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High power passively mode-locked dissipative soliton fiber laser featuring cladding pumped non-CVD-thulium doped fiber

D. A. Gaponov[1,*] R. Dauliat[1], D.Darwich[1], T. Mansuryan[1], R. Jamier[1], S. Grimm[2], K. Schuster[2], and P. Roy[1]

[1]*Xlim UMR CNRS-Université de Limoges n°7252, 123 Av. Albert Thomas 87060 Limoges, France*
[2] *Institute of Photonic Technology, Albert Einstein Straße 9, 07745 Jena, Germany*
**Corresponding author: d.gaponov@novae-laser.com*[**]

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The characterization of a thulium-doped fiber made from the new powder technology in the mode-locking regime is reported. High average output power of 185 mW at a repetition rate of 9 MHz was achieved directly from the oscillator, which is resulting in 21 nJ of pulse energy. The single-pulse operation regime was confirmed by careful numerical modeling of the laser cavity.
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1.Introduction

Owing to considerable recent progress in different fields of science and technology, high power ultrafast laser sources emitting around 2 μmwavelength range attract an increasing attention. In this context, fiber based systems have assert their strengths/potential due to noticeable compactness and robustness, while state-of-the-art results in term of absolute values are still lower compared to those obtained from ytterbium doped fiber sources.

Various amplification techniques could be used to achieve either high energy or high peak power at this wavelength. Recently, 100 kW in peak powerwas obtained [1] with CPA & gain-switched (ns) seed pulse. In turn, mode-locked seed oscillator used in MOPA scheme allowsreachingμJ-level in pulse energy with sub-ps pulses[2,3]. Moreover, impressive results wererecently demonstrated with CPA systems based on Tm-doped rod-type fibers. Sub-ps pulses were amplified to reach 152 W in average power and 4 MW in peak power [4].

To achieve a high average power directly at the output ofthe ultrafast oscillator,one must provide effective stretching of the pulse inside the cavity during its round-trip. One of the regimes in whichthis could be realized, is theso-called dissipative solitonic (DS) regime which demands netnormal cavity dispersion. Furthermore, it has been shown that the energy scaling is directly related with absolute value of normal dispersion [5,6]. In contrastto the case of Yb-doped sources, where afiber chromatic dispersion is naturally normal for λ> 1.5 μm, one must use dispersion compensating elements (either bulk, or specialty fiber based) inside the cavity to provide such an operating regimeat 2 μm [7]. Typically, pulse energy measured directly at the output of a passively mode-locked thulium fiber oscillators in net normal dispersion cavities is in order of few mW [8]. Recently, a hundreds-mw average output power level was demonstrated exploiting high-order solitonic concept[9], where even few nanojoules pulses providedup to 21 kW in peak powerdue to their sub-ps nature.

In this paper we demonstrated the generation of high average power (185 mW) andhigh energy (21 nJ) picosecond pulsesin thenet normal dispersion cavity based on thecladding-pumped Tm-doped fiber fabricated using one of the newest glass manufacturing technologies.This process, called "Repusil", consisting in the synthesis of doped optical glass by sintering and vitrification of silica powders.Repusil-based fibers havealready demonstrated remarkable capabilities for the fabrication of efficient and homogeneous active materials [10], rendering them relevant competitors to existing methods of fiber fabrication.Obtained performances in terms of average and peak powers directly at the oscillator output are not the record ones at this wavelength range; however, to the best of our knowledge, they are the highest in terms of average power and pulse energy directly at the output of the thulium modelocked fiber lasers with a net *normal* dispersion cavity.

2. Fiber preparation and characterization in continuous wave (CW)regime

The material processing for the fabrication of doped silica is based on the REPUSIL process and described in [11]. The active material is made starting from pure silica particles which are doped in an aqueous dispersion with rare earth precursor (0.81weight % Tm^{3+} with ratio Al^{3+}: Tm^{3+} = 6:1). This synthesis technology allows high batch to batch reproducibility and thesilica rodsshow a high homogeneity: low radial (see Fig 1.a) and longitudinal variation of a refractive index:2.10^{-4}. It is worth to note that with obtained performances this Repusil technology could be especially useful in fabrication of large cores/volumes and overpasses the limitation of traditional MCVD process on the ability to accurately control the refractive index profile.

[**] Currently works in NOVAE SAS, Limoges, France

The fabricated fiber has a core diameter equal to 8 μm, an D-shaped outer cladding of122x146 μm, and is coated with a low index polymer (NA~0.35) providing an efficient cladding pumping. Itsrefractive index profile is presented in the Figure 1. The V number is estimated to be 2.36 at λ= 1900 nm which confirms that the fiber is truly singlemode in the working region (a near-field image of the fundamental mode at λ= 1960 is shown in the inset to Fig.1b).The measured cladding absorption reaches5 dB/m at λ= 790 nm while the background losses were estimated to be 0.1dB/m at λ=930nm and 0.5dB/m at λ=1335nm. It should be noted that the level of grey losses are quite high, compared to MCVD-based fibers, but dissipative solitonic cavity could tolerate them and is an ideal candidate for such a fiber to be implemented in. The performance of the fabricated fiber was tested in a continuous wave regime in a simple 4%-99% laser cavity, giving 43 % of slope efficiency with 5 m long sample.

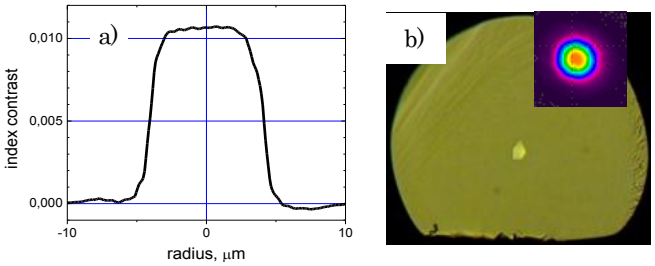


Fig. 1.a) the refractive profile of the fabricated powder thulium-doped fiber, b) corresponding fiber cross-sectionmicroscope image, inset – a near-field image of the fundamental mode at λ = 1960 nm.

3. Experimental set-up

Our oscillator, shown in Figure 2, is based on a Fabry-Perot cavity. To operate in a net normal cavity regime, the dispersion compensation (DC) has been achieved with the help of a commercially available OFS80 fiber, the chromatic dispersion of which is calculated to be +0.0489 ps²/m at λ=1960 nm. A small piece of single-mode fiber (SMF-28) has been put in between the Tm-doped fiber and the DC fiber in order to facilitate the splicing and a control of the total cavity dispersion. To evacuate the unabsorbed pump, the end of the active fiber was placed in a high-index polymer. The cavity has been passively mode-locked using a commercially available Saturable Absorber (BATOP-SAM-1960-54). The length of the active Tm-doped fiber (TDF) has been optimized to fit the working wavelength of SA mirror (SAM)λ=1960 nm and estimated to be ~2 m.

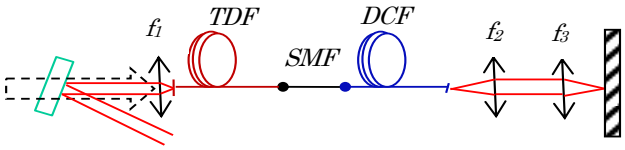


Fig. 2. Principal scheme of the oscillator:TDF – active thulium-doped fiber under test, SMF – transition single-mode fiber (SMF28), DCF – dispersion compensating (OFS80) fiber.

This fiber length still provided efficient laser operation, which was confirmed by the cut-back slope efficiency measurements – drop of only few percents compared to 5 m active fiber sample was observed.The fiber is cladding pumped with a multimode diode operating at λ = 793 nm from free-space using a couple of f_1=8 mm lenses.The free 0° cleaved fiber-facet acts as output coupler. A careful alignment of the focalization on SAMwith the pair of $f_{2,3}$=8 mm lenses enables a stable self-starting mode-locking.

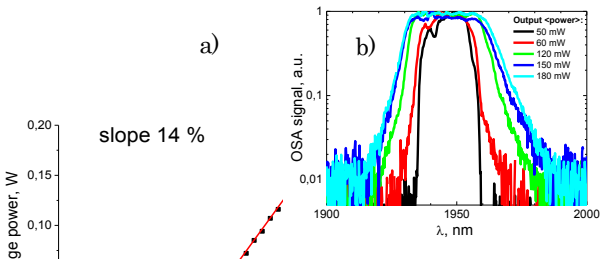


Fig. 3. a) Oscillator efficiency and output average power versusthe launched pump power; inset – pulse train, b) spectral evolution with respect to the output average power in the monopulse regime.

4. Experimental results

Up to 185 mW (f=9 MHz, E_p~21 nJ) of average power was obtained at the output of the oscillator in the single-pulse regime (see fig. 3a). Further increase of the pump power led to the doubled or even tripled pulse operation with respect to the fundamental frequency. We address this issue to the excessive energy fluence incident on SAM. Spectrums at different output average powers are presented in figure 3b. The full width at half maximum (FWHM) varied from 16.6 nm up to 34 nm at maximum signal power level.

The temporal characterizationwith 85 ps range autocorrelator (Femtochrome FR-103-XL) showed no additional replicas when pump power lies in the single-pulse region (up to 185 mW) (see Fig. 4). A typical autocorrelation trace for the output power Ps = 50mW (E_p~5.6 nJ), which lies in the beginning of the monopulse region, is presented in Fig. 3a. The autocorrelation FWHM (corresponding spectrum FWHM = 16.6 nm) was measured to be 24.4 ps which gives 15.8 ps of pulse duration (supposing sech²pulse shape).

5. Pulse compression experiment

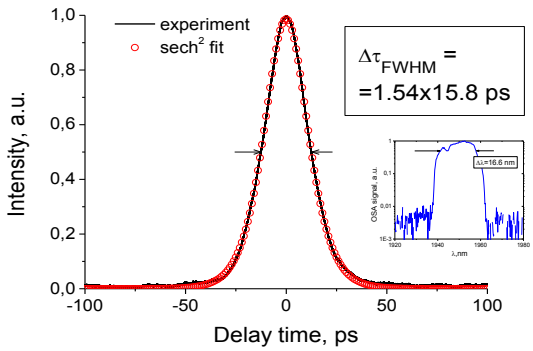


Fig. 4. The autocorrelation trace and corresponding spectrum (in the inset) at the output average power Ps=50 mW

Afterwards, a pulse compression experiment was conducted using a pair of 600 l/mm diffraction gratingswith a blaze wavelength of 1.6 μm. However, at λ=1.95 μm these gratings become efficient only for one polarization with diffraction

efficiency of 90%. Therefore a Glanpolarizer and two half-wave plates were used to maximize a) the average power of the pulse in the compressor andb) the signal in the autocorrelator (AC) (see Fig.5). It is worth to note that the polarizer also acts as the optical isolator preventing fromthe parasitic back reflections to the oscillator cavity thatcould easily disturb the mode-locking regime.Due to the mentioned limitations the overall compression efficiency in this configuration was not exceeding 33 %.

At the maximum output average power, however, the Glan polarizer did not provide a high optical isolation and the mode-locking regime was disturbed after few minutes of operation. Therefore the average output power providing unperturbed regime was fixed to be 100 mW (E_p = 11nJ) that gave an output pulse spectrum FWHM of 22.6 nm (see Fig. 6a). The corresponding autocorrelation traces for the pulse before and after compression are presented in Fig.6 (b and c, respectively). The 11.5 ps pulse was compressed down to 1.9 ps (assuming sech² profile, P_{peak} = 1.9 kW).A time-bandwidth product for the compressed pulse is equal to 2 that is approximately 2.5 times higher than typical values (~ 0.8) for dissipative solitonic regime.

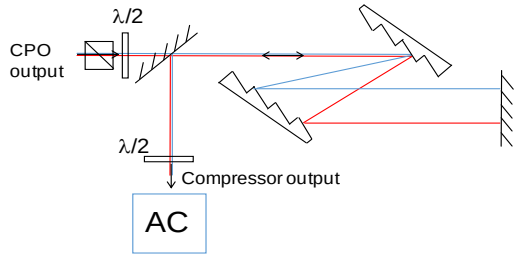


Fig.5. Pulse compression set-up. AC – autocorrelator.

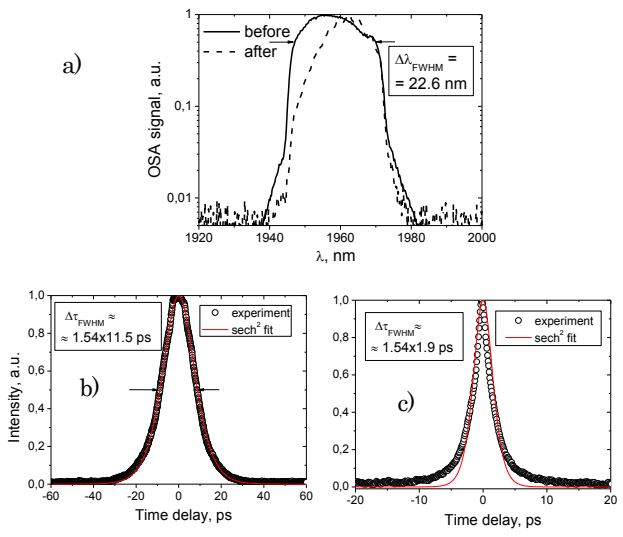


Fig.6.Compression experiment: spectrums and autocorrelation tracesof the pulse *before (a-solid line, b)* and *after(a-dashed line, c)*compression.In Fig. 6b,c the solid red line represents sech²fit to the experimental data.

This could be explained by not optimal alignment of diffraction gratings in our set-up (one could see a slight cut of the short wavelengths components in compressed pulse spectrum, Fig 6a). One could mention also, that more efficient gratings (etc, working in transmission, polarization independent) together with a better compressor alignment immediately allows to reach 10 kW peak power level in this system.

5. Numerical modeling

To confirm the monopulse operation, a numerical modeling was made with the help of a commercially available software [12] based on the split step Fourier method. The schemeused in the calculations is illustrated in Fig. 7. The elements lengths (L) were taken to fit the experimental cavity: L_{TDF} = 1.9 m, L_{OFS80} = 7m, L_{SMF28} = 2.1 m, $L_{free\text{-}space}$ = 0.4 m). The SAM parameters were chosen respecting the datasheet: a relaxation time ofτ = 10 ps and a modulation depth ofΔR= 30 %. The dispersion parameter of SMF28 fiber is known to be $\beta_{2,SMF}$ = -0.0679 ps²/m at 1.9 μm [8],



Fig.7.Configuration of the element blocks used in the numerical modeling of the experimental cavity from Fig.2. Dashed lines with arrows illustrate cavity round trip. OC – output coupler element

which corresponds to -0.0778 ps²/m at 1.96 μm. For TDF the dispersion was estimated to be $\beta_{2,TDF}$=-0.07875 ps²/m at 1.96 μm. Thus the cavity has a moderate level of the net normal dispersion $\beta_{2,net}$ = +0.0586ps². The Fresnel 4% reflection at the fiber end-facet provided the positive feedback in the laser cavity. The gain FWHM was measured to be $\Delta\lambda$=160 nm and assumed to have a Gaussian shape .

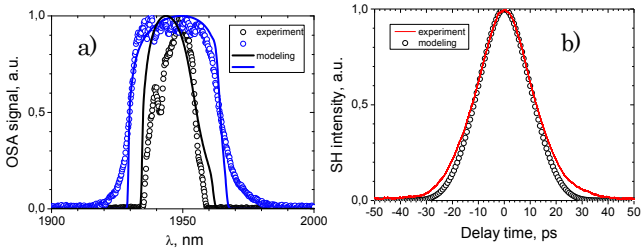


Fig.8.Experimental (open circles) and corresponded calculated (solid lines) of *a)* spectra and *b)* autocorrelation traces for monopulse ML regime. *a)* Black color for lower and Blue color for upper ML thresholds, respectively, *b)* for lower ML threshold

The modelling process initiated by the "quantum-noise" allowed us to identify the region of the monopulse operation of the oscillator. This is illustrated in Fig.8where a comparison between the experimental and theoretical spectra as well as the corresponding autocorrelation traces are presented for minimum and maximum pump power providing monopulse operation. It is worth to note that the spectral &temporalcharacteristics in this range are matching quite well with that observed in the experiment. The gain saturation energy E_{sat} was varied in the range between 0.1 and 0.4 nJ. With further increasing of E_{sat} (which is, in turn, proportional to the pump power) converging to the stable solution was not possible.

6. Conclusion

In conclusion, we presenteda detailed characterization of afiber made from anovel powder technology in the mode-locking regime

initiated by a commercially available saturable absorber. The stable self-starting operationregime could be preserved during hours when proper alignment is achieved. In terms of performance we demonstrated up to the 185 mW of average power (14 % slope efficiency, pulse energy E_p = 21 nJ) insingle pulsed regime, confirmed by the theoretical modelling of the cavity. However, an improper isolation at the laser output allows the hours-long operation of the laser at the power level less than 100 mW only and pure single-pulse regime in not stable region, still needs to be confirmed experimentally in stabilized system.Precise measurements of the pulse duration were done at 50 mW of output average power (E_p=5.6 nJ) for uncompressed pulsesin the beginning of the single-pulse regime region and at 100 mW (E_p=11 nJ) of average powerduring the compression experiment. The 11.5 ps pulseswere compressed down to 1.9 pscorresponding to a peak power P_{peak} = 1.9 kW. The bulk compression scheme did not allow increasing the peak power in compressed pulse due to the low optical efficiency of diffraction gratingsavailable in the experiment.

The presented results confirmthe interest of such kind of fibers to be implemented in potentially all-fiber schemes for operation in mode-locking regimes. Moreover, relatively high (185 mW) average power output directly at the output of the oscillator was demonstrated at wavelength of 1.96 µm.

Acknowledgments

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