High-power, air-cooled Thulium doped fiber amplifier with 71 % slope efficiency

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Many applications can strongly benefit from high-power, high energy laser systems emitting in the 2 µm wavelength region. These sources can be used for metrology, as well as for medical applications and material processing [1]. Among all the solid-state lasers able to emit in the 2 µm spectral region, Thulium (Tm-) doped fiber laser systems are particularly well suited to handle high power operation [2]. The main challenge is that, when using the conventional pump wavelength of around 790 nm, these fibers tend to generate a high heat load even at moderate output powers, especially for pulsed operation. Therefore, usually, the active fiber in these systems has to be water cooled [3]. The issue with water cooling is that it increases the size and weight of the system thus, making it less portable, and reduces the overall wall-plug efficiency of the system. In this context there are plenty of application that require, or at least would benefit from, air cooling and high wall plug efficiency. Air-cooling would significantly decrease the complexity of such systems, which is highly preferred for medical and industrial applications in various environmental conditions [4]. The elimination of active water cooling could also reduce the introduced noise, allowing for potentially high stable operation mode. Additionally, the efficiency of the wall plug can be increased by eliminating the use of commonly employed chillers. This, however, is quite challenging to achieve using state-of-the-art pumping scheme (at ~790 nm) for Thulium [4]. In fact, there are very few Tm-doped, air-cooled systems reported to date and we are not aware of any operating beyond 10 W [4] . Due to the high absorption cross-sections and the commercially availability these Tm-doped fiber lasers are usually pumped around 790 nm. From a theoretical perspective, the large difference between the absorption wavelength at ~790 nm and the emission wavelength at 2000 nm results in a high quantum defect of almost 60 %. This means that ~60 % of the energy would be transferred to heat thus generating a strong heating of the fiber. High thermal load limits the power scalability of a Tm-doped fiber laser due to several reasons. The emission and absorption cross-sections depend on the temperature and, if it increases, the cross-sections will be reduced [5]. In turn, if this happens, the efficiency will drop further leading to an even higher heat load at the same output power. Additionally, the thermal load leads to mode field shrinking which can promote the onset of nonlinearities and can, therefore, hinder high energy extraction in pulsed systems [6]. Besides, at a certain level of heat load the effect of transverse mode instability (TMI) occurs [3]. Therefore, a strategy to reduce the thermal load inside of Tm-doped fiber lasers is needed to be able to scale the output power further. Crucially, the efficiency can be significantly increased when pumping at 793 nm by exploiting cross-relaxations processes. This way, the efficiency can be raised beyond the stokes limit to up to ~80% [7]. The problem is that these processes become significantly less effective in pulsed systems since they rely on a low inversion level. A promising alternative, that also works in pulsed systems, is that of in-band pumping. Thulium gain media possess a broad absorption spectrum between 1550 nm and 1900 nm. By pumping Tm-doped fiber laser in this in-band wavelength span, slope efficiencies of 62 % up to 92 % could already be shown [8,9]. Due to the absorption cross-sections, pump wavelengths at the edges of the in-band pumping region (i.e. around 1550 nm and around 1900 nm) require either core pumping and or long fiber lengths [10], making high-power pulsed operation difficult. In these systems, the fiber length should be relatively short in order to avoid the onset of nonlinearities. This means that the pump wavelength should be chosen in a region with a high absorption coefficient which, in this case corresponds to the spectral region between 1600 nm and 1700 nm [10]. In our experiment, we used a pump wavelength of 1692 nm due to the availability of pump sources and our aim for high efficiency [11]. Further, this wavelength allows for double cladding pumping.

In this contribution we present the results of a highly efficient, air-cooled, Tm-doped fiber laser system cladding pumped at 1692 nm. The system is schematically depicted in Figure 1 (left side). It consists of a and a commercially available photonic crystal fiber (PCF) with a core to cladding ratio of 50/250µm as active fiber.

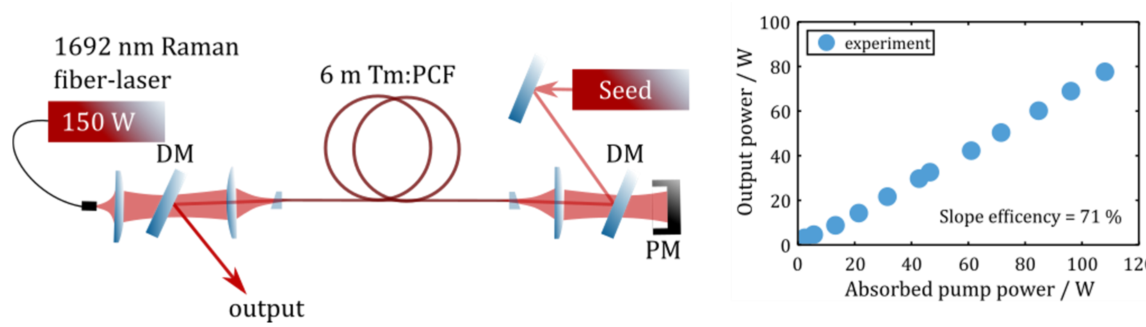

Figure 1: Setup of the amplifier experiment consisting of a seed source, the 6 m long, air-cooled, Tm-doped PCF and the pump source. DM: dichroic mirror, PM: thermal power meter to measure the residual pump (left picture). Output power as function of the absorbed pump power for the experiment (right plot).

The active fiber is 6 m long and cladding pumped at 1692 nm in the counterpropagating direction with respect to the launched signal. The pulsed seed signal is high as 5 W with a repetition rate of 80 MHz and a pulse duration of 0.6 ns centered at 1960 nm with 52 nm bandwidth (stretched fs pulses). The maximum attained output power was 78 W with a slope efficiency of 71 %, as can be seen from Figure 1 on the right-hand side.

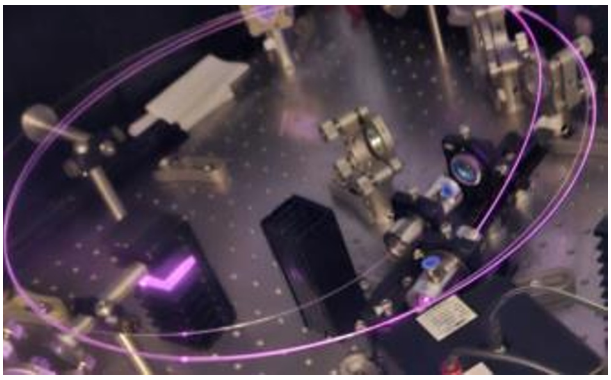

Figure 2: Picture of the air-cooled PCF operating at 78 W.

We stopped at this power level to prevent the glue of the fiber holders from suffering thermal damage due to stray light. This part of the design can be improved and should allow reaching even higher output powers. A picture of the active fiber at high power operation (78 W) is also shown in Figure 2. The in-band pumping at 1692 nm has enabled the highest average output power reported to date from an air-cooled, Tm-doped fiber laser system with Yb-like efficiency.

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