

A 70 W thulium-doped all-fiber laser operating at 1940 nm

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Received August 29, 2019; accepted September 27, 2019; published September 30, 2019

Abstract—An all-fiber thulium-doped fiber laser operating at a wavelength of 1940 nm is reported. A maximum output continuous-wave power of 70.7 W with a slope efficiency of 59%, determined with respect to the absorbed pump power, was demonstrated. The laser delivered almost a single-mode beam with a beam quality factor of <1.3 .

Fiber-based laser sources comprising continuous-wave (CW) [1-2], nanosecond [3-5], picosecond [6-8], femtosecond [9-11] fiber lasers and amplifiers as well as supercontinuum sources [12-14] offer the efficient generation of laser radiation from compact low-maintenance devices, which have created a wide range of applications in the industry. Especially medical applications like surgery of soft biological tissues have gained a lot of interest recently [15-17]. Lasers used in microsurgery operate at wavelengths corresponding to local peaks at $\sim 2.94 \mu\text{m}$ and $1.94 \mu\text{m}$. The former wavelength can be provided by Er:YAG lasers whereas the latter wavelength can be generated by thulium-doped bulk and fiber lasers. Compared with bulk solid-state lasers, cladding-pumped fiber lasers offer a compact solution to the need for both high power and good beam quality [18]. High power diode-pumped Tm^{3+} -doped fiber lasers (TDFLs) are high efficiency emission sources in the $1.9\div 2.1 \mu\text{m}$ region [19-21]. Furthermore, medical TDFLs have several potential advantages over the $2 \mu\text{m}$ holmium lasers, like continuous or pulsed output, less thermal damage to a tissue, they are more compactable, and have better beam quality, which is important when the laser output has to be integrated with a fiber probe of small core diameter. TDFLs proved to be useful in ablation of urinary tissues, laser lithotripsy and vaporization of the canine prostate [22-23] as well as they are also effective pump sources to acquire high power mid-infrared ($3\div 5 \mu\text{m}$) laser output [24-25].

Recent optimization of high concentration Tm-doped fibers (TDFs) has enabled the demonstration of $>65\%$ slope efficiency from a fiber laser operating at around $\sim 2 \mu\text{m}$, pumped at a wavelength of $\sim 790 \text{ nm}$ [26] and the output CW power of 1kW generated from thulium fiber laser and amplifier has been reached [27]. This demonstration was possible thanks to the recent

development of large mode area (LMA) Tm-doped fibers employing the use of an up-doped pedestal surrounding of the rare earth doped core.

Most reports on high power fiber lasers concern setups where double-clad LMA fibers with a core/clad diameter of $25/400 \mu\text{m}$ are used. Such an approach is reasonable since it allows better thermal management of active fibers. However, on the other hand these fibers have relatively low absorption at 790-nm pump wavelength, which forces the use of longer fibers and thus makes the system more expensive. Therefore, to develop a CW TDFL with moderate output power it is reasonable to apply fibers with a smaller core/clad diameter ratio having higher absorption and a reduced length. Another issue, important from the practical point of view, is laser simplicity and reliability.

In surgery TDFLs operating in CW and Q-CW modes with an output CW power of $40\div 100 \text{ W}$ are needed. As it was already mentioned earlier, most of the commercial products as well as literature reports concern lasers built with the use of TDFs with a core/clad diameter of $25/400 \mu\text{m}$ [e.g. 28, 29]. There are only sparse reports on lasers based on LMA TDFs with a smaller inner clad diameter. Although the development of TDFLs is advanced enough, reaching even a commercialization stage, improving their operation while keeping the construction simple, reliable and cost-effective are still the subject of many research works.

In this Letter we report a fiber Bragg grating (FBG) based fiber laser, delivering an output CW power of 70.7 W at $1.94\text{-}\mu\text{m}$ -wavelength with 59.15% slope efficiency, pumped with 140.7 W of 793-nm radiation.

The laser, in a linear cavity, is formed by one highly reflective mirror in the form of a commercially available FBG (Teraxion) having 99% reflectivity at 1941 nm and a Full-Width at Half-Maximum (FWHM) of 2.5 nm, an active fiber, and the 4% Fresnel reflection from the active fiber end facet. The 4.1-m long TDF, manufactured by Nufern, was a step index, LMA double-clad fiber with a core/clad diameter of $25/250 \mu\text{m}$ and corresponding numerical apertures (NAs) of 0.09/0.46. It was characterized by a high dopant concentration with high pump conversion efficiency optimized for operation at 2-

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μm -wavelength. The clad absorption at a pump wavelength of 790 nm was 9.5 dB/m, as specified by the manufacturer. It was directly pumped by two laser diodes (LD) each delivering up to 80 W of CW power at 792-nm-wavelength out of fiber pigtails with core/clad diameters of 200/220 μm . The pump radiation was launched into the active fiber via a (2 \times 1)+1 pump combiner with a signal feedthrough. The output port of the combiner was directly spliced to the input port of the FBG. At the output, a 790 nm / 1940 nm dichroic mirror was used to separate signal radiation from the unabsorbed pump power.

A Tm-doped fiber laser is a quasi three-level system lasing through transition to the ground state, thus being sensitive to temperature fluctuations [2]. Therefore, to achieve high efficiency, reliability and high output beam stability, proper heat management of active fiber is crucial. In the developed laser the active fiber and passive components of the laser were placed inside a specially designed aluminium heat sink, kept at a temperature of $18\pm 1^\circ\text{C}$.

The whole laser system was developed in all-fiber architecture, making it more resistant to environmental factors like dust, vibration and humidity, comparing with classical bulk laser setups. Figure 1 presents an exemplary image of a splice between 25 μm core passive FBG pigtail (left) and the active 25 μm core TDF with pedestal (right) with a splice attenuation value of 0.08 dB. As can be seen, its quality is very good, which is a result of suitable experimental procedure determining the optimal splice parameters for this particular case.



Fig. 1. Exemplary picture of a splicing point between the FBG pigtail (a) and the LMA TDF (b).

In the first part of the study, we measured the output power and central linewidth of the pump LDs and adjusted the temperature of the cold plates, on which the diodes were mounted, to maintain emission at a central wavelength of 792 nm. In the next step the laser cavity length was optimized to achieve maximum slope efficiency. To this end, we used different lengths of the TDF (3.9 m, 4 m, 4.1 m, 4.2 m, 4.3 m, 4.5 m) and run the laser at its maximum performance. The results of these measurements are illustrated in Fig. 2. One can see that there is an optimal TDF length, for which the slope efficiency, determined with respect to the launched pump power, is the highest. Changing the active fiber length

from 4.5 m to 3.9 m, the slope efficiency varied from 48% to 54% with the maximum for the TDF length of 4.1 m. Applying longer pieces of active fiber led to lower efficiency due to higher cavity losses and reabsorption processes. On the other hand, using shorter pieces of Tm fiber led to a decrease in laser gain and thus drop in output power and generation efficiency.

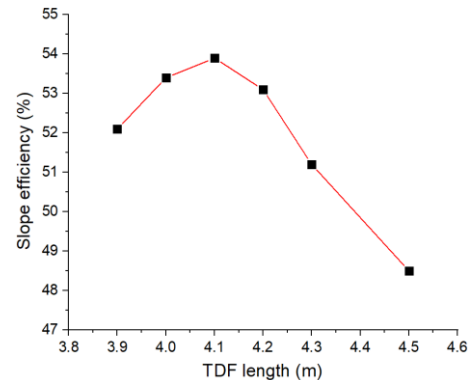


Fig. 2. Optimization of TDF length.

In the final configuration of the laser setup the optimal 4.1-m-long TDF was applied. The maximum pump power launched into the fiber was 140.7 W, of which 131.7 W was absorbed by the active dopant. The dependence of output power as a function of absorbed pump power is shown in Fig. 3. The maximum output power was measured to be 70.7 W with a slope efficiency of 59.15%. To the best of authors' knowledge, both CW output power and slope efficiency are one of the highest achieved directly from a single 1940-nm Tm-doped fiber oscillator utilizing an LMA TDF with a core/clad diameter of 25/250 μm .

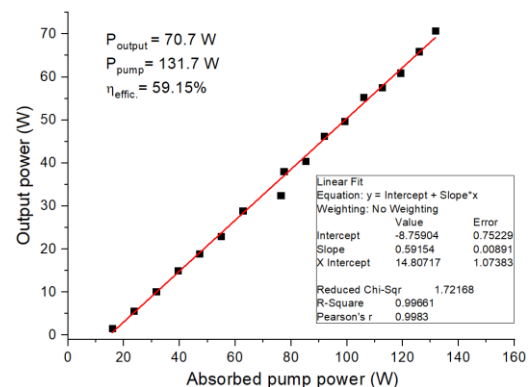


Fig. 3. Laser output power versus absorbed pump power.

Further improvement of the laser efficiency can be achieved by more precise optimization of the laser cavity, especially using a TDF with more optimized dopant concentration. One can see that the output power increases linearly with the rise of absorbed pump power without any

roll-off showing that further power scalability can be easily achieved increasing the pump power.

Figure 4 shows the emission spectrum of the laser at the maximum output power. It reveals the main peak at 1941.67 nm and smaller two satellite peaks at 1940.95 nm and 1939.4 nm, which resulted from the feature of the FBG used in the experiment. For higher powers the FBG could not completely confine the spectral bandwidth due to its relatively low side-mode suppression (12.5 dB), which probably resulted in the feedback at the two shorter lines. However, this feature of the spectral characteristic is not a problem when the laser is to be used for surgery and it should not affect the effectiveness of laser interaction with a tissue.

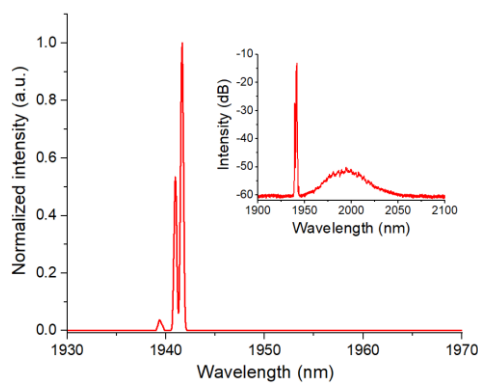


Fig. 4. Laser spectrum at 70 W.

The inset in Fig. 4 presents the spectrum recorded in a wavelength span of 200 nm. A small signal with a maximum peak at $\sim 2 \mu\text{m}$, coming from amplified spontaneous emission, can be noticed. Nevertheless, the dynamic range was ~ 40 dB showing a good signal-to-noise ratio.

The beam quality of the laser output was measured by using a pyro-electric thermal camera to record a two-dimensional intensity beam profile around the waist formed by an AR-coated plano-convex 20 mm effective-focal-length singlet lens. The results are given in Fig. 5.

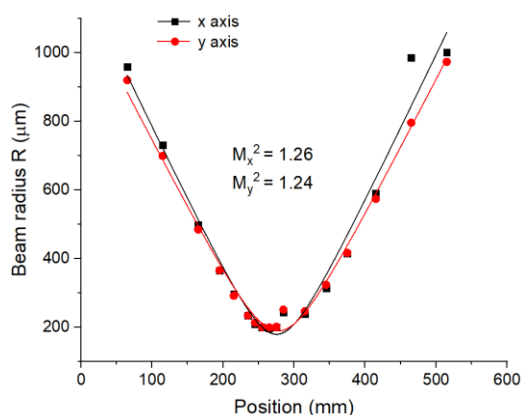


Fig. 5. Measurements of the beam radius as a function of the distance from the focusing lens. Data points represent measured data and curve fits to the data.

Using a Gaussian fit to the measured beam size as a function of distance in the focal region we determined the M^2 factor to be 1.26 and 1.24 along x- and y-axes, respectively. These values are typical of LMA fibers. However, it is worth adding that putting the TDF in a coil with a smaller diameter should lead to discrimination of higher order modes and thus further improvement of the beam profile.

In conclusion, we have successfully developed an efficient Tm-doped fiber laser operating at a wavelength of $1.94 \mu\text{m}$. It generated 70.7 W of output power with a slope efficiency reaching 59.15% determined with respect to absorbed pump power. The laser has a simple, all-fiber and cost-effective construction meeting the requirements of many applications.

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