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A new material for high power laser fibers

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ABSTRACT

We have developed a new technique to produce a Yb-doped fused silica bulk glass which is very well suited for fiber laser applications. The starting point is a liquid suspension of SiO_2 particles which is doped by a solution of rare earth ions. After dehydration, purification and vitrification we achieve a bubble-free homogeneous Yb-doped fused bulk silica, which is further processed by the plasma outside deposition (POD) technique into preforms for active laser fibers with a large active fiber core. The laser function of our Yb-doped silica was successfully proved in a side-pumped fiber laser setup. We present the results of the laser experiments.

Keywords: Rare earth doped silica, Yb-doping, active large core fibers, side-pumped fiber laser

1. INTRODUCTION

Within the last few years, a rapid development of high power fiber lasers based on rare earth doped active laser fibers has proceeded. In particular, the fiber design has been optimized towards high power laser emission in the range of some kW and a high efficiency in combination with an enhanced beam quality [1, 2, 3, 4, 5]. This excellent beam quality, which is almost independent of the output power, is one of the biggest advantages of these high power fiber lasers. Hence, the fiber lasers are already wide-spread for many industrial applications such as laser cutting and welding [5, 6].

Most commercially available rare earth doped active laser fibers are produced by a combination of MCVD (modified chemical vapor deposition) and subsequent solution doping technique [7, 8]. In the MCVD process, a thin porous fused silica soot layer is deposited onto the inner surface of a substrate tube. The porous soot layer is soaked with a solution of rare earth ions (solution doping) and then vitrified in a furnace. The solution doping step is necessary, because neither gaseous rare earth compounds nor high vapor pressure liquids exists as precursor states. Hence, a direct growth and sintering of rare earth doped silica is not easily possible. For good homogeneity of the doped soot film, the maximum film thickness, which can be grown in one MCVD and solution doping cycle, is limited. The MCVD and solution doping process can be repeated in several cycles to get thicker rare earth doped layers, but the defect rate rises significantly, the homogeneity deteriorates with every process cycle, and the additional interfaces between every doped layer can be a problem. After the deposition of the rare earth doped layer(s), the tube has to be collapsed to produce an active fiber core rod, which is then used to manufacture a laser active fiber. The optical properties of such an MCVD-fiber with a single doped layer are excellent. Hence, the MCVD process in combination with solution doping is very well suited to produce active fiber preforms for single mode fibers with a small active core diameter; however, this process is not capable of producing preforms and consequently fibers with very large diameter active cores. Besides the solution doping process, other active fiber production processes are known, such as the direct nano-particle deposition (DND) process, which was developed by Liekki [9]. In the DND process, an aerosol of the doping solution is fed together with $SiCl_4$ into a soot burner to produce doped SiO_2-nanoparticles which can be deposited on a substrate and sintered.

To our knowledge, no rare earth doped bulk silica is commercially available at the moment. We report here on our development of a novel technology to produce a rare earth doped fused bulk silica in particular Yb-doped material. We

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present the results of our fiber preform and active laser fiber development as well as the laser results in a side-pumped fiber laser setup.

2. FABRICATION OF YB-DOPED FUSED BULK SILICA

We have developed a new process to fabricate rare earth doped bulk silica. In contrast to the above described doping methods, our new technique for the production of rare earth doped glass is not a deposition method like MCVD or DND. We start with synthetic porous SiO_2 nano-particles, which we dissolve in a liquid to form a thixotropic suspension. This suspension is doped by the addition of a solution of rare earth ions and other co-dopants (e.g., Yb, Er, Nd, Al ...). Thereafter the suspension is moved, dehydrated and granulated to get a Yb-doped granulate. After several dehydration and purification steps, the granulate was sintered in a furnace to achieve a bubble-free homogeneous Yb-doped bulk silica.

The challenge was to optimize the production parameters and production steps to enhance the quality of the doped fused silica to fulfill the high material demands for fiber laser applications. Hence, one of the major objectives in the development of the Yb-doped bulk silica was to enhance the material homogeneity to keep the tight geometrical and optical tolerances which are very important for fiber laser applications. It is well known that the higher the Yb-concentration in the silica, the lower the viscosity and the fiber drawing temperature, respectively. A non-homogeneity of the doping level in the dimension of the doped granulate particles can cause strong variations in the fiber diameter by viscosity fluctuations in the material when drawing a fiber.

Furthermore, the material non-homogeneities affect a significant light scattering in the fiber, which leads to an increase of the background attenuation. A large background attenuation caused by stray light makes the fiber laser inefficient and raises the laser-threshold drastically. We achieved an exceptional material homogeneity by optimizing the doping process. Thus, we could increase the homogeneity of the Yb-doping level of different granulate grains. Thereafter, the previously observed diameter fluctuations vanished when drawing a fiber. The better homogeneity was associated with a significant drop of the background attenuation of an ultra large core active laser fiber at 1200 nm to a value of 0.02 dB/m (see below). This low background attenuation makes the material interesting for fiber laser applications.

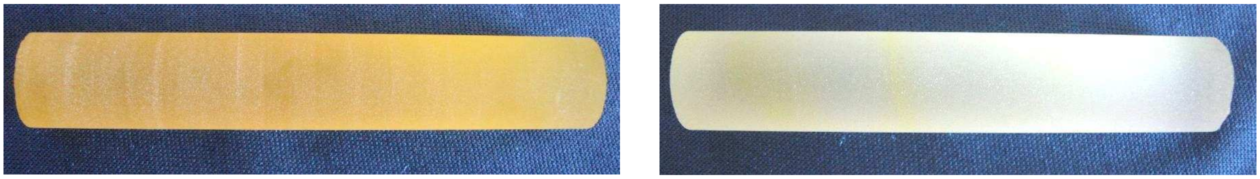

Fig. 1. Left: Non-optimized Yb-doped silica rod. The strong yellow color is caused by Yb^{2+} which leads to an additional absorption band in the blue wavelength range. Right: Optimized Yb-doped silica rod. Only a slight yellowish discoloration is visible. Since the surfaces of both samples are ground and not polished, the sample seems to be opaque.

Furthermore, we were able to minimize the number of bubbles, the defect density, and the crystallization behavior by optimizing the vitrification step and the sintering parameters. Now we have achieved a bubble-free and defect-free Yb-doped bulk silica. Yb is typically incorporated in the glass matrix as Yb^{3+}. Yb^{3+} is responsible for the laser activity of the doped silica. Depending on the sintering parameters, some of the Yb^{3+} ions can be reduced to the chemical valence Yb^{2+}. But, Yb^{2+} reduces the fluorescent lifetime and the laser efficiency [10] and causes additional absorption bands in the blue wavelength range. These absorption bands lead to a yellowish color impression of the non-optimized doped silica samples (see Fig. 1). We have seen that this yellowish discoloration is intensified with increasing Yb-concentration in the glass matrix. It was possible to reduce the yellowish discoloration significantly by optimizing the sintering step und the sintering parameters. In Fig. 1, two different material samples are shown. In the left photo, one can see a non-optimized Yb-doped rod, which possesses the strong yellowish discoloration described above. In the right photo, a typical optimized Yb-doped rod is shown with only a slight yellowish discoloration visible. The doping level of both samples is in the range of 0.250 mol % Yb_2O_3. Both samples are adequately co-doped with aluminum to reduce the clustering effects, which are well known in the literature [11]. The surface of both samples is ground and not polished. Hence, the samples seem to be opaque, but both samples are transparently vitrified.

The newly developed fused bulk silica has the following key parameters: Very high Yb-doping levels are adjustable. Up to now, bulk silica with a doping level of 0.25 mol % Yb_2O_3 has been successfully produced; but even higher doping levels should be possible. The possible maximum rod geometry is currently in the range of 15 mm diameter and 150 mm length, but bigger dimensions should be possible in the future. Our Yb-doped bulk silica features a very good material homogeneity with a low graininess, a low defect density (bubbles, inclusions, and crystallizations), and a reduced yellowish discoloration as well as a high purity, which is chemically controlled in every production step. The material properties of our Yb-doped bulk silica are very well suited for laser fiber production. The developed material enables new active laser fibers designs such as ultra large core fibers or special micro-structured fiber designs.

3. FIBER PREFORM PRODUCTION FOR SIDE-PUMPED FIBER LASERS

The objective was to develop a fiber preform with a large active core design for side-pumped fiber laser applications. Because of the special pumping concept, a multiple cladding structure was not necessary; hence no pump light has to be guided in a pump cladding as it is in end-pumped fiber laser setups.

Therefore, a preform design with a large active core and a single cladding with a reduced refractive index was preferred. The fiber preforms were produced using the Plasma Outside Deposition (POD) process [12]. This process facilitates the deposition of a highly fluorine doped cladding with a depressed refractive index down to -26×10^{-3} below fused silica. Plasma torches prepare the reactants O_2, a silicon compound and a fluorine containing gas to deposit highly fluorine doped fused silica layers onto the Yb-doped fused silica substrate rod. The fluorine doped cladding is needed to enable the light guiding behavior of the fiber and to set the numerical aperture (NA) of the straight fiber. It is important to choose an adequate cladding thickness to reduce the guiding losses, which are caused by the evanescent light penetrating the cladding. As a rule of thumb, the cladding thickness should be at least ten times the wavelength of the guided light to minimize these attenuation effects. A schematic sketch and a photo of the POD process are shown in Fig. 2. In the photo, one can easily see the substrate core rod in the middle of the picture and the plasma flame, which prepares the reaction compounds and deposits the fluorine doped fused silica layer to produce the fiber preform.

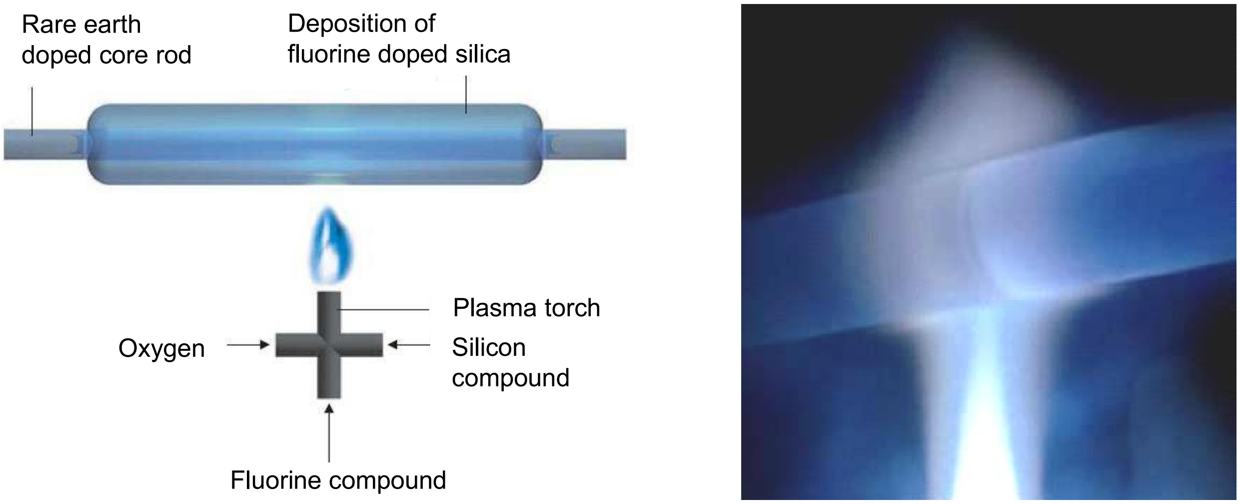

Fig. 2. Left: Schematic sketch of the laser fiber preform production process. The fluorine doped cladding glass, which is produced by the Plasma Outside Deposition (POD) technique, is deposited onto the rare earth doped core rod. Right: Photo of the POD process, showing the substrate core rod and the plasma flame which prepares the reactants.

We have demonstrated that it is possible to deposit a fluorine doped cladding onto a highly Yb-doped core rod with the POD process. Hence, the POD process is very well suited to produce preforms with a very large active core for fiber laser applications.

Before and after the preform production with our POD process, we have measured the refractive index profile of the Yb-doped core rod or the preform. Fig. 3 shows a typical refractive index profile of the fiber preform. The core of the preform features a fine refractive index homogeneity. The refractive index characteristic of core is not influenced by the POD preform production process. The increase of the refractive index fluctuation in the centre of the preform is a numerical artifact which is caused by the profile calculation algorithm. Furthermore, the rounding of the profile at the interface between core and cladding is caused by the circular geometry of the core rod and is therefore a numerical artifact as well. The real refractive index profile is step-like. Furthermore, one can see the depressed refractive index of the fluorine doped cladding. The refractive index step between core and cladding, measured in the profile in Fig. 3, corresponds to a numerical aperture (NA) of 0.25. This exceptionally high refractive index step is chosen to reduce high bending losses for the side-pumped fiber laser application, where the fiber has to be coiled. Furthermore, it is possible to calculate the cladding to core diameter ration (CCDR) from the refractive index profile (see Fig. 3). The profile corresponds to a CCDR of 1.2.

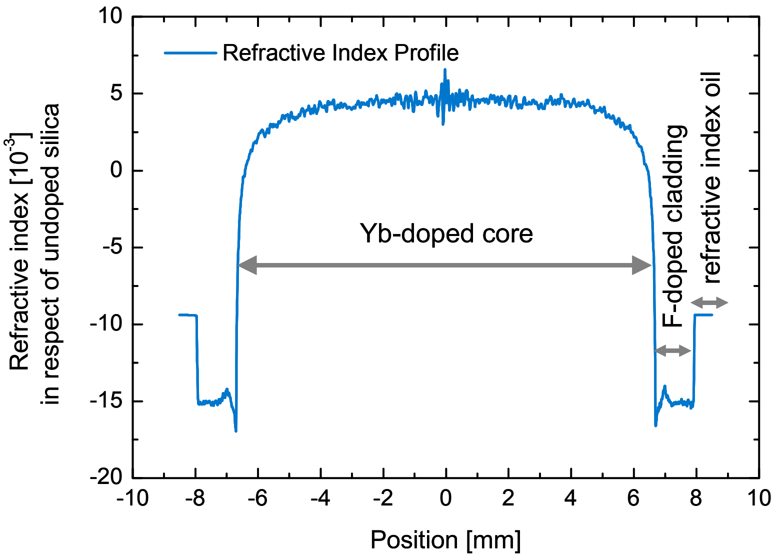

Fig. 3. Refractive index profile of a step index fiber preform. The core of the preform is doped with Yb- and Al-ions. The profile shows a very good material homogeneity. The increase of the refractive index fluctuations in the middle of the preform is a numerical artifact, which is caused by the calculation algorithm of the profile. For further details see text.

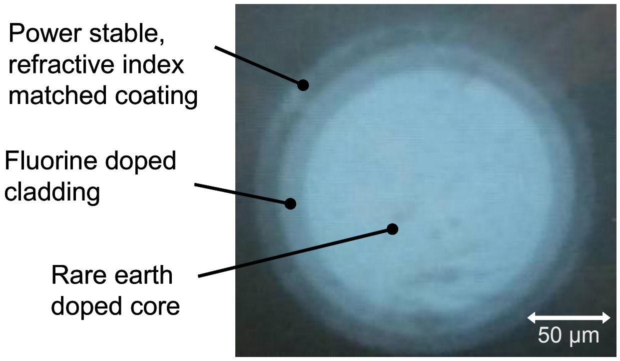

Fig. 4. Cross section of a Yb-doped ultra large core fiber for side-pumped fiber laser applications. The rare earth doped fiber core with a diameter of 150 µm is surrounded by a fluorine doped silica cladding with a depressed refractive index (respectively un-doped silica) and an outer diameter of 180 µm. The bare fiber is surrounded by a commercially available coating (outer coating diameter 205 µm), which is specially selected to fulfill the requirements of the side-pumped laser application.

The produced active preforms were drawn into fibers. After increasing the material homogeneity by optimizing the production parameters of the Yb-doped bulk silica, we were able to draw active fibers. The excellent material homogeneity is a very important material feature. As already mentioned above, a poor material homogeneity and a fluctuation of the doping level can cause problems when drawing a fiber. A bad homogeneity will cause fiber diameter variations, which prevent stable fiber drawing conditions. The cross-section of a cleaved ultra-large mode step index active fiber, which was specially developed for the side-pumped fiber laser setup, is shown in Fig. 4. The Yb-doped laser active fiber core is cladded by the above mentioned fluorine doped POD silica layer. The nominal core diameter of the fiber is 150 µm and the cladding diameter is 180 µm. The resulting cladding thickness of 15 µm is chosen to fulfill the above mentioned ten times cladding thickness rule of thumb to prevent strong additional fiber attenuation by the evanescent light field. The bare fiber is surrounded by a very thin fiber coating to protect the fiber when the fiber is bent in the side-pumped setup. The coating has a diameter of 205 µm which corresponds to a very thin coating thickness of 12.5 µm. The thin coating thickness was chosen for effective cooling of the fiber. One important objective was to select a coating with a refractive index matched to the refractive index of the cladding to reduce reflection losses. Furthermore the coating has to be transparent at the pumping wavelength in the range of 900 nm to 1000 nm and it has to withstand the high excitation pump power. We have selected a commercially available coating which preserves all of these conditions very well.

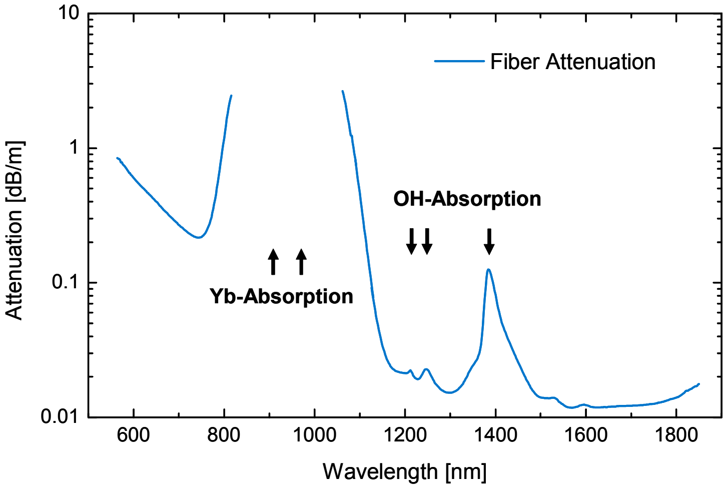

Fig. 5. Attenuation spectra of a typical multimode fiber sample (active core diameter 150 µm, cladding 180 µm). The absorption peaks of the Yb-atoms at 915 nm und 976 nm were not resolved. The background attenuation measured at 1200 nm is 0.02 dB/m. The height of the OH-Absorption peak corresponds to a very low OH-content of 2 ppm, which is typical for the Yb-doped bulk silica.

The attenuation of the active fibers is measured by the well-known cutback method. In this method, the fiber transmission (T_l) through a long fiber and the transmission through a short fiber (T_s) are measured. We have coupled the excitation light of a halogen lamp with a microscope objective into the fiber core. The numerical aperture (NA) of the microscope objective was higher then the NA of the fiber to guarantee the full mode excitation of the multimode fiber. A refractive index matching oil was used to lift cladding and coating modes. The fiber attenuation α was calculated from the two transmission spectra and the difference of the two fiber lengths (Δl) as follows:

$$\alpha = \frac{-10 \cdot \log_{10}\left(\frac{T_l}{T_s}\right)}{\Delta l} \tag{1}$$

A typical attenuation spectrum of a Yb-doped large core multimode fiber is shown in Fig. 5. The Yb_2O_3-content of the fiber was 0.25 mol %. The fiber core diameter was 150 µm and the cladding diameter was 180 µm. The numerical aperture (NA) of the fiber was 0.24. The two absorption peaks at 915 nm and 976 nm, which are typical for the Yb-absorption peaks, can be seen in the attenuation spectra, but the two peaks are not resolved because of the high doping level of the fiber. The attenuation, which we typically measure at 1200 nm, characterizes the intrinsic background material attenuation. We have reached an attenuation value of 0.02 dB/m at 1200 nm. This low background attenuation is mainly achieved by the good material homogeneity. A poor material homogeneity would result in an increase of the attenuation due to stray light effects. Furthermore, there are additional attenuation bands especially at 1246 nm and 1383 nm. These vibration modes are caused by OH, which is incorporated in the SiO_2 glass matrix during the production process of the fused bulk silica. It is possible to calculate the OH-content of the glass matrix from the height of the absorption band at 1383 nm [13]. The measured value for the attenuation at 1383 nm corresponds to a typical OH-content of 2 ppm. The OH-content can also have an influence on the fiber attenuation due to additional OH-absorption bands at the excitation wavelength range from 900 nm to 1000 nm. A high OH-content can reduce the laser efficiency, but the OH-content of 2 ppm in our material is low enough to neglect any negative effects at the excitation wavelength. In comparison to this, a typical MCVD-fiber has an OH-content of 0.5 ppm at 1383 nm.

4. SIDE-PUMPED FIBER LASER SETUP

We have chosen a side-pumped fiber laser setup as a model system to test the optical laser properties of the new Yb-doped bulk silica. In this laser setup, the excitation light is coupled through the fiber coating and cladding material and the fiber is pumped directly through the outer fiber surface. For such a side-pumped fiber laser setup, a large laser active cross section of the fiber is expedient. Because of the special pumping concept and the large active fiber core, the beam quality requirements of the pump light sources are not as high as in a single mode end pumped fiber laser setup, where the pump light has to be coupled into an active fiber with a small cross section. Hence, it is possible to use more cost efficient pump diodes with a more economical beam quality in the side-pumped setup. Furthermore, it is possible to abandon the use of expensive coupling and beam shaping optics. The availability of rare earth doped bulk silica facilitates such a suitable ultra large mode area fiber design as seen in Fig. 4.

Due to the ultra large active fiber core (150 µm), this side-pumped laser setup is a multimode system and the beam quality is not comparable to that of a single mode fiber laser. But the setup has still an acceptable very high beam quality and combines the refinement of the low beam quality of the pump diode lasers with a cost efficient pumping concept. The beam quality of the side-pumped fiber laser is also better than that of a fiber coupled direct diode laser setup with comparable manufacturing costs. The beam quality of the fiber coupled direct diode laser is approximately 40 mm × mrad whereas the quality of the side-pumped fiber laser comes up to about 17 mm × mrad. The increase in the beam quality by a factor of 2.35 leads to a 5.5 times larger radiant flux density at the workpiece and thus exceeds the limit of $1 \cdot 10^6$ W/cm² which is necessary for fine cutting and deep welding applications.

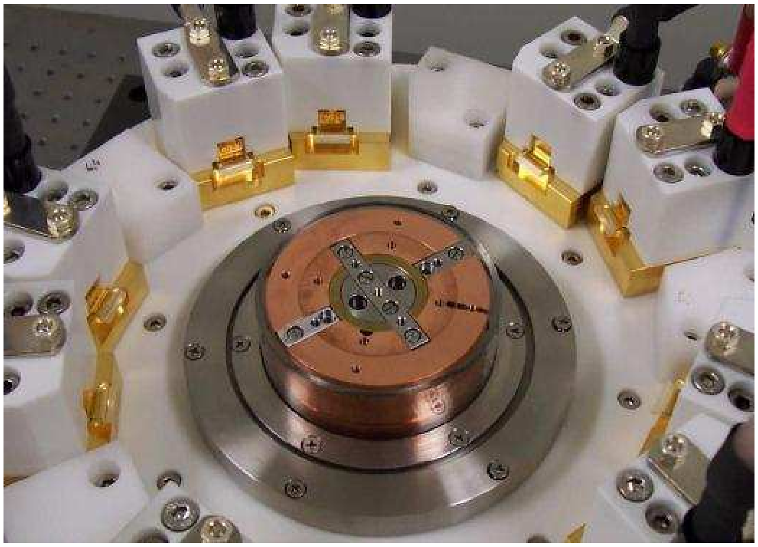

Fig. 6. Photo of the developed side-pumped fiber laser setup. The laser active fiber is coiled inside a copper disk (see center of the figure). The copper disk is used as a heat sink. The excitation light of several pump diode lasers, which are arranged circularly around the copper disk, is coupled though a window into the disk and enters the fiber through the side surface of the fiber.

A photograph of the developed side-pumped fiber laser setup is shown in Fig. 6. The laser active fiber, which is not seen in the figure, is spooled inside a copper disk. The disk is needed to manually stabilize the fiber coil. Furthermore, the copper disk acts as a heat sink to remove the generated heat and cool the excited fiber. The active fiber is surrounded by a refractive index matched cooling fluid for an efficient heat transfer to the copper disk. The fiber is pumped by several diode lasers, which are arranged circularly around the copper disk. The excitation laser light of the diodes is coupled through a window into the copper disk and enters the fiber through the fiber side surface. 976 nm pump diode lasers were chosen because the wavelength fits excellently with the Yb absorption maximum of the fiber at 976 nm to ensure a high pumping efficiency. The emission wavelength of each diode laser was stabilized by gratings, because a wavelength shift of the diode laser would reduce the laser efficiency significantly since the full width of half maximum of the Yb absorption peak at 976 nm is quite small (< 5 nm). The end faces of the fiber were polished manually. The laser cavity is produced by the bare fiber and the reflectivity of the polished fiber end faces. The laser results presented below were achieved without additional cavity mirrors, which are typically used to increase the numbers of light cycles in the laser cavity. The laser setup without additional cavity mirrors is a so-called single pass laser. The maximum pumping power of the laser setup was 1.5 kW.

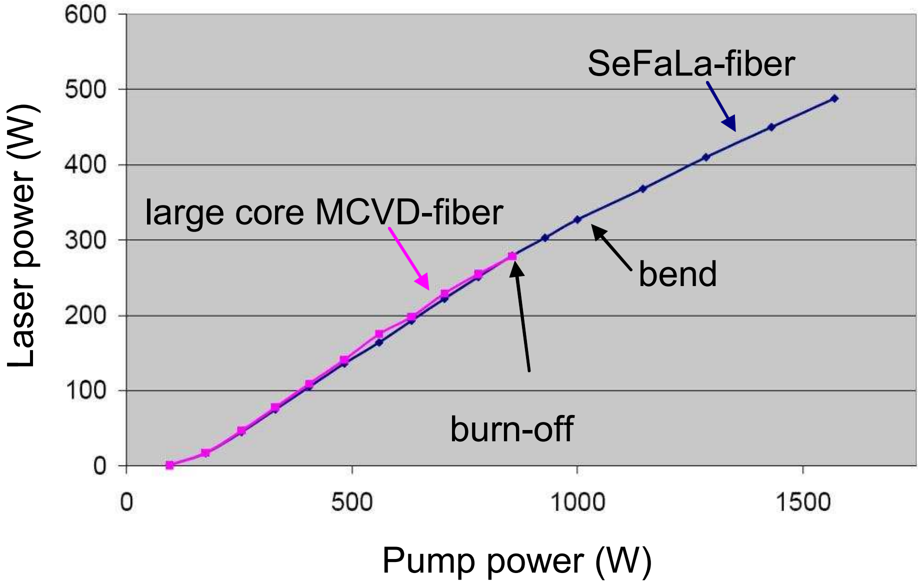

Fig. 7. Performance diagram of the side-pumped fiber laser setup. The setup was tested by two different types of fibers: A large core fiber produced by MCVD, and a fiber manufactured with our novel Yb-doped bulk silica (SeFaLa-fiber). The maximum output cw power was 490 W.

The developed side-pumped fiber laser setup was tested by two different types of fibers. One fiber was manufactured at the Institute of Photonic Technology in Jena (Germany) by the conventional MCVD and solution doping technique. The active area of the MCVD fiber was grown in several doping cycles. The MCVD fiber featured an elliptical fiber core with a core diameter between 60 µm and 90 µm. The other fiber (SeFaLa-Fiber) was produced by our new doping method and has a Yb-doped bulk silica core. The cross section of the fiber is shown in Fig. 4. The performance diagram of the side-pumped fiber laser setup is shown in Fig. 7. The initial slope of both fiber types is more or less identical. The fiber laser emission starts at a minimum pump power of about 150 W. In both cases, we had a wall plug (electrical optical) efficiency of 19 %, whereas a comparable fiber coupled direct diode laser system achieves an efficiency of typically 30 %. The difference of the efficiency is mainly caused by losses induced by the external 976 nm stabilization of the pump laser bars using volume bragg gratings and by the high laser threshold in the side-pumped fiber laser because of the high number of active ions in the fiber respectively the corresponding thermal population of the lower laser level. Compared to end-pumped fiber laser setups, which utilize the light guiding mechanism also for the pump light, side-pumped setups need a higher concentration of active ions to absorb an acceptable amount of pump power in rather short absorption distances. Moving to higher pump powers will lead to a wall plug efficiency of estimated 23 % due to the lower influence of the threshold in the side-pumped fiber laser setup.

The performance of the MCVD fiber was exceeded by the SeFaLa-fiber, because the MCVD fiber burned off at a fiber laser emission power of 280 W. The SeFaLa-fiber endured the maximum pump power of 1.5 kW without a burn-off. It was possible to extract a maximum laser emission power of 490 W from the SeFaLa-fiber. There is a slight bend in the middle of the performance slope at a pump power of about 1 kW. This bend was caused by an insufficient cooling efficiency and was remedied with a new fiber laser prototype.

5. RESULTS AND CONCLUSION

We have presented the development results of a new doping method to produce a rare earth doped fused bulk silica. To our knowledge, no comparable bulk silica is commercially available in the market at the moment. Our new material features a high doping level (up to 0.25 mol % Yb_2O_3 and above), a high material purity, a low defect and bubble density and a low background attenuation. Due to the excellent material homogeneity, the rare earth doped material is very well suited for ambitious fiber laser applications. The bulk material enables new special fiber laser designs such as ultra large mode area fibers and special micro-structured fibers.

Furthermore, it was shown that the plasma outside deposition (POD) technique is very well suited to deposit a fluorine doped fused silica layer on the outer surface of a rare earth doped core rod to produce a laser fiber preform.

The laser properties of the rare earth doped fibers, based on our novel Yb-doped bulk silica, have been demonstrated in the model system of a multimode side-pumped fiber laser setup. This laser concept was matched to our requirements to use cost efficient pump diodes. It was possible to extract 490 W laser emission out of the fiber with a wall plug (electrical optical) efficiency of 19 %.

Although the achieved OH-content, background attenuation, defect density and homogeneity of our presented Yb-doped fused bulk silica is already good and very well suited for fiber laser applications, the material still has a high optimization potential for further improvement of the optical material properties. The results of the large active core fiber design for the special side-pumped fiber laser system will be transferred to other fiber designs.

6. ACKNOWLEDGEMENT

The results presented in this paper were achieved during our cooperation within the fiber laser development project "SeFaLa". SeFaLa is a German acronym for side-pumped fiber lasers.

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REFERENCES

1. N. S. Platonov, D.V. Gapontsev, V. P. Gapontsev, V. Shumilin, "135W CW Fiber Laser With Perfect Single Mode Output", in Proc. Conference on Lasers and Electro-Optics, Long Beach, USA, 2002, post-deadline paper CPDC3
2. Y. Jeong, J. Sahu, D. Payne, and J. Nilsson, "Ytterbium-doped large-core fiber laser with 1.36 kW continuous-wave output power", Opt. Express **12(25)**, pp 6088-6092 (2004)
3. J. Nilsson, J. K. Sahu, Yoonchan Jeong, W. A. Clarkson, R. Selvas, A. B. Grudinin, S.-U. Alam, "High Power Fiber Lasers: New Developments", in Advances in Fiber Devices, Proc. SPIE **4974**, pp 50-59 (2003)
4. S. Norman, M. Zervas, A. Appleyard, M. Durkin, R. Horley, M. Varnham, J. Nilsson, Y. Jeong, "Latest development of high power fiber lasers in SPI", in Fiber Lasers: Technology, Systems, and Applications, Proc. SPIE **5335**, pp 229-237 (2004)
5. "Fiber Laser – Market Review and Forecast 2006", Report OM-35, Strategies Unlimited (2006)
6. L. Quintino, A. Costa, R. Miranda, D. Yapp, V. Kumar, C.J. Kong, " Welding with high power fiber lasers – A preliminary study", Materials & Design **28(4)**, pp 1231-1237 (2007)
7. J. Stone, C. A. Burrus, "Neodymium-doped silica lasers in end-pumped fiber geometry", Appl. Phys. Lett. **23(7)**, pp 388-389 (1973)

8. J. E. Townsend, S. B. Poole, D. N. Payne, “Solution-doping technique for fabrication of rare-earth-doped optical fibres”, Electronics Letters **23(7)**, pp 329-331 (1987)
9. M. Rajala, K. Janka, S. Tammela, P. Stenius, P. Kiiveri, M. Hotoleanu, “Advantages of direct nanoparticle deposition (DND) technology in active fiber production”, LIEKKI OY (2003, update May 2005)
10. J. Kirchhof, S. Unger, A. Schwuchow, S. Grimm, V. Reichel, “Materials for high-power fiber lasers“, J. Non-Cryst. Solids **352**, pp 2399-2403 (2006)
11. P. W. France (Ed.) “Optical fibre lasers and amplifiers“, Blackie and Son Ltd, 1991
12. A. Langner, G. Schötz, J, Vydra “Specialty fibres for light transmission from UV to IR”, Photonik international 2007, pp 10-12 (2007)
13. O. Humbach, H. Fabian, U. Grzesik, U. Haken, W. Heitmann, “Analysis of OH absorption bands in synthetic silica”, J. Non-Cryst. Sol. **203**, pp 19-23 (1996)