High power, 100 W-class, thulium-doped all-fiber lasers

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Abstract—In this work, sub-kilowatt, compact thulium-doped fiber laser systems, operating at a wavelength of 1940 nm, have been presented. The continuous-wave laser power generated out of a single oscillator was 90 W with a slope efficiency of 56.7%. Applying a master oscillator – power amplifier configuration, an output power of 120.5 W with a slope efficiency of 58.2% was demonstrated. These are the first results of the works aimed at developing kW-class "eye-safe" laser systems in Poland.

Rare-earth-doped silica fiber lasers and amplifiers are currently considered as the best sources for many high-power applications [1]. These compact and robust devices have already found many applications in industry and scientific research. In particular, thulium-doped fiber lasers (TDFLs) have driven great attention recently because of their "eye-safety" operation [2–4]. Broad emission of Tm^{3+} ions in silica hosts, ranging from ~1700 to 2100 nm, makes it an excellent tool in spectroscopy [5], military technique [6], medical field [7] as well as in nonlinear frequency conversions to mid- infrared wavelengths – via supercontinuum and optical parametric generation [8–9]. Furthermore, the rapid development of pumping laser diodes (LDs) and the double-cladding fiber pumping technique, continuous wave (CW) TDFLs have been commercialized successfully [10].

There are three potential regions of wavelengths to consider for the pumping of TDFLs. The first one spreading from 1.1 to 1.2 μm ($^3H_6 \rightarrow ^3H_5$ transition) is currently considered as less useful due to the lack of high power and high brightness solid-state laser sources, including semiconductors ones, operating in this regime. The second pump region covering the wavelengths from ~1.5 to 1.9 μm ($^3H_6 \rightarrow ^3H_4$ transition) is often called in-band or resonant pumping. The relatively small difference between pump and emission wavelengths results in a very small quantum defect and thus high slope efficiency. On the other hand, the main limitation of power scaling when using resonant pumping is, like in the previous case, the unavailability of appropriate laser diodes emitting in this spectral range. To achieve a pump power level of hundred watts or more, Er- or Er:Yb-doped fiber lasers have been employed as extremely high brightness pump sources operating at wavelengths of 1.5÷1.6 μm [11]. Although this approach allows achieving slope efficiency of over 70%, the generation efficiency of Er/Er:Yb lasers is ~40% (determined with respect to the 976-nm pump wavelength) resulting in only ~15% of wall-plug efficiency of the whole laser system. Besides, applying in-band pumping the pump radiation is directly launched into a small area core of a fiber. Due to a high value of core absorption it enables the use of short pieces of active fibers, thus reducing the price of the whole system. On the other hand, it is hard to inject a high pump power into such a small diameter core of a fiber, which, in turn, limits the output laser power. Therefore, the most commonly used scheme for pumping TDFLs is the use of 790-nm wavelength ($^3H_6 \rightarrow ^3H_4$ transition), which can be generated by commercial, high-efficiency and high-power semiconductor laser diodes. Using 793-nm-wavelength LDs, the Stokes limit of TDFLs working at ~2 μm is only about 40% [12]. However, owing to the non-radiative cross relaxation process in Tm^{3+} ions, this pump scheme can also lead to operation efficiency of 80%, yielding quantum efficiency of 200% in the two-micron band [12]. That was the main reason why TDFLs pumped at 790-nm wavelengths have been exploited during the last decade. The progress in drawing Tm-doped fibers (TDFs) with an optimized dopant concentration and fiberized components resulted in several demonstrations of high-power thulium fiber laser systems, e.g. [10], [13–15]. Despite these significant achievements, studies on power scaling as well as improvements of output parameters of Tm-doped fiber lasers and amplifiers are still being carried out. Furthermore, it has been noticed that there is a lack of reports on European demonstration of high-power ~2 μm fiber based laser systems.

In this letter, we present two CW, high power, thulium doped fiber laser systems operating at the same 1.94 μm wavelength: (1) a compact, linear cavity TDFL, utilizing a fiber Bragg grating (FBG), delivering up to 90 W of output power and (2) a Master Oscillator Power Amplifier (MOPA) system with an output power of over 120 W.

The TDFL was based on a simple Fabry-Perot cavity scheme with a high reflectivity (HR) FBG and output coupler (OC) of 4% Fresnel reflection from the perpendicularly cut active fiber. The HR FBG has a reflectivity of 99.02%, transmission bandwidth of 1.92 nm

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at 13 dB and a central wavelength of 1939.96 nm. At the output, we utilized a dichroic mirror (DM) to separate signal laser radiation from unabsorbed pump power at 790 nm. The setup of the developed TDFL is shown in Fig. 1.

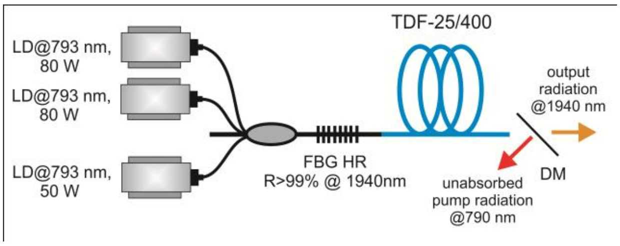

Fig. 1. Setup of TDFL. LD – laser diode, TDF – thulium-doped fiber, DM – dichroic mirror, FBG – fiber Bragg grating.

The HR FBG was spliced to the commercially available large mode area (LMA) TDF with a core/clad diameter of 25/400 μm and numerical apertures of 0.09/0.46. The clad absorption at a pump wavelength in the active fiber was 2 dB/m, as specified by the manufacturer. The active fiber was pumped through a multimode pump combiner with a signal feedthrough by the laser radiation delivered from three laser diodes emitting up to 210 W.

At the beginning of the study we utilized a 5-m-long TDF, but the laser operated with poor efficiency (below 50%). Therefore, in the next step, the length of active fiber was optimized and finally the TDF with 4.55 m in length was applied. As a result, an output CW power of 90 W with a slope efficiency of 56.7% was achieved, measured for an absorbed pump power of 170 W (Fig. 2).

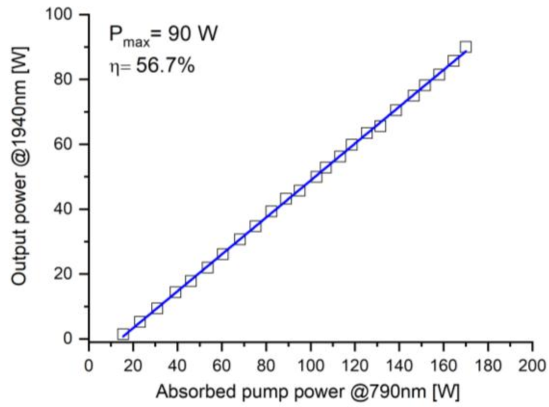

Fig. 2. TDFL output power versus absorbed pump power.

The optical spectrum measured for maximum output power is presented in Fig. 3. The laser generated at a wavelength of 1941.6 nm with a 3 dB bandwidth of 0.52 nm. As can be seen, the spectrum is clear, without any components coming from amplified spontaneous emission.

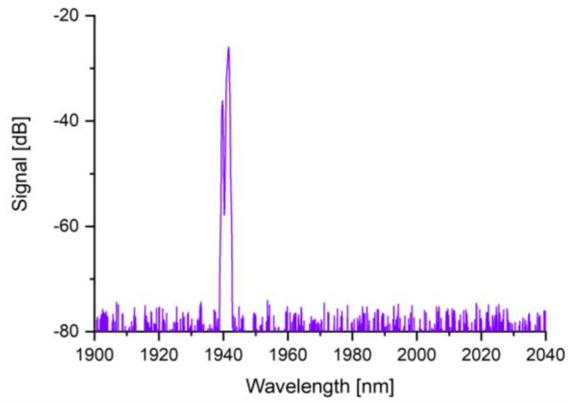

Fig. 3. Optical spectrum of the TDFL at maximum output power.

Further power scaling of the developed TDFL was limited by a significant amount of laser radiation propagated backward, through the feedthrough port of the combiner. The input signal pigtail of the combiner was not a part of the laser cavity but used to monitor the generated power. For maximum laser performance, over 9 W of 1940-nm-wavelength laser radiation was generated backward through the unused feedthrough port. Since the technological limit for power propagated through this part of the combiner is 10 W, we did not increase the pump power beyond 170 W so as not to damage the combiner.

In the second part of the study, bearing in mind the limitation of the setup presented in Fig. 1, we decided to develop a MOPA system for further power scaling. The experimental setup of a thulium-doped fiber MOPA system developed in all-fiber architecture is depicted in Fig. 4.

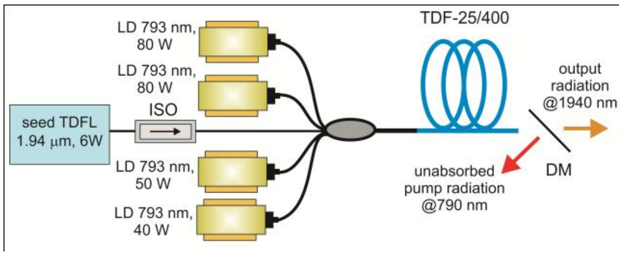

Fig. 4. Setup of the TDF MOPA system.

A home-made, linear cavity TDFL based on FBGs was used as a seed. It operated at a wavelength of 1940 nm and was characterized in [17]. A high power, 10 W power handling, double-stage fiber optic isolator with optical isolation of 32 dB was placed behind the seed to block any undesirable back-coming radiation. The thulium-doped fiber amplifier (TDFA) was pumped with the use of a (6+1)×1 multimode pump combiner with a signal feedthrough at 1.94 μm. As an amplifying medium we utilized a 4.52-m-long piece of LMA 25/400 TDF having 2 dB/m clad absorption at 793 nm, the same one that was used in the single oscillator layout. The active fiber was pumped by radiation delivered from four fiber pigtailed laser diodes (2×80 W, 50 W and 40 W). The maximum pump power launched into the TDF was 226.5 W, of which 208 W was absorbed by the active dopant.

The MOPA output power generated at 1940 nm, measured behind the dichroic mirror, as a function of the absorbed pump power is presented in Fig. 5. The output power of the TDFA was measured for two values of the seed power: 3 W and 5.7 W. When the power of 5.7 W was launched to the amplifier input, the maximum output CW power of 120.5 W with a high slope efficiency of 58.2 % was generated at its output. For a lower input signal (~3 W) the MOPA system generated the power of 116.5 W. For this case the slope efficiency decreased to 56.1%. The higher seed signal launched into the TDF made the amplifier operate in saturation with higher efficiency. As it was emphasized in the introduction, due to the cross-relaxation energy transfer between Tm^{3+} ions [12], the achieved values of the slope efficiency are higher than the theoretical ones resulting from the Stokes limit. Furthermore, as can be seen in Fig. 5, the output power increases linearly with the rise of absorbed pump power showing that further power scalability can be easily achieved by increasing the pump power.

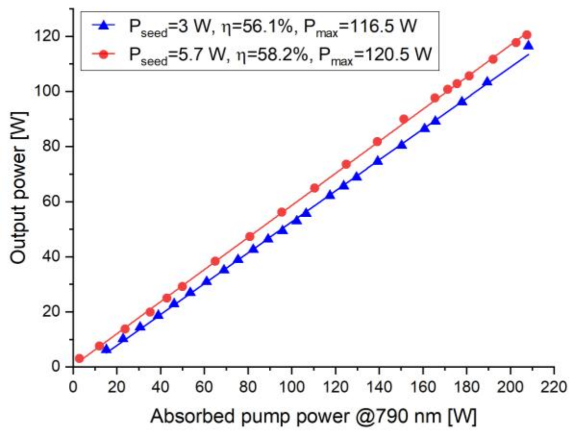

Fig. 5. Output power of the TDF MOPA system versus absorbed pump power at 790 nm. The seed output power: 3 W and 5.7 W.

The optical spectrum of the seed laser and spectra generated out of the amplifier, measured for different output powers, are depicted in Fig. 6. It can be seen that the spectra at the TDFA output are very similar to the spectrum of the seed TDFL. The main peak with a 3-dB spectral width of 0.35 nm is located at 1939.4 nm and a small satellite peak can be noticed at 1937.8 nm. The two peaks in the output spectrum resulted from the parameters of the FBGs, which were characterized by quite low side-mode suppression.

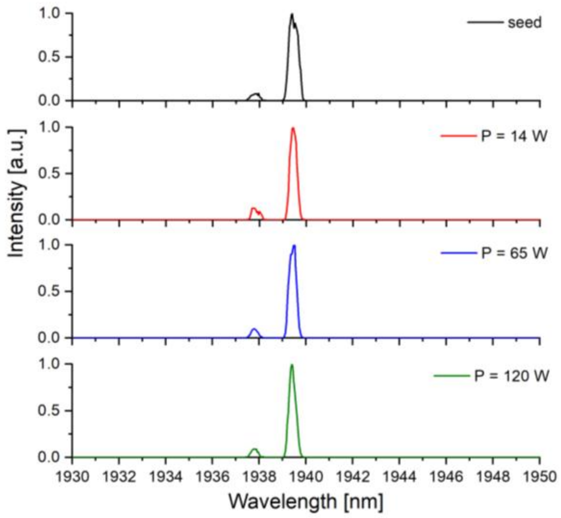

Fig. 6. Optical spectrum of the seed and TDF MOPA system recorded for 14 W, 65 W and 120 W of output power.

In conclusion, a high power 1.94 μm Tm-doped fiber laser and a Tm-doped fiber amplifier delivering over 90 W of CW output power have been developed. The laser systems operated with a slope efficiency of over 56% without any roll-off of power characteristics. It shows that the output power can be further scaled up by using a higher number of more powerful laser diodes. This will be the subject of our future research.

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