Yb^{3+} doped single-mode silica fibre laser system for high peak power applications

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Abstract—We present ytterbium doped silica single-mode fibre components for high power and high energy laser applications. We developed in-house a fibre laser with a high efficiency of 65% according to the launched power, a threshold of 1.16 W and a fibre length of 20m. We also elaborated a fibre with 20 μm in core diameter suitable for amplifying the beam generated in an oscillator. We implemented in-house made endcaps to prove the utility of the fibre towards high peak power applications.

Ytterbium-doped silica fibres are the main component of high power or energy fibre lasers. Currently, ytterbium doped silica fibre lasers are of increasing importance in industry, especially automotive and other means of transport, as well as in construction. Mainly, high power lasers are used for cutting or welding metal plates (e.g. cutting any 2D shapes) due to their much higher energetic efficiency compared to other technologies [1]. Their high energetic efficiency is due to the simplicity of energy levels and low quantum defect of ytterbium ions. In the case of further power scaling the pumping in–band is also frequently applied [2−3].

Power scalability and high beam quality of fibre lasers are related with an increase in the fundamental mode field area of a fibre waveguide, which has a significant influence on reducing the existing limitations like nonlinear effects [e.g., Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBS)] or the fibre damage threshold [2, 4].

The silica damage threshold is to be considered as a surface damage threshold (occurring on the boundary of glass and air), and a bulk damage threshold (inside the glass), as those two parameters differ significantly.

The surface damage threshold of a silica material was determined by the following formula for pulsed radiation at a wavelength of 1064 nm [5]:

$$D = 22 \cdot t_p^{0.4}\ [\mathrm{J/cm^2}], \tag{1}$$

where t_p is the pulse length expressed in nanoseconds.

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According to the above formula, the damage threshold energy for a 10 ns pulse duration is 55.3 J/cm^2. Therefore, the smallest mode area diameter for a pulse energy of 1 mJ and duration of 10 ns is 48 μm. In order to obtain an optical fibre capable of generating a specific energy value, it is necessary to design and manufacture a fibre with a sufficiently large core.

The material strength inside the silica (bulk damage threshold) for a pulse regime is much higher. Smith and Do [6] measured and determined the silica bulk damage threshold of 4.75 $kW/\mu m^2$ (i.e., 3.8 kJ/cm^2) for 8 ns pulses and the wavelength of 1064 nm. Therefore, special attention in the project should be paid to the surface damage threshold, which can be also increased by using endcaps at the ends of the fibre. In this paper we present Yb^{3+} doped silica fibres with high beam quality for high power and high energy laser applications. We developed in-house a single-mode fibre laser with a high slope efficiency of 65% according to the launched power, a threshold of 1.16 W and a fibre length of 20 m. We also elaborated a fibre with 20 μm in core diameter suitable for amplifying the beam generated in an oscillator. We implemented in-house made endcaps to prove the utility of the fibre for high peak power applications.

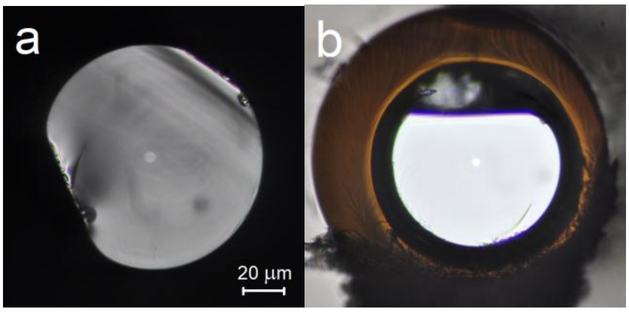

Fig. 1. The photo of the cross-section of the developed D-shape Yb^{3+} doped silica fibre with the 10.5 μm in core diameter and 200 μm in cladding diameter (a), the fibre with low index outer cladding (b).

For the development of a single-mode fibre we used an ytterbium doped aluminosilicate MCVD rod acquired from Optacore (presently Lumentum Inc.). The outer diameter of the MCVD rod, processed with an F300 Heraeus silica tube, was 15 mm and the inner ytterbium doped area diameter was 5 mm, with step-index like profile. The doped rod was drawn in a fibre drawing tower down into a 2.3 mm diameter rod, which was implemented inside the silica tubes creating the cladding in the final fibre. The outside silica tubes were also F300 Heraeus to achieve a homogeneous refractive index of the fibre cladding. The proportions of the inner rod and outer tubes were properly selected to achieve the final fibre with 10.5 µm in core diameter and a 200 µm cladding. The outside tube was grounded and polished at one side for the D-shape fibre design, increasing the pump absorption in the final fibre [7]. Then the preform was drawn down to a final fibre with designed dimensions (Fig.1).

Due to the fact that the difference in the refractive index of the doped core and the undoped silica within the Optacore rod was 14×10^{-4}, theoretically, the core diameter of an intrinsically single-mode step-index fibre for a cut-off wavelength equal to 1.05 µm (V = 2.405) is below 12.6 µm. We assumed that generation from Yb doped silica fibre would occur above the 1.05 µm wavelength, as usually reported [7−8]. The core glass was doped with Yb_2O_3 at the average level of 0.069 mol%, which gave the maximum absorption of 316 dB/m at 975 nm. The estimated absorption of the fibre was about 0.62 dB/m with consideration of spectrum of pump diode.

The D-shape fiber was coated with a low index polymer to achieve a double-clad structure, commonly used in fibres for laser applications [8]. The absolute value of the refractive index of polymer at 975 nm was 1.41, resulting in a numerical aperture of pump waveguide of NA = 0.34. The final fibre diameter with the coating was 370 µm.

The background loss of the developed fibre was measured beyond the Yb absorbing band at a wavelength of 1310 nm resulting in 15 dB/km promising highly efficient laser performance.

The developed fibre was examined in a laboratory laser setup (Fig. 2). The laser cavity was formed by a Fresnel reflection of 3.4% from the surface of the one end of the fibre, and by a butt coupled mirror, with high reflectivity (HR = 99%) for pump and generation wavelength. For pumping we used a multimode laser diode at 973.5 nm pigtailed with a 100 µm core fibre with a numerical aperture of NA= 0.22 and a top-hat profile of the output beam. The spectrum of the laser diode was about 4 nm, as usually met in high power pumping diodes. The laser diode was driven using a standard Laser Diode Driver with a built-in diode temperature controller (LIMO LDD60-5). We used an optical system formed by a pair of identical aspherical lenses (f = 20 mm) to couple efficiently the pump beam into the internal cladding of the tested fibre. We used a dichroic mirror (98% reflectance for the wavelengths above 1020 nm and 97% transmission for the wavelengths below 985 nm) to separate the laser output from the pump radiation. The dichroic mirror was set at an angle of 20 degrees with respect to the laser output incident beam. We assumed that the coupling loss between pump delivery system and the internal cladding of the examined fibre, was only 3.4%, related to Fresnel reflection losses.

We tested the fibre in a laser setup. We have obtained a single mode performance and a slope efficiency of 65% was obtained for a fiber length of 20 m. The threshold of the launched power was 1.16 W. The maximum power of single-mode laser output was 7.8 W, limited by the available pump power. The fibre length was chosen according to estimated pump absorption.

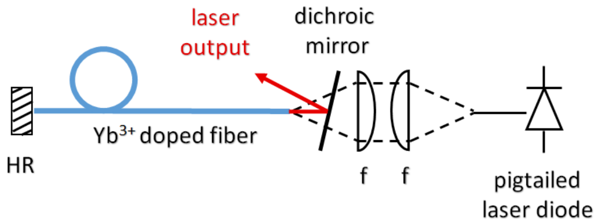

Fig. 2. The laboratory laser setup with a dichroic mirror, aspheric lenses with equal focus length f, laser diode at 973.5nm, and a highly reflective mirror (HR).

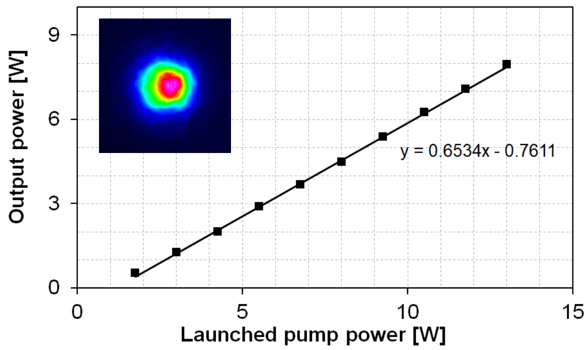

Fig. 3. The output power versus launched power for the laser with a tested Yb^{3+} doped fibre length of 20 m. The squares indicate the measurement points with a linear approximation. Registered beam profile (inset).

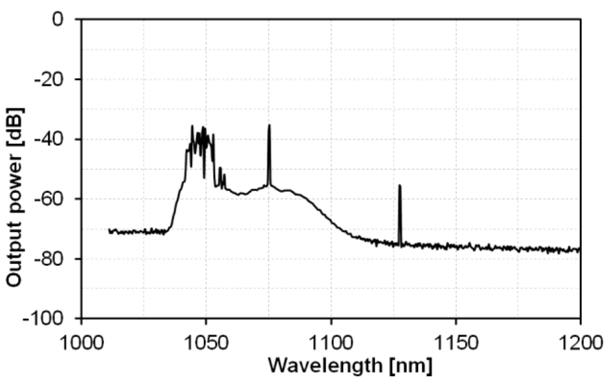

Fig. 4. The spectrum of the fibre laser at a maximum output power of 7.8 W for a 20 m length fiber.

The laser spectrum (Fig. 4) shows laser spiking in a wide range of wavelengths appropriate for Yb ions emission. The most intensive lasing was detected at 1050 nm and 1080 nm in transversally single-mode performance. This type of relatively broad spectrum of fibre laser generation is typical when non-selective refractive mirrors are used in the fibre resonator. The use of frequency selective elements in the laser setup, e.g. Bragg grating, would result in narrowing the oscillator spectrum.

The demonstrated fibre laser was intended for use in the construction of a 'seed' type laser (laser beam generator). High power or energy devices usually require multistage setups, consisting of a seed laser determining good beam quality, and one or two amplifier stages increasing the output power [7−8]. The amplifying stages use a larger core diameter to overcome peak power limitations, as discussed before. However, to maintain single mode performance, increasing the core size requires simultaneous lowering of a refractive index difference between the core and the cladding, which meets the technological limits and increases the bending loss of the fibre [9]. We developed the fibre with 20.9 μm in core diameter suitable for amplifying the beam from a seed fibre oscillator. This fibre had a V-parameter of 3.99 at 1050 nm, theoretically supporting few transversal modes, but coiling the fibre with an appropriate radius would attenuate a higher order mode through bending losses, and only the fundamental mode could be guided and amplified [9]. The fibre was prepared in a double-clad design with an internal cladding of 407 μm suitable for coupling a high power pump. The outer cladding was made with a low index polymer creating the waveguide for the pump with NA=0.45.

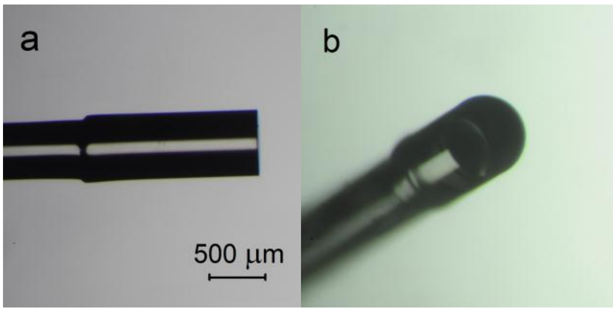

Fig. 5. The photo of the endcap of 500 μm in diameter and 1.4mm in length spliced to the fibre with a 20.9 μm core and 400 μm.

We elaborated in–house the endcaps, which are pieces of coreless silica rods allowing to increase the laser beam area and lowering the beam intensity at the boundary of glass and air, preventing the damage threshold at a demanded power range. Additionally, as the endcaps are relatively short, they do not distort the beam quality of the light leaving the fibre waveguide [10]. The designed endcaps of a diameter of 500 μm were about 1.4 mm in length, being attached with a laboratory splicer (3SAE LDS 2.5) to the end of the fibre (Fig. 5). The endcaps were also polished. Theoretically, thanks to the endcaps the beam diameter could be increased up to 124 μm, which was far enough for allowing the output of 1mJ in 10 nanoseconds regime without silica surface damage. The damage resistance was proved in the experiment in which the tested fibre was illuminated with a high energy laser (Litron Nano S 130-10) with 7 ns pulses. The measured maximum output energy from the 20.9 μm fibre core with endcaps was 1.6 mJ, which is several times higher than a maximum energy of 80μJ achieved from the same fibre but without endcaps.

In this paper we presented silica single-mode fibre components for high power and high energy laser applications. We developed in-house the fibre laser with a high efficiency of 65% according to the launched power, a threshold of 1.16 W and a fibre length of 20 m. We also elaborated the fibre with 20 μm in core diameter suitable for amplifying the beam generated in a seed oscillator. We implemented made in-house endcaps to prove the utility of the fibres towards high peak power applications. Ytterbium fibre lasers are most suitable lasers due to their advantages like power scalability, high efficiency, very good beam quality, high reliability and relative simplicity of laser design.

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