100 W - pump limited Yb^{3+} doped silica fiber laser

Marcin Franczyk,*[1] Dariusz Pysz,[1] and Ryszard Buczyński[1,2]

[1]*Institute of Microelectronics and Photonics, Łukasiewicz Research Network, Al. Lotnikow 32/46, 02-668 Warsaw, Poland,*
[2]*Faculty of Physics, Warsaw University, Pasteura 5, 02-093 Warsaw, Poland*

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Abstract—We present the laser system based on developed in-house Yb^{3+} doped silica fiber with a large core with a diameter of 21 µm, dedicated to high-power applications. In the laser system, we achieved a maximum output power of 107 W, limited by the available pump diode in 25 m long fiber with a high slope efficiency of 65 %. The laser was generated at a wavelength of 1080 nm and with a beam quality of $M_x^2 = 1.43$ and $M_y^2 = 1.44$.

High-power laser systems based on Yb^{3+} doped fibers are critical in the current industry, especially in the automotive, aerospace, or construction, where they are used for cutting or welding metal elements, or in defense, where they are currently tested for neutralizing small aircraft, e.g., drones [1]. Yb^{3+}-doped fiber laser systems are in demand due to the possibility of obtaining high radiation powers of up to 6 kW in single-mode output with excellent beam quality $M^2 < 1.3$ [2] or up to 10 kW with beam quality of $M^2 < 2$ [3]. Moreover, due to low Stoke's shift of Yb3+ ions, the high efficiency makes fiber laser devices cost-effective radiation sources.

High-power laser performance with a good-quality beam requires expanding the fundamental mode field guided in the fiber core to increase the power threshold of nonlinear effects like stimulated Raman scattering (SRS) or stimulated Brillouin scattering (SBS) [4]. On the other hand, the upper limit of the fiber core size is affected by the transversal mode instability (TMI) [5] or the thermal lens effect [4]. These effects determine the fiber core size, typically 20-25 µm at the highest powers of Yb^{3+} fiber laser systems [2][6].

In this article, we present the Yb^{3+}-doped fiber laser system that we developed in-house. We improved the system presented previously [7] and obtained a maximum output power of 107 W with a high slope efficiency exceeding 65 % and beam quality of $M^2 = 1.44$. The maximum power was limited by the available power of the pump diode.

The laser fiber was developed similarly to the method presented in a previous publication [7]. To fabricate the fiber, we used a ytterbium-doped aluminosilicate rod developed with MCVD technology (Optacore, now Lumentum Inc.). The MCVD rod, processed with an F300 Heraeus silica tube, had an outer diameter of 15 mm and a ytterbium-doped area inside of 5 mm in diameter, forming a step-index-like profile. The difference in refractive indices of the doped core and undoped silica cladding was 1.4×10^{-3} at 633 nm, according to information obtained from the rod supplier. The average Yb_2O_3 dopant concentration in the MCVD rod was 0.069 mol.%, resulting in a maximum absorption of 316 dB/m at 975 nm.

At the beginning of the fiber fabrication process, the MCVD rod was drawn down into a rod with a diameter of 2.3 mm, which was placed in F300 silica tubes, similar to the rod-in-tube technique. The silica tubes were carefully selected to obtain the final large core fiber with the designed dimensions, i.e., a 20 µm core diameter and 400 µm cladding. Additionally, we implemented the D-shape inner cladding to increase the pump absorption in the final fiber [8]. We ground and polished the outer tube on one side to obtain the D-shape fiber structure. The entire bundle of the prepared preform was then drawn on a fiber drawing tower into the final fiber, shown in Fig. 1.

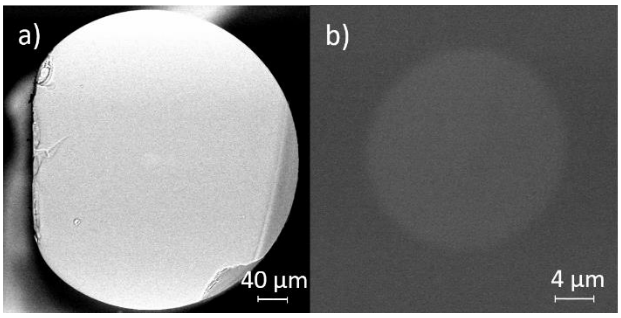

Fig. 1. SEM images of a cross-section of the fabricated Yb3+-doped fiber with a D-shape cladding with a maximum diameter of 408 µm and 362 µm on the cut side (a), and 21 µm fiber core of (bright area) (b). The shown fiber was stripped of its polymer coating.

The fabricated fiber had a core with a diameter of 21 µm and D-shape cladding with a maximum dimension of 408 µm and 362 µm on the cut side. We used a low-index polymer coating (OF-138, MyPolymers) to create a double-clad fiber structure commonly used in high-power laser and amplifier applications [8]. According to information obtained from the vendor, the polymer in its cured state had a refractive index of 1.379 at 950 nm. Based

* E-mail: marcin.franczyk@imif.lukasiewicz.gov.pl

on this, we assumed that the numerical aperture of the pump waveguide in the double-clad structure should be NA_{clad} = 0.45 at 976 nm, considering that cured polymer has a similar refractive index at 950 nm and 976 nm. The total diameter of the fabricated fiber, including the polymer, was 510 µm.

Based on the refractive index profile parameters of the MCVD rod, the calculated numerical aperture of the fiber core waveguide was NA_{core} = 0.063, and the normalized frequency was V = 3.93 at 1070 nm, indicating a few-mode waveguide. However, the obtained numerical aperture and normalized frequency values are very similar to those used in large mode fibers in standard commercial designs, in which the numerical apertures of fibers with a 20 µm core are in the range of 0.06–0.065 [9,10]. The single-mode performance in large-mode fiber, a few-mode waveguide, is often induced by bending the fiber with a suitable radius. Bending the fiber suppresses higher-order modes due to their increased loss. In contrast, the fundamental mode loss is low enough to achieve high laser efficiency with high beam quality suitable for high-power applications [2,6].

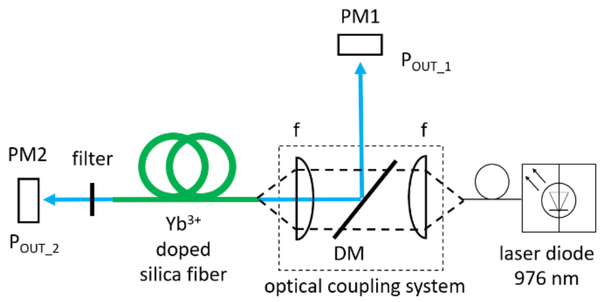

Fig. 2. The laboratory laser setup used for active fiber testing: DM – dichroic mirror, f – aspheric lenses with equal focus length, PM1 and PM2 – power meters, filter – long pass filter.

The fabricated fiber was tested in a laboratory laser setup shown in Fig. 2. Compared to the previous system presented in [7], the setup was modified to test active fibers pumped at high power. We modified the optical coupling system by replacing the dichroic mirror designed to operate at an angle of a maximum of 20 degrees to the incident laser beam with a dichroic mirror designed to operate at an angle of 45 degrees. This change allowed the use of a dichroic mirror between aspheric lenses *f* and positioning it in the path of the pump beam at the largest beam diameter, where the pump radiation intensity is the lowest in the entire coupling system, thus limiting the risk of damage to the specialized coating of the dichroic mirror. We decided not to use a high-reflective (HR) butt-coupled mirror at the end of the tested fiber because the mirror would be damaged at high power due to too high intensity of the laser beam propagating in the fiber core. Instead, the laser cavity was created by Fresnel reflections of 3.4% from the surfaces of the fiber, with both ends cleaved perpendicularly. The fiber was pumped with a multimode laser diode with emission at a wavelength of 976 nm (*FWHM* = 1 nm), a maximum output power of 180 W, and a top-hat profile of the output beam. The diode was pigtailed with a 200 µm core fiber with a numerical aperture of *NA* = 0.22. The diode was part of an integrated pumping system consisting of a diode laser driver and a built-in diode temperature controller (BWT DS3-51522-K976AN1RN-180.0W). To couple efficiently the pumping beam into the internal cladding of the tested fiber, we built an optical coupling system composed of a pair of identical aspherical lenses *f* with anti-reflective coating (AL2520-B, Thorlabs), each with a focus length of 20 mm. The beam waist of the pumping system was 208–211 nm, measured with a mid-infrared beam profiler (Nanoscan2 Pyro/9/5um, Ophir) at a beam intensity of 13.5%. To confirm the stability of the beam waist diameter as a function of emitted power, we measured the beam waist diameter at different diode output powers at 0.47 W, 1.0 W, 4.8 W, and a maximum of 7.5 W limited by the operating range of the pyroelectric detector. To separate the laser output from the pump radiation, we used a dichroic mirror DM (DMSP1000L) with a reflectance of R = 98.7% at an emission wavelength of 1070 nm and transmission T = 94.3% at 976 nm. In the laser setup presented, we expected the coupling loss between the coupling system and the tested fiber to be limited to only 3.4% of the Fresnel reflection loss from the fiber end surface because the beam waist diameter and numerical aperture of the coupling system were adjusted to the diameter and numerical aperture of pump waveguide in the tested fiber.

We measured the generated power with power meters PM1 and PM2 with thermal sensor heads (S322C and S314C, Thorlabs, respectively). At the P_{out2} laser output, we used a long-pass filter (FELH1000, Thorlabs) with high transmission (T = 97.6% at 1080 nm) and low transmission (T<0.1% at 976 nm) to separate generation power from the pump radiation not absorbed by the tested fiber. The generation spectrum was recorded with a Fourier Transform optical spectrum analyzer (OSA205C, Thorlabs) placed at the PM2 site.

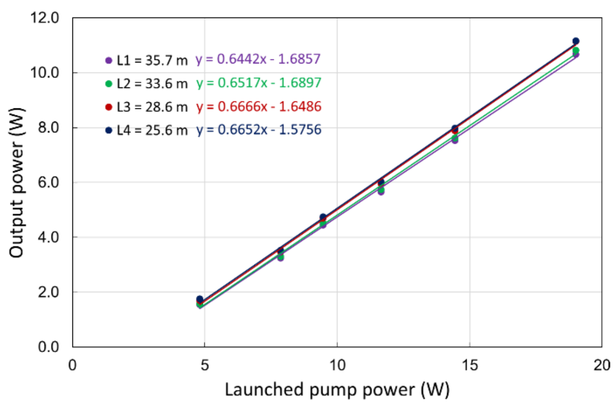

Fig. 3. The laser output power, as a sum of powers from both fiber ends (P_{out1} + P_{out2}), versus launched pump power for several fiber lengths L1, L2, L3, and L4 tested in the laser setup. The highest efficiency of 66.7% was obtained for a fiber with a length of L3 = 28.6 m.

Several fabricated fibers, ranging from 25.6 m to 35.7 m in length, were tested in the laser setup described in the previous paragraph. The results of fiber laser operation are shown in Fig. 3. The highest slope efficiency of 66.7% was obtained for a 28.6 m long fiber operating with a power of a few Watts. A slightly lower efficiency of 66.5% was recorded for a 25.6 m long fiber, which we used for tests at up to the maximum pump power available in our new laser setup. The maximum power of 107 W was obtained as the sum of P_{out1} and P_{out2} power from both ends of the tested fiber (Fig. 4). The generation spectrum at wavelength of about 1080 nm with an FWHM = 9 nm was registered at the PM2 site at an output power P_{out2} = 2.38 W (Fig. 5). The M^2 parameter was determined to be M_x^2 = 1.43 and M_y^2 = 1.44 using the standard method in accordance with the ISO 11146 norm [11]. The laser generated a beam of good quality but with some higher-order mode content that could not be entirely suppressed by bending the fiber. During the measurements, the fiber was placed on a metal board with a bending diameter of 31 cm.

In this article, we presented the laser system we developed in-house, adapted to high power requirements. The optical elements used in the laser setup, including lenses, dichroic mirror, and filter, should be resistant to the operation of the pump diode system with a power of up to 1 kW. However, endcaps should probably be applied to the ends of the tested fiber to increase the fiber damage threshold [7]. So far, in the tests presented in this article, we used a pump diode with a maximum power of approximately 180 W. We achieved over 65 % laser slope efficiency, which resulted in a maximum laser power of 107 W. Further research is planned to increase the pump power available soon.

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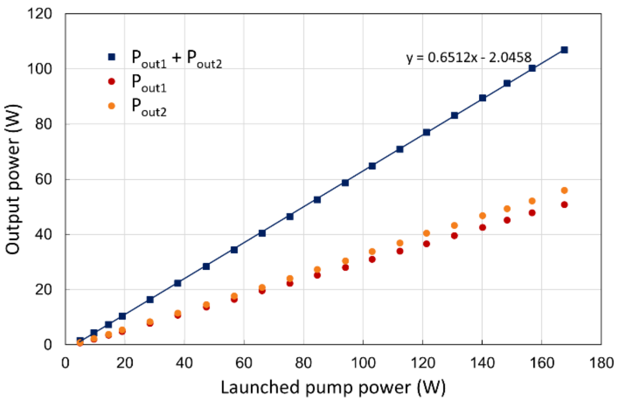

Fig. 4. The laser output power versus launched pump power for 25.6 m long fiber for up to the maximum pump power available in the laser setup. The maximum output power was 107 W, as the sum of the output powers obtained from both fiber ends P_{out1} and P_{out2}

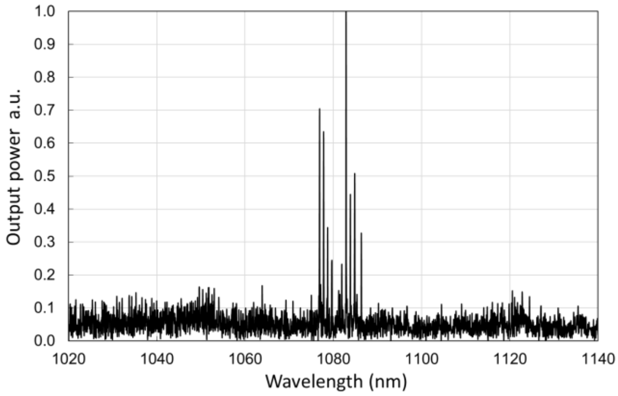

Fig. 5. The spectrum of the laser generation for 25.6 m long fiber at about 1080 nm with the FWHM = 9 nm. The spectrum was registered at P_{out2} power of 2.38 W.

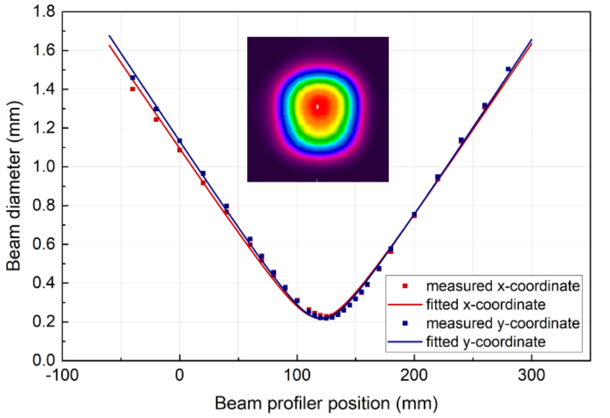

Fig. 6. The beam quality characterization; M_x^2 = 1.43 and M_y^2 = 1.44 were obtained at P_{out2} power of 2.38 W, registered beam profile in the waist (inset).

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