Watt-level Yb-doped silica glass fiber laser with a core made by sol-gel method

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A Yb-doped silica glass fiber laser with a core made by sol-gel method is reported. The maximum power of 1.14 W is obtained with a pump power of 5.46 W at a wavelength of 976 nm. The slope efficiency is 34%. The refractive index fluctuation across the core is below 5×10^{-4} at a doping level of Yb 0.15 mol%, A_2O_3 4.0 mol%, and P_2O_5 2.0 mol%. High background attenuation of 6 dB/m at 1 053 nm limites the slope efficiency and maximum output power.

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Yb-doped silica glass fiber laser attracts much attention in the world wide because of its potential in power scaling while maintaining a good beam quality[1−3]. High quality large core Yb-doped silica glass fiber is the key element of a high power fiber laser.

Yb-doped silica glass fiber generally is produced by modified chemical vapor deposition (MCVD) with solution or vapor doping method. However, it shows limits[4,5] for active large core fiber fabrication, especially for large core active photonic crystal fiber (PCF) fabrication. As we know PCF is usually made by stack and draw method. A large homogenous rare earth doped silica glass rod, which works as the core of an active PCF, is hard to obtain by this method. Due to this reason, it is important to find a new way to produce high quality rare earth doped silica glass, which cannot only be used in active large core double clad fiber, but also be used in active large core PCF.

Andreas Langner group[1,5] reported a Yb-doped silica fiber with a core produced by sintering silica granulates. About 5 000-W continuous fiber laser has been achieved in a single fiber[4]. The homogeneity of the Yb ions distribution in the core region was much better than that of fiber made by MCVD method. However there was no detailed report about the fabrication process of the Yb-doped silica glass. Rare earth doped silica glass fiber can also be produced by sol-gel method[6−8]. Unfortunately the output laser powers from these fibers were all limited to milliwatts level.

In this letter, the breakthrough work of the Yb-doped silica glass fiber laser with a core made by sol-gel method will be reported. The maximum power of 1.14 W at 1 038 nm had been achieved at a pump power of 5.46 W. The slope efficiency was 34%. The output laser power is only limited by the obtainable pumped power. As we know this is the highest power ever reported in a double clad Yb fiber with a core made by sol-gel method. The fiber fabrication process and its optical properties will be demonstrated.

In the sol preparation process, tetraethoxysilane (TEOS), C_2H_5OH, $AlCl_3\cdot6H_2O$, and $YbCl_3\cdot6H_2O$ were used as precursors. Deionized water was added to sustain the hydrolysis reaction. The above-mentioned analytically pure grade chemical reagents were mixed and stirred for 20 h at 50 °C to form homogeneous and clear doping sol. The sol was heated from 80 to 1 100 °C to achieve dried gel powder. The gel powder melted into bulk glass at 1 750 °C for 3 h in vacuum state (10^{-4} Torr). The glass was molded into a glass rod on an oxy-hydrogen flame lathe. After cutting, grinding and polishing, a Yb-doped silica glass rod worked as the core of fiber preform was formed. It consists of 0.15 mol% Yb_2O_3, 4.0 mol% Al_2O_3, 2.0 mol% P_2O_5, and 93.85 mol% SiO_2. A preform was made by putting the active glass rod into a pure silica glass tube (from Heraeus company). In the fiber drawing process, silicone was coated outside to protect the fiber mechanically. The core/inner clad/out clad diameters of the fiber were 25/200/300 μm. To increase the coupling efficiency, a hexagon inner clad was produced to suppress the stable helix lights which scarcely passed through the core.

In order to measure the refractive index profile of the core of the Yb-doped fiber, a single clad fiber with a diameter of 15/115 μm was also made. The fiber cross section and its refractive index profile was measured by Photon Kinetics S14 refractive index profiler (Fig. 1). The background attenuation was measured by cut back method.

The absorption spectrum of the Yb-doped silica glass was measured by a spectrophotometer (Lambda 900 UV-VIS-NIR, Perkin-Elmer, USA).

A plane-parallel Fabry-Perot resonator was constructed to test the laser efficiency of the double clad Yb-doped silica fiber pumped by a diode laser at a wavelength of 976 nm (Fig. 2). The pumped laser beam from a coupled transmission fiber was collimated by an aspherical lens with a NA of 0.25 and a focus length of 11 mm. After that, the beam was focused into the double clad Yb-doped fiber by another aspherical lens with a NA of 0.3 and a focus length of 6.16 mm. A dichroic mirror (transmission (T) 99% @976 nm, reflectivity (R) 99% @1 040 nm) was butt-coupled to the Yb-doped fiber.

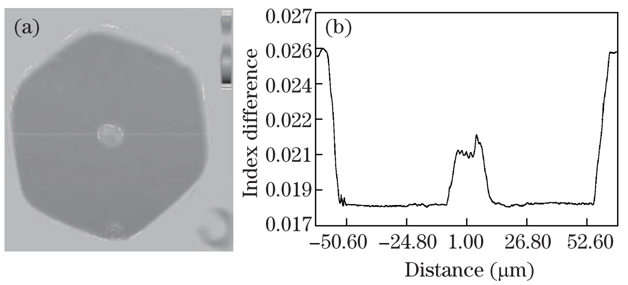

Fig. 1. (a) The cross section and (b) the index profile of the single mode Yb fiber with a core made by sol-gel method.

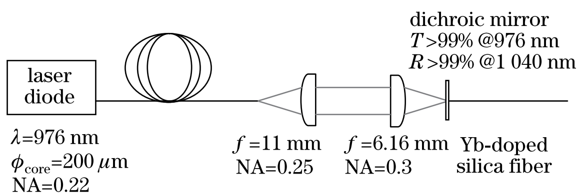

Fig. 2. Experimental setup.

The fiber output end face with 5% Fresnel reflection worked as another cavity mirror. A filter with a transmission less than 0.5% at 976 nm was inserted before a spectrum meter or a power meter to make sure that only the emission light was detected. The fiber fluorescence spectrum was measured by a spectrum meter (Blue-Wave Miniature Spectrometers, StellarNet, USA). The near field mode distribution across fiber facet was tested by a beam profiler (BP109-IR2, Thorlabs, USA).

Figure 1 shows the single clad fiber cross section and its corresponding refractive index profile. As we mentioned, the Yb-doped silica glass was melted from gel powder at 1 750 °C. There is no stir in this process. It is easy to find some non-uniformly distributed light and dark areas in the core. This leads to a high background attenuation of 6 dB/m at 1 053 nm in the core. Although the absorption at this wavelength contributes to the high loss, we thought it is not the main reason. How to decrease the background loss is an urgent problem we should solve at present.

The homogeneity of refractive index profile across the core is better than that reported in Rsfs. [8] and [9]. The refractive index fluctuation across the core is below 5×10^{-4} compared with the cladding pure silica glass. This indicates that our technique is more suitable to make high quality Yb-doped silica glass rod. The index difference of the core and the clad is between 0.003–0.0035, which determines the double cladding fiber (DC fiber) is multimode fiber with a core numerical aperture (NA) of about 0.09.

Figure 3(a) shows the absorption spectrum of the Yb-doped silica glass. An absorption peak locates at 976 nm. It is a typical absorption band of Yb^{3+} ions. The emission spectrum of the Yb-doped DC fiber pumped by 976-nm diode laser with a power of 0.55 W is shown in Fig. 3(b). Part of the emission light near 980 nm is blocked out by the filter. Even though, the emission band is still wider than 120 nm. It provides choices for various wavelength fiber laser generation.

Figure 4 displays the laser output power as a function of pumped laser. The laser spectrum and its near field distribution are shown inset. The fiber laser starts at a pump power of 1.6 W. The center wavelength of the fiber laser locates at 1 038 nm. After that, the output power increases with the pump power almost linearly and reaches a maximum value of 1.14 W at a pump power of 5.46 W. The optical slope efficiency against pump power is 34%. The high attenuation violently reduces the laser emission efficiency and the attainable output power. On the other hand, laser efficiency is also related to the fiber structure. The present fiber structured may limit the efficiency.

The near field intensity distribution of the mode displays two different profiles in the X and Y directions, corresponding to beam quality factors $M_x^2 = 1.5$ and $M_y^2 = 2.4$ respectively. These results are consisted to the NA of the core. In the Y direction it is not a typical Gaussian profile. This is related to the non-homogeneity

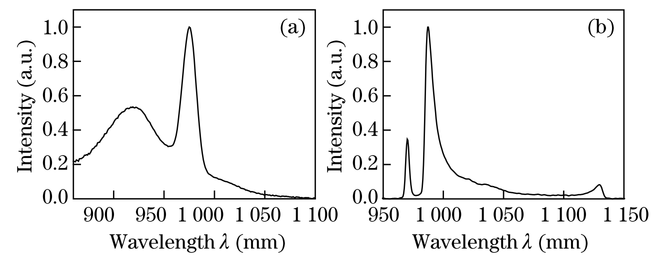

Fig. 3. (a) Absorption spectrum from the Yb-doped silica glass chip. (b) Emission spectrum from the Yb-doped DC fiber.

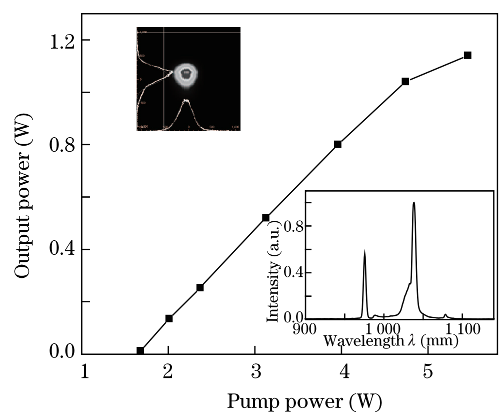

Fig. 4. Output power as a function of pumped power. Inset are mode field distribution (up left) and laser emission spectrum (down right).

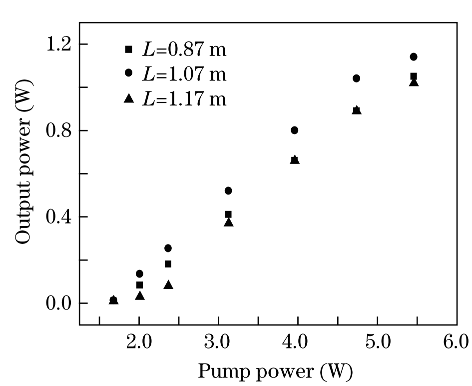

Fig. 5. Output power as a function of pumped power at different fiber lengths.

of Yb^{3+} ions dispersion and the refractive index fluctuation across the core.

It is also noticed that there is aberrancy at the available maximum pumped power. In order to find out the reason, the laser powers from different lengths of fiber are plotted either (Fig. 5). The largest power is obtained at a fiber length of 1.07 m. When the fiber length is shorter than this number the laser power increases linearly as the pumped power increases. When the fiber is longer than the optimal length, the aberrance phenomenon happens again. This is caused by movement of the balance between net gain and the whole loss of the cavity. When the loss is larger than the gain the light conversion efficiency and the output power would be reduced.

In the latest work, the background attenuation from the non-homogeneity of Yb^{3+} ions is reduced. A large core photonic crystal fiber has been fabricated and a much higher output power is obtained. These results will be published elsewhere.

In conclusion, a Yb-doped DC silica glass fiber laser with a core made by sol-gel method is constructed. More than 1-W output power at 1 038 nm with a slope efficiency of 34% is obtained. To our knowledge, this is the highest power obtained in a DC Yb-doped silica sol-gel fiber. The refractive index fluctuation across the core is below 5×10^{-4} at a doping level of Yb 0.15 mol %, Al_2O_3 4.0 mol%, and P_2O_5 2.0 mol%.

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