High-power double-clad large-mode-area photonic crystal fiber laser

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A high power double-clad ytterbium-doped large-mode-area photonic crystal fiber (LMA PCF) laser was demonstrated using a unique Fabry-Perot (F-P) configuration. The pump source is a fiber coupled diode array operating at 976 nm. A continuous wave (CW) output power of 50 W at ~ 1.04 μm with a slope efficiency of 76.3% is obtained. Single transverse mode operation is achieved without any thermal-optical problems. This laser has the potential for scaling to much higher output power.

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High power fiber lasers based on ytterbium-doped large-mode-area photonic crystal fiber (LMA PCF) have been the focus of considerable research[1−3]. Output powers up to 260 W based on the LMA PCF were obtained without any thermo-optical problems or reduction in slope efficiency, only limited by the available pump diode lasers[3]. High power fiber lasers based on the conventional ytterbium-doped step-index fibers require relatively large mode areas to avoid the fiber surface damage caused by the high optical intensity. Unfortunately, the large mode area in conventional fibers results in degraded beam quality. PCF provides a solution to this problem.

PCFs, also called microstructure optical fibers or holey fibers, consist of a solid glass core and a cladding containing numerous periodically situated air-holes or voids in a glass base material which act to lower the effective refractive index of the cladding[4]. The high accuracy and flexibility of the control of the geometric microstructure provide PCFs a large number of useful properties that are not obtainable in conventional solid optical fibers[5]. It is crucial that LMA PCF also can be strictly single-mode over a wide wavelength range. Actively doped LMA PCFs also have been realized[6]. The requirement of a small refractive index difference between core and cladding regions for LMA fibers, which makes them difficult to design using conventional fiber due to the need of dopants, is overcome in a PCF as it was realized by a particular geometric size and arrangement of holes eliminating the need for dopants. The gain medium of a fiber laser can be fabricated by introducing a rare-earth ion doping into the core of the PCF. Even the double-clad concept can be transferred to such fibers[6], with the promising feature of a high numerical aperture (NA) of the inner cladding. The combination of these fiber designs with Yb-doped core results in unique properties for high power lasers.

High power output of fiber lasers based on conventional Fabry-Perot (F-P) configuration is much more challenging due to the higher pump power densities and the optical damage or degradation of the optical film of the dichroic mirror. For solving these problems, a unique F-P configuration was used to reduce pump power densities of the dichroic mirror. In this letter, the output power of 50 W with a slope efficiency of 76.3% is achieved without any thermo-optical problems, dichroic mirror surface damage, and degradation of the optical film.

The inner cladding of the LMA PCF (provided by the Crystal Fiber A/S, as shown in Fig. 1) consists of a hexagonal lattice of air holes with a diameter (d) of 2 μm and a spacing (Λ) of approximately 11.5 μm ($d/\Lambda = 0.17$). Three capillaries are replaced by ytterbium-doped rods which has been demonstrated to be advantageous for LMA PCFs during the stacking process[7], resulting in a triangularly shaped core with a diameter of about 28 μm after drawing the fiber. The core NA is 0.05 and the first cladding diameter is 150 μm with an effective NA of 0.55. The outer cladding diameter of the fiber is about 450 μm, and acrylate is applied as coating material.

The fiber was end-pumped by a fiber coupled diode array ($\lambda = 976$ nm). The diameter (D) of the fiber bundle was 400 μm and the NA_0 is 0.22. This output was matched to the 150-μm diameter inner cladding of the PCF using a pair of objective lenses ($f_1 = 15.6$ mm, $\mathrm{NA}_1 = 0.25$ with distance of 8.8 mm; $f_2 = 4.5$ mm, $\mathrm{NA}_2 = 0.65$ with distance of 0.56 mm) with a separation of 80 mm. The lens pair without antireflection coating

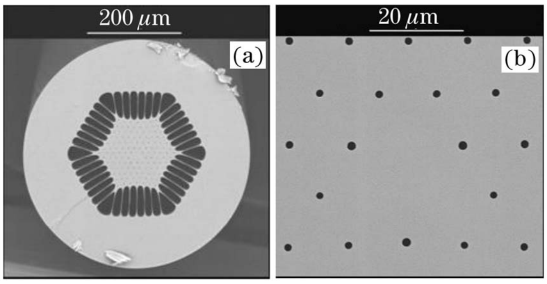

Fig. 1. Cross section images of the air-clad ytterbium-doped LMA fiber (a) and close-up of core region (b).

at 976 nm gave a transmission of 65% and a nominal spot size of 115 μm ($D \times f_2/f_1$) at a nominal NA of 0.76 ($\mathrm{NA}_0 \times f_1/f_2$). The NA is higher than the specified acceptance angle of the output objective lens and the mismatch introduces aberrations into the system which reduces the coupling efficiency into the PCF.

The schematic experimental setup is shown in Fig. 2. The PCF has a pump light absorption of 9.6 dB/m at 976 nm, so fiber length of 3 m ensures that the entire launched pump radiation is absorbed. The cavity is formed between an external, high reflecting dichroic mirror at the pumped end of the fiber, and a perpendicularly cleaved, 4% Fresnel reflection facet in the other end. It is different from the conventional F-P cavity in that the external dichroic mirror is placed between the lens pair coupling the pump light rather than very close to the fiber end. This is done in order to reduce the pump power per area of the dichroic mirror and hence avoid optical damage or degradation of optical film of the dichroic mirror which is a severe problem for the high power output fiber laser.

Figure 3 shows the measured output power of the fiber laser as a function of the launched pump power. The coupling efficiency in the inner cladding is 53.3%, measured by the cutting back method. Laser output centered at 1.04 μm is observed when the launched pump power is increased to 0.9 W. The output power of 50 W is achieved when the whole pump power is up to 143 W, and the corresponding optical-to-optical conversion efficiency is more than 35% (from the end of the fiber bundle of the diode array to the output end of the 3-m PCF). 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 the inner cladding[2].

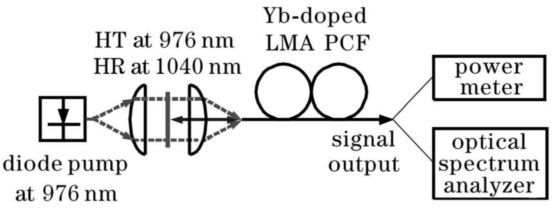

Fig. 2. Experimental setup of high-power double-clad LMA PCF laser. HT: high transmission; HR: high reflection.

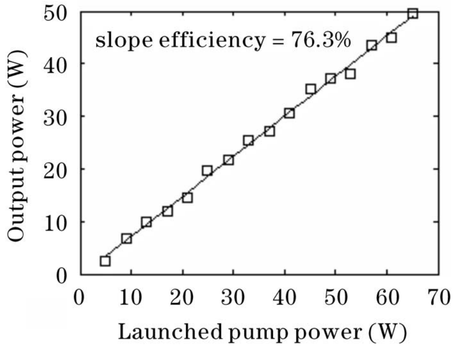

Fig. 3. The power characteristic of the laser.

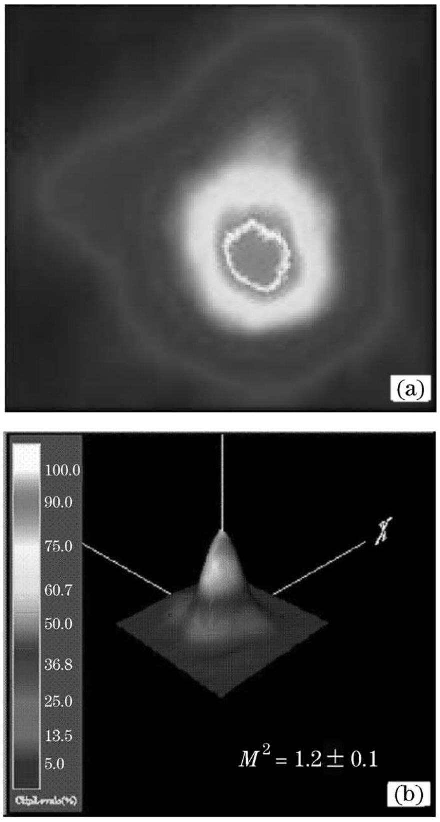

Fig. 4. Measured intensity distribution of the emitted beam (a) and beam quality factor of the center part (b).

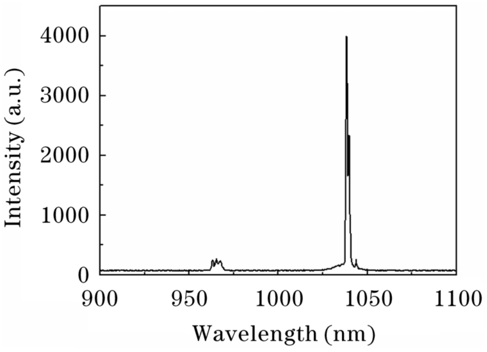

Fig. 5. Output spectrum of the fiber laser.

Higher-order mode (LP_{11}) operation occurred once in a while with 20-cm spool diameter of the fiber. Adjusting the spool diameter and operational stability condition can obtain stable single transverse mode operation of this fiber laser. Figure 4 shows the measured beam profile emitted by this high power fiber laser with 35-cm spool diameter of the fiber. The center part of beam profile, where most of the power is located, possesses a nearly round and Gaussian like intensity distribution. The M^2-value is measured to be 1.2 ± 0.1, meaning a nearly diffraction-limited beam. During most of the operating period the laser wavelength remains stable at 1.04 μm. No significant wavelength shift as the pump power increased is observed. Figure 5 shows the spectrum of maximum output power (50 W). A small part of pump light (about 0.8 W) is still not absorbed due to either the short length of the fiber or the special geometric structure of inner and outer cladding.

In conclusion, a 50-W cladding pumped air-clad PCF laser has been demonstrated. Single-transverse mode operation is achieved from a 3-m-long ytterbium-doped LMA fiber with slope efficiency of 76.3%. No thermo-optical problems or dichroic mirror surface damage are observed using the unique F-P configuration with this power level. This kind of high power operational single-mode fiber laser has the potential for scaling to much higher output powers and provides a base for higher power output through coherent beam combining.

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