% and good beam quality ($M^2 = 1.2 \pm 0.1$) are achieved without any thermo-optical problems, dichroic mirror surface damage, and drop of the slope efficiency in this system.

OCIS codes: 140.3480, 140.3510, 060.2430.

High power fiber lasers based on ytterbium-doped large-mode-area photonic crystal fiber (LMA PCF) have been the focus of considerable researches[1−5]. Output power of 260 W of the fiber laser based on LMA PCF was obtained without any thermo-optical problems or reduction in slope efficiency, only limited by the available pump diode lasers[4]. Output power of 1.53 kW of the fiber laser based on LMA PCF was achieved[5], which can be compared with 1.36-kW output power based on the conventional ytterbium-doped double-cladding fibers[6]. High power fiber lasers based on the conventional ytterbium-doped step-index fibers require relatively high cladding numerical aperture (NA), large core size, and short fiber length for high power scaling. Unfortunately, higher cladding NA (> 0.55) is difficult to be obtained using conventional technology and the step-index core technology limits the mode-field diameter (MFD) to around 25 μm for single-mode operation[7]. PCFs technology can solve the above problems. The high accuracy and flexibility of the control of the geometric microstructure provides PCFs with a large number of useful properties that are not obtainable in conventional solid optical fibers[8]. It is crucial that LMA PCF also can be strictly single-mode over a large wavelength range. The requirement of a small refractive index difference between core and cladding regions for LMA fibers, which makes them difficult to be designed using conventional fiber due to the need of dopants, is easy to be satisfied in PCF as it was realized by a particular geometric size and arrangement of holes eliminating the need for dopants.

In this letter, the output power of 103 W based on LMA-PCF is achieved with high beam quality ($M^2 = 1.2 \pm 0.1$) at high-power operation using an improved Fabry-Perot (F-P) configuration. In our configuration, a dichroic mirror with high transmission at the pump wavelength of 970—980 nm and high reflection at the signal wavelength of 1020—1080 nm was placed into the coupler directly, which is more compact compared with the laser cavity configuration than using a pair of dichroic mirrors[9]. Moreover, the dichroic mirror can be adjusted conveniently and does not make an impact on the coupling of the pump lights. The laser output coupler was formed by a dichroic mirror with 5% feedback at 1040—1080 nm instead of 4% Fresnel reflection which has the strict requirement for the planeness of the end facet of the fiber. Both end facets of the LMA PCF used in our experiment are polished at the angle of 6° in order to avoid 4% Fresnel reflection which will bring compound cavity in the fiber laser system and reduce the pump reflection back to the pump power source at the fiber facet which is very important in the strong pump fiber laser. Through the improved measures above, a highly efficient F-P cavity configuration is obtained with slope efficiency of 83.2% and provides a possible way for the ultra-high power fiber laser.

LMA PCF used in this paper is provided by the crystal fiber A/S. The inner cladding of LMA PCF (Fig. 1(a)) consists of four rings of air holes with a diameter d of ~ 1.1 μm and a spacing Λ of approximately ~ 12.3 μm ($d/\Lambda = 0.09$). The ytterbium-doped core area (Fig. 1(b)) is formed by seven missing air holes and has a diameter of 40 μm (mode-field-area ~ 1000 μm^2). The effective core NA is 0.03 and the first cladding diameter is 170 μm with an effective NA of 0.62 at 950 nm. The outer cladding diameter of the fiber is about 590 μm, and acrylate is applied as coating material. The pump light absorption

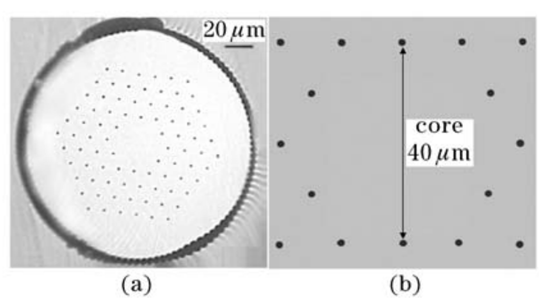

Fig. 1. Cross section image of the inner cladding (a) and core area (b) of LMA PCF.

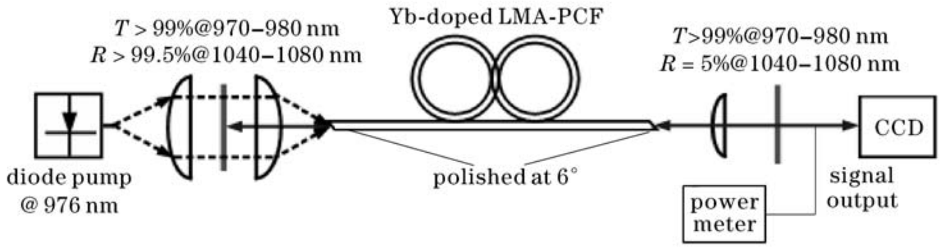

Fig. 2. Schematic of the experimental setup.

of this structure is $\sim$ 13 dB/m at 976 nm and the background propagation losses are as low as 10 dB/km at 1300 nm.

Two fundamental tasks shall be accomplished for the coupling of the high-power double-clad LMA PCF laser. One is to transform highly divergent light from fiber bundle into the collimated beams using bulk optics. The other is to transform collimated beams into the tightly focused spots that match the properties of LMA PCF. In our experiments LMA PCF was end-pumped by a fiber coupled diode array (λ = 976 nm). The diameter of the fiber bundle was 400 μm and the NA was 0.22. This output was matched to the 170-μm diameter inner cladding of PCF using a pair of antireflection coated aspheric lenses. The first lens is the act of collimating and the second one is the act of focusing. The lens pair with an antireflection coating at 976 nm gave a transmission of 99% and a nominal spot size of 162 μm at a nominal NA of 0.55.

The schematic of experimental setup is shown in Fig. 2. The LMA PCF has a pump light absorption of $\sim$ 13 dB/m at 976 nm, so the fiber length of 2 m used in the experiments can almost satisfy the entire absorption of the launched pump radiation. At the pump end of the laser cavity, high-reflectivity feedback was provided by a dichroic mirror with transmission of 95% at 970—980 nm and reflection of 99.5% at 1020—1080 nm. The laser output coupler was formed by a dichroic mirror with 5% feedback at 1020—1080 nm at the other end of the fiber. Both ends of PCF are hermetically sealed (collapsing the holes) and connected with high power SMA-905 connectors designed to prevent possible thermal damage to the fiber coating by any non-guided pump or signal power or by the heat generated in the laser itself. The collapsed distance after polishing is about 650 μm so as to avoid contamination of end facets and internal microstructure of LMA PCF. Both end facets of LMA PCF are polished at the angle of 6°. In order to observe the near-field characteristic, the output beam is finally detected with a charge coupled device (CCD) camera connected to a mode profiling system.

Figure 3 shows the measured power from the output of the fiber laser as a function of the launched pump power. The coupling efficiency in the inner cladding is about 60.5%, which is measured by the cutting back method using about 5-cm-long LMA PCF in our experiments. Laser output centered at 1.04 μm is observed when the launched pump power is increased to 0.9 W. The slope efficiency is about 83.2%. The output power of 103 W is achieved when the whole pump power is up to 210 W, and the corresponding optical-to-optical conversion

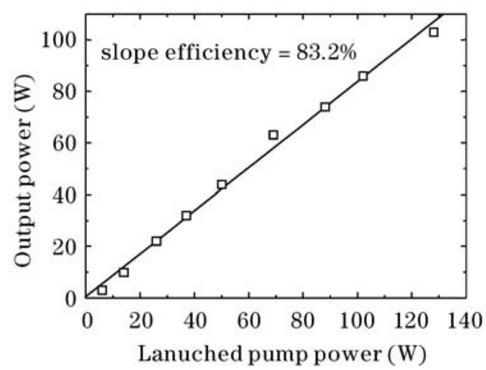

Fig. 3. Power characteristic of LMA PCF laser.

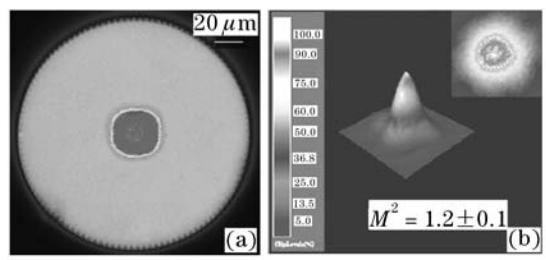

Fig. 4. Near-field image at a fiber bending diameter of 30 cm (a), the signal beam profile and M^2-value with 30-cm spool diameter of the fiber (b).

efficiency is more than 49%. This power level is achieved without any thermo-optical problems, dichroic mirror surface damage caused by the high optical intensity, reduction in slope efficiency or degradation of the coating. Compared with the conventional ytterbium-doped double-clad fiber lasers, there are no losses of any kind due to the unconventional shape of the active core and inner cladding[3].

Figure 4(a) shows near-field beam profile at bending diameter of 30 cm. It can be seen that the pump light is guided in the first cladding and signal light is guided in the core by total internal reflection. Mode field diameter (MFD) of the signal beam is about 38 μm and single transverse mode is obtained when adjusting the bending diameter from 20 to 40 cm. The beam profile possesses a nearly round and Gaussian like intensity distribution at 30 cm bending diameter compared with the triangular shape obtained from another PCF laser system[10] and M^2-value is measured to be 1.2 $\pm$ 0.1, meaning a nearly diffraction-limited beam, but the bending loss for the fundamental mode is so small that the mode is almost constant in intensity when the bending diameter increases. Figure 4(b) shows the M^2-value of the beam profiles with 30-cm spool diameter of the fiber. During most of the operating period the laser wavelength remained stable at 1.04 μm. No significant wavelength shift was observed as the pump power increased.

In conclusion, a 103-W cladding pumped LMA-PCF laser using an improved F-P configuration with a high slope efficiency of 83.2% has been demonstrated. Single-transverse mode operation is achieved with high beam quality ($M^2 = 1.2 \pm 0.1$). No thermo-optical problem or dichroic mirror surface damage are observed using this improved F-P configuration with this power level. This kind of high power operational single-mode fiber laser using the improved F-P configuration has the potential for scaling to much higher output powers and provides a base for higher power output through coherent beam combining.

This work was supported by the National Natural Science Foundations of China under Grant No. 602537060 and 10390160. K. Li's e-mail address is likang@opt.ac.cn.

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