Amplification of nanosecond pulses to megawatt peak power levels in Tm^{3+}-doped photonic crystal fiber rod

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We report amplification of sub-10–100 ns pulses with repetition rates from 1 to 20 kHz in a rod-type thulium-doped photonic crystal fiber with 80 μm core diameter. The rod is pumped with a 793 nm laser diode and produces the highest peak power at 1 kHz repetition rate with 6.5 ns pulse duration and more than 7 W average output power. This result exemplifies the potential of this fiber design to scale pulse peak powers and pulse energies to the megawatt and multi-millijoule range in the 2 μm wavelength regime. © 2013 Optical Society of America

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Although fiber lasers typically offer relatively high average power output, high spatial beam quality, and efficient thermal management, pulsed fiber system performance is constrained either by energy extraction or peak power limitations. The latter manifests itself in nonlinear effects, such as self-phase modulation and stimulated Raman and Brillouin scattering, as well as fiber facet damage, which are all inversely proportional to mode field area (MFA) [1]. Given the degree to which photonic crystal fiber (PCF) and the rod-type PCF have enabled ultralarge MFA scaling, such fiber designs have led to an unparalleled performance evolution of fiber laser systems based upon ytterbium doping [2].

The simplest way to generate nanosecond pulses is direct Q-switching of a laser cavity with a doped fiber as active medium. Schmidt *et al.* presented a rod-type ytterbium-doped PCF with a 70 μm diameter core that produced sub-10 ns pulses with up to 2 mJ pulse energy when actively Q switched with an acousto-optical modulator (AOM) [3]. Further power and energy scaling is possible using a master oscillator power amplifier (MOPA) configuration. Such systems incorporating very large MFA PCF rods have generated nanosecond pulses at 1 μm wavelength with near diffraction limited beam quality with more than 4 MW peak power [4] and 26 mJ pulse energy [5].

The generation of high peak power pulses in the 2 μm wavelength regime is of particular interest for pumping optical parametric oscillators/amplifiers. Considering their relatively "eye-safe" nature, thulium-based fiber laser systems are also interesting for applications such as lidar. Relative to 1 and 1.5 μm, the 2 μm wavelength leads to an increased threshold for nonlinear effects, potentially enabling greater peak power scaling; however, this has not yet been demonstrated. To date, some of the most notable achievements are the generation of Q-switched ns pulses with up to 270 μJ energy with a Tm^{3+}-doped double-clad silica fiber [6] and an all-fiber-based single-frequency system producing nanosecond pulses with over 78 kW peak power in MOPA configuration [7].

We have recently reported on the continuous wave (CW) lasing performance of a new class of flexible thulium-doped PCF with ~1017 μm^2 MFA, single-mode beam quality ($M^2 < 1.15$), and polarized output at 2 μm [8]. This fiber laser was then actively Q switched with an AOM and delivered polarized, diffraction-limited output with 435 μJ energy, 8.9 kW peak power, and ~49 ns pulse duration [9]. Subsequently, we investigated the performance of a novel thulium-doped PCF rod with 80 μm core diameter in CW lasing and amplification configurations with more than 20 W output power and near diffraction limited beam quality [10]. At the same time Jansen *et al.* reported more than 50 W output power in CW lasing with a novel 81 μm diameter core large pitch thulium-doped PCF rod design [11].

Here we present for the first time the amplification of nanosecond pulses using the same PCF rod as presented in [10] and show that multiple millijoule pulse energies with megawatt peak powers are feasible at 2 μm wavelength utilizing this PCF architecture.

Figure 1 schematically shows the experimental setup of the MOPA presented in [12] with the PCF rod in the final amplification stage. The seed oscillator consists of a 10/130 μm thulium-doped polarization maintaining (PM) fiber (Nufern) with an AOM (NEOS Technologies) as the Q switching element. The oscillator produces 100 ns pulses with 750 mW average power at a repetition rate of 20 kHz and 1965 nm wavelength. An electro-optical modulator (EOM) (Fastpulse Technologies)

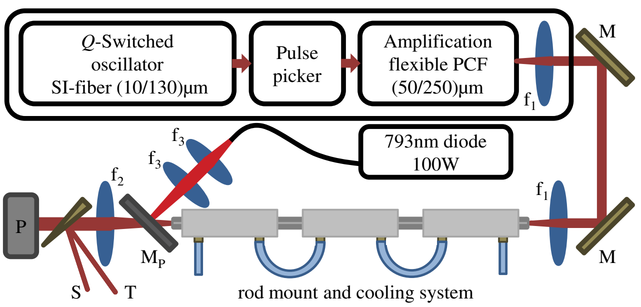

Fig. 1. (Color online) Experimental setup of the amplification system: MOPA in dashed box; lenses $f_1 = 25$ mm, $f_2 = 50$ mm, and $f_3 = 100$ mm; mirrors M HR at 2 μm; pump mirror M_P HR at 790 nm; beam-splitting wedge used for beam diagnostics.

capable of gating times <6.5 ns is utilized as a pulse slicer in order to enable greater control of repetition rate and pulse duration. An example of the pulse slicing is shown in Fig. 2, in which a pulse is cut out of the original 107 ns oscillator pulse. The created output was then coupled into a PM flexible PCF (NKT Photonics) with 50 μm core diameter. The amplified signal was first collimated by an antireflective lens ($f_1 = 25$ mm) and then directed to an identical focusing lens for coupling into the PCF rod (NKT Photonics), using two high-reflectivity (HR) mirrors (M). Passive coupling efficiencies into the PCF rod of approximately 60% were achieved and are comparable with the CW result in [10]. The rod was pumped by a 790 nm, 100 W laser diode with 200 μm diameter delivery fiber (DILAS Diode Laser). The pump beam was coupled into the rod by a 1∶1 telescope ($f_3 = 100$ mm) and a dichroic mirror (M_P) reflecting 790 nm and transmitting light at 2 μm wavelength. For diagnostic purposes, the amplified signal was subsequently split into three beams using the Fresnel reflection and transmission of a wedge. An extended InGaAs photodiode was used for the temporal characterization of the pulse. Additionally the spectrum of the output was continuously observed for all pump powers.

The maximum output powers from the flexible PCF preamplifier were determined by observing the evolution of the spectrum and the pulses with increasing pump power. An extracavity electro-optic pulse picker (Quantum Technologies) was used to confirm that at least 88% of the energy was confined in the pulse. According to our observations the average power was then limited to 66 μJ/250 μJ at 6 ns and 10 kHz/1 kHz. When the flexible PCF was not seeded, the ASE output was <40 mW for 80 W maximum pump power.

The amplification in the PCF rod was investigated for 20, 10, and 1 kHz repetition rate. Measurements of the average output power for different launched pump powers are shown in Fig. 3. The calculated slope efficiencies for different combinations of repetition rates and pulse widths (100 ns or 6.5 ns FWHM) are summarized in Table 1. The slope efficiency decreases with repetition rate and pulse duration, with a maximum slope efficiency of 16.8% at 20 kHz and 1965 nm, as compared to the CW result of 20.1% at 1960 nm found in [10]. Based upon the large reduction in slope efficiency associated with the change in repetition rate from 20 to 10 kHz at 100 ns pulse duration and given the seeded pulse energy was kept constant at approximately 200 μJ, it is clear the

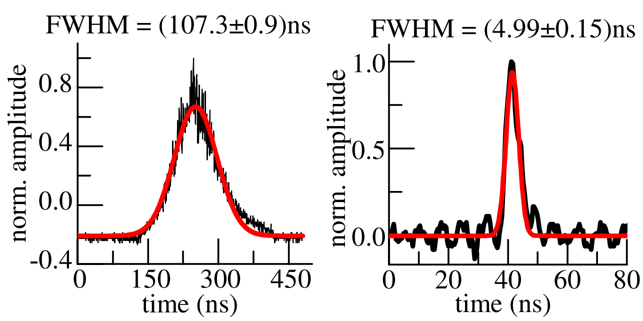

Fig. 2. (Color online) Creation of 5 ns pulses using an EOM as pulse slicer; FWHM was determined with Gaussian fits.

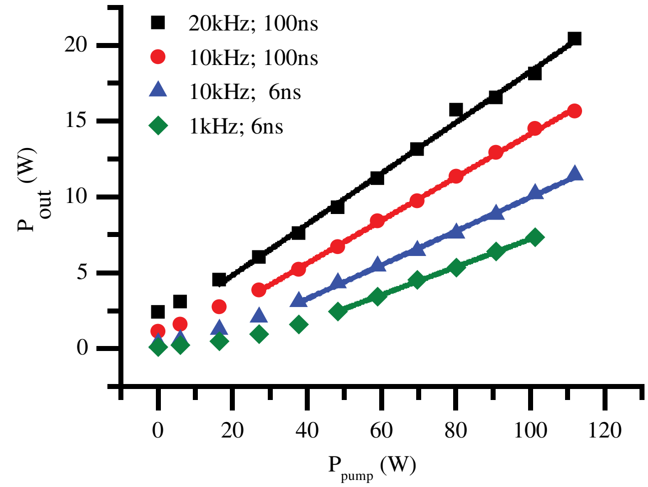

Fig. 3. (Color online) Output power over launched pump power for different repetition rates and pulse durations.

Table 1. Seed Powers and Slope Efficiencies for Different Repetition Rates and Pulse Durations

f (kHz)	Seed Power (W)	Pulse Width (ns)	Slope Efficiency (%)	Error (%)
20	4	100	16.8	0.4
	2	100	14.2	0.2
10	0.66	6	11.2	0.2
1	0.25	6	9.2	0.2

primary effect on slope efficiency is the duty cycle of the amplifier. With 6.5 ns pulse duration, the maximum average output power was 10.2 and 7.3 W at 10 and 1 kHz, respectively.

In Fig. 4 the spectrum of the signal at 1 kHz, 6.5 ns, shows ASE at −30 dB from the peak and a narrow peak with 1 nm width (FWHM). The ratio of spectrally integrated ASE to pulse average power was found to be smaller than 2.7%. The inset in Fig. 4 displays the pulse in the temporal domain with a measured duration of 6.31 ns. The temporal profile of the pulse is accompanied with

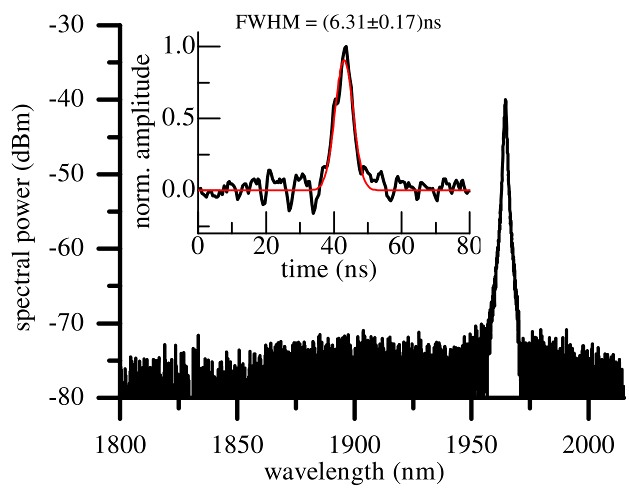

Fig. 4. (Color online) Spectrum and pulse at 7.3 W average power and 1 kHz repetition rate. The ratio between spectrally integrated ASE and average power is always <3%.

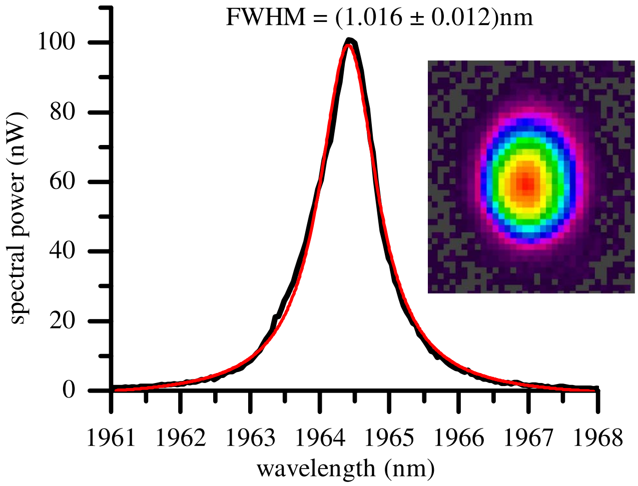

Fig. 5. (Color online) Linear plot of the spectrum and image of output beam at 7.3 W average power and 1 kHz repetition rate.

a modulation, which is associated with electrical noise from the high-voltage driver for the pulse slicer and not the optical pulse. A linear plot of the spectral peak with a Lorentzian fit to determine the FWHM is depicted in Fig. 5, along with an image of the collimated beam (inset). The beam quality is consistent with that observed in [10], corresponding to an M^2 of ~1.3. At pump powers of 100 W, the cladding light power did not exceed 10% of the total average power.

Based simply upon the output power, repetition rate, 10% cladding light, Gaussian pulse shape, and 97% of the signal power contained in the pulse, the output at 6.5 ns corresponds to 1 mJ/6.4 mJ pulse energy and 150 kW/0.92 MW peak power for 10 kHz/1 kHz, respectively. In order to validate this impressive result, we utilized an energy meter and pulse picker after the output of the PCF rod to temporally isolate the pulses from possible ASE content. Without seeding the rod, the ASE content did not exceed 500 mW at 100 W pump power. Taking all factors into account, the maximum peak power is at least 0.89 MW in the worst case.

Unfortunately the pump end facet of the rod was damaged before a complete data set could be collected, but initial indications support our analysis. Interestingly, the facet damage occurred at ~1.5 W output power (50 W pump) and 1 kHz repetition rate. Because the given level is approximately 5 times lower than the maximum achieved, we believe that the damage was caused by contamination of the fiber end facet.

The absence of roll-off or energy saturation proves this novel thulium-doped PCF rod is capable of greater power scaling. Likewise, we see no evidence of nonlinear spectral or temporal pulse degradation. Careful analysis confirms we have achieved megawatt-level peak power with multi-millijoule pulse energies in the 2 μm wavelength regime. To the best of our knowledge, the presented result is to date the highest peak power generated in a thulium fiber laser.

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References

1. D. J. Richardson, J. Nilsson, and W. A. Clarkson, J. Opt. Soc. Am. B **27**, B63 (2010).
2. A. Tünnermann, T. Schreiber, and J. Limpert, Appl. Opt. **49**, F71 (2010).
3. O. Schmidt, J. Rothhardt, F. Röser, S. Linke, T. Schreiber, K. Rademaker, J. Limpert, S. Ermeneux, P. Yvernault, F. Salin, and A. Tünnermann, Opt. Lett. **32**, 1551 (2007).
4. C. D. Brooks and F. Di Teodoro, Appl. Phys. Lett. **89**, 111119 (2006).
5. F. Stutzki, F. Jansen, A. Liem, C. Jauregui, J. Limpert, and A. Tünnermann, Opt. Lett. **37**, 1073 (2012).
6. M. Eichhorn and S. D. Jackson, Opt. Lett. **32**, 2780 (2007).
7. Q. Fang, W. Shi, K. Kieu, E. Petersen, A. Chavez-Pirson, and N. Peyghambarian, Opt. Express **20**, 16410 (2012).
8. N. Modsching, P. Kadwani, R. A. Sims, L. Leick, J. Broeng, L. Shah, and M. Richardson, Opt. Lett. **36**, 3873 (2011).
9. P. Kadwani, R. A. Sims, L. Leick, J. Broeng, L. Shah, and M. Richardson, in *2012 Solid State Diode Laser Technology Review Technical Digest* (Directed Energy Professional Society, 2012).
10. C. Gaida, P. Kadwani, L. Leick, J. Broeng, L. Shah, and M. Richardson, Opt. Lett. **37**, 4513 (2012).
11. F. Jansen, F. Stutzki, C. Jauregui, J. Limpert, and A. Tünnermann, Opt. Lett. **37**, 4546 (2012).
12. P. Kadwani, A. Sims, L. Leick, J. Broeng, L. Shah, and M. Richardson, in *Specialty Optical Fibers*, OSA Technical Digest (online) (Optical Society of America, 2012), paper SW2F.3.