# *Q*-switched thulium-doped photonic crystal fiber laser

**Pankaj Kadwani,[1,*] Norbert Modsching,[1,2] R. Andrew Sims,[1] Lasse Leick,[3]
Jes Broeng,[3] Lawrence Shah,[1] and Martin Richardson[1]**

[1]*Townes Laser Institute and CREOL, The College of Optics and Photonics,
4000 Central Florida Boulevard, Orlando, Florida 32816, USA*

[2]*West Saxon University of Applied Sciences, Dr.-Friedrichs-Ring 2a, Zwickau 08056, Germany*

[3]*NKT Photonics A/S, Blokken 84, DK-3460 BirkerØd, Denmark*
**Corresponding author: pkadwani@creol.ucf.edu*

Received January 6, 2012; revised March 6, 2012; accepted March 7, 2012;
posted March 12, 2012 (Doc. ID 160737); published May 9, 2012

We report a novel, Tm-doped photonic crystal fiber (PCF) actively *Q*-switched oscillator that provides ~8.9 kW peak power with 435 μJ, 49 ns pulses at 10 kHz repetition rate at 2 μm wavelength. This fiber has a mode-field area >1000 μm$^2$, the largest of any flexible PCF providing diffraction-limited beam quality to the best of our knowledge. As an application, the oscillator is used as pump to generate >350 nm broadening in ~50 m of SMF-28 fiber. © 2012 Optical Society of America

*OCIS codes:* 140.3510, 060.5295, 140.3540.

Pulsed Tm fiber-based laser systems operating in the "eye-safe" wavelength region ($\lambda > 1.4$ μm) are promising for applications such as light detection and ranging (lidar), differential absorption lidar, and as pumps for mid-IR generation. Fiber lasers are particularly attractive for such applications because the beam quality can be independent of output power and they can be robustly engineered. Although they are an excellent choice for high average powers, obtainable pulse energy is limited by nonlinearities like stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) due to long interaction lengths and small mode areas. Novel fiber designs aimed at increasing modal area have been realized at 1 μm [1], but there is significant room for development of advanced fiber architecture for operation at the 2 μm wavelength.

State-of-the-art nanosecond Tm:fiber laser development is exemplified by the laser system described by Creeden *et al.*, a gain-switched Tm:fiber master oscillator power amplifier system for pumping a ZGP optical parametric oscillator (OPO) [2]. Although this system produced ~6.6 kW peak power with 30 ns pulses at 20 W average power at 2 μm wavelength, only ~60% of the output power was linearly polarized, and thus useful for OPO pumping. Polarized gain-switched Tm:fiber laser systems have achieved pulse durations as short as 25 ns; however, pulse energies were limited to 35 μJ [3] and 100 μJ [4]. *Q*-switching has also been used in Tm-doped silica fiber laser systems, producing 2.3 mJ, 320 ns pulses with an electro-optic modulator [5] and 270 μJ, 41 ns pulses with an acousto-optic modulator (AOM) [6]. However, in both of these cases, the large mode area (LMA) fiber was not polarization maintaining (PM) and the output was not polarized.

In previous attempts to generate high peak power pulses by *Q*-switching a Tm-doped, PM-LMA fiber laser with 25 μm diameter core and 400 μm cladding (Nufern), we were limited to peak power <2.5 kW with 125 ns, 300 μJ pulses [7]. Efforts to increase the peak power further were frustrated by increasing higher order mode content with increasing gain when using LMA fiber in a *Q*-switched oscillator configuration. Pulses have been amplified to greater than 10 s of kW peak power as in [8], but to amplify transform-limited pulses, complex, multi-step amplification architecture is required [9].

Relative to conventional step-index fibers, photonic crystal fibers (PCFs) offer significantly larger mode area while maintaining single-mode beam quality, thus increasing damage and other detrimental nonlinear thresholds. We have recently reported on the continuous wave (CW) performance of a new class of Tm-doped PCF fiber lasers with ~1017 μm$^2$ mode field area, single-mode beam quality ($M^2 < 1.15$), and polarized output at 2 μm [10]. Here, we report for the first time the *Q*-switched operation of this PCF fiber laser, demonstrating polarized, diffraction-limited output with 435 μJ energy and ~49 ns pulse duration. The ~8.9 kW peak power of this polarized source is to the best of our knowledge the highest reported in a Tm-doped, *Q*-switched fiber oscillator [6,7,11]. This polarized source is particularly promising as a pump for mid-IR generation. We demonstrate this by producing supercontinuum emission from 1.95–2.35 μm in SMF-28 fiber with this laser.

The system is configured as a copropagating, end-pumped cavity (Fig. 1). The pump is a 100 W, 793 nm diode laser (DILAS) delivered by a 200 μm, 0.22 NA fiber. The pump is launched into the PCF using a 1∶1 telescope and the reflection from a dichroic mirror (HR at 790 nm, HT at 2000 nm) with a launch efficiency of ~82%. The intracavity optics include a 26 mm triplet lens for laser collimation, a polarizing beam cube and a halfwave plate for polarization control [10], an AOM for active

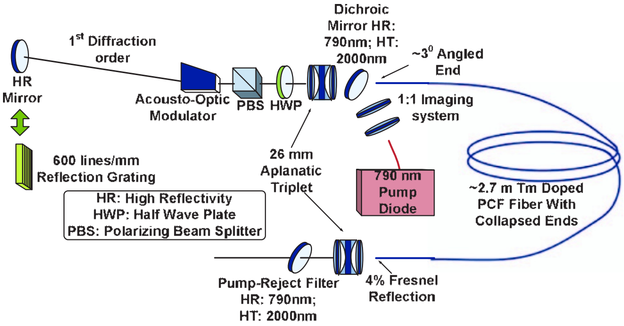

Fig. 1. (Color online) Schematic of the *Q*-switched oscillator.

$Q$-switching, and a highly reflective end mirror. The intracavity facet was angle cleaved to ~3° to reduce feedback, whereas the opposite fiber facet was flat cleaved, forming an output coupler from the ~4% Fresnel reflection.

The PCF in these experiments (fabricated by NKT Photonics A/S) is identical to that in [10], except the length was ~2.7 m. The 50 $\mu$m diameter (~0.04 NA) core is doped with 2.5 wt. % $Tm_2O_3$. The 250 $\mu$m diameter signal cladding consists of a hexagonal lattice of air holes with hole size to pitch ratio ($d/\Lambda$) of 0.18 and a pitch of 12.8 $\mu$m, surrounded by circular air cladding with >0.45 NA for the pump. The measured pump absorption is ~5.8 dB/m, higher than standard Tm LMA fiber despite the lower Tm dopant level because of the larger core/cladding overlap. Correspondingly, the total pump absorption was >15.6 dB, implying that a shorter PCF could have been used (and thus, shorter pulses generated) without efficiency penalty. However, we kept the fiber longer to better suppress high-order modes (hence, improving beam quality) via bending. The PCF incorporates boron-doped stress elements to induce birefringence ($>10^{-4}$) in the core, which yielded a polarizing behavior [12] as the PCF operated single mode. An intracavity cube polarizer was added to improve the polarization extinction ratio for core light from ~15 dB ex-fiber to >18 dB.

The PCF end facets were prepared by first collapsing the air holes using a Vytran GPX-3400 Glass Processing Station and then cleaving using a Vytran LDC-200 cleaver. The PCF was coiled to a ~35 cm bend diameter with the first ~28 cm placed in a water-cooled $V$-groove while the remaining >2.4 m was cooled with forced air.

The slope efficiencies for the total output power were 25.9%, 31.9%, and 33% for 10, 20, and 50 kHz, respectively (Fig. 2) with no roll-off. As observed in CW operation [9], the system shows excellent PM/polarizing properties with single-mode beam quality. The $M^2$ was measured to be <1.15 at all power levels.

Figure 3 plots the usable output, which we define as that light which is transmitted through a polarizing beam cube after eliminating any signal light propagating in the cladding with an aperture. The usable power is consistently above 80% of the total output power in all circumstances. As in [10], this includes ~8% cladding light losses and about 8%–10% transmission losses associated with the half wave plate and beam cube.

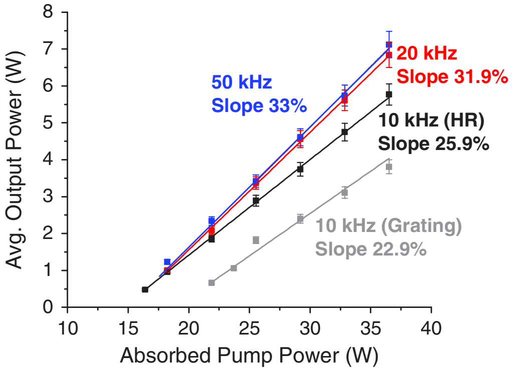

Fig. 2. (Color online) Total average power for $Q$-switched operation at 10, 20, and 50 kHz repetition rates with HR mirror as feedback element. The slope is also shown with reflection grating, producing narrow-linewidth output at 1998 nm and 10 kHz repetition rate.

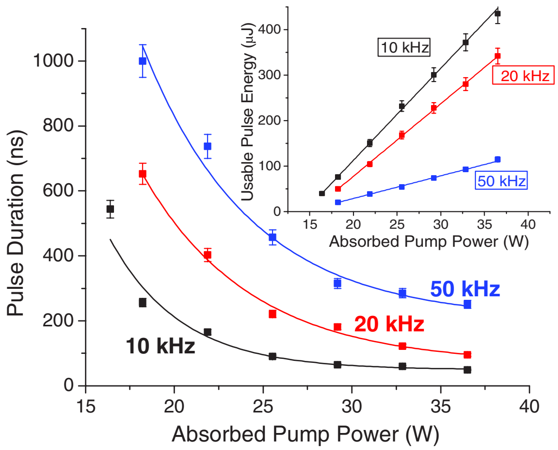

Fig. 3. (Color online) Variation of pulse duration and pulse energy (inset) with absorbed pump power.

Maximum peak power and pulse energy (~8.9 kW and ~435 $\mu$J, respectively, for 49 ns pulses) were obtained at the 10 kHz repetition rate. For the same pump power (~37 W), pulse energies of 340 and 115 $\mu$J were also obtained for 20 and 50 kHz, respectively. Operation at lower repetition rates was increasingly unstable (30%–40% pulse-to-pulse amplitude jitter at 1 kHz), and thus not pursued.

To prevent quantum-defect heating from softening/melting the polymer coating near the fiber facet, we kept the absorbed pump power<40 W, which presently limits our laser performance. The excess heat stems from the relatively low PCF optical efficiency, in turn ascribed to the PCF lower Tm doping concentration compared to standard LMA fibers (~2.5 versus ~4 wt. %) and insufficient cooling of the fiber. We have so far not reached the limits in pulsed operation, but we estimate ~2 mJ will be sufficient to cause facet damage for ~50 ns pulses with the current fiber facet treatment. The lowest nonlinear threshold is for SBS, which we estimate to occur at ~32 kW peak power assuming a linewidth of ~0.1 nm at 2 $\mu$m. SRS thresholds are about an order of magnitude higher than SBS owing to lower Raman gain in silica.

One of the advantages of this source as a pump for mid-IR generation source lies in its broad tunability, taking advantage of the wide Tm emission bandwidth. We have verified the tunability of this source by replacing the HR mirror with a 600 lines/mm, gold-coated reflection grating blazed for 1900 nm (Fig. 4). We have demonstrated similar tuning behavior in a Tm-doped single mode 10/130 $\mu$m PM fiber oscillator [13]. The water absorption lines are seen in the amplified spontaneous emission (ASE) spectrum due to the humidity in the free space section in the cavity and in the optical spectrum analyzer (Yokogawa Co.). Using the grating, the highest peak power was achieved at 1995 nm and 10 kHz repetition rate, where it produced 67 ns, ~6 kW pulses (400 $\mu$J pulse energy).

To demonstrate the utility of this laser as a pump for mid-IR supercontinuum generation, we collected the output spectrum after transmission through SMF-28 optical fiber by cutting back the fiber from 50 m to 25, 10, and

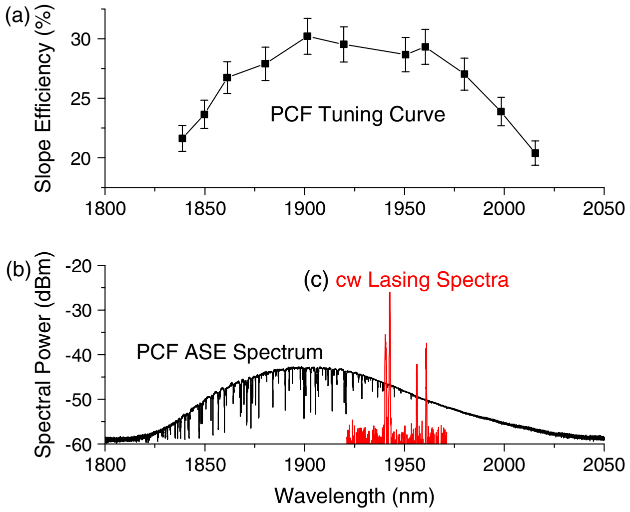

Fig. 4. (Color online) (a) Variation of CW slope efficiency with wavelength, (b) ASE output spectrum of the PCF (black), and (c) CW lasing spectra with HR as feedback at 2 W output (red).

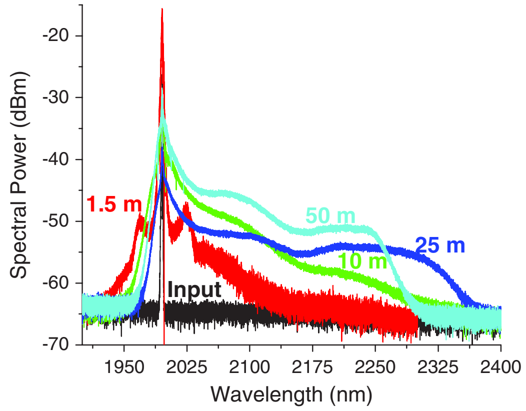

Fig. 5. (Color online) Evolution of spectral broadening in SMF-28 at 1.5, 10, 25, and 50 m. The onset of modulation instability is seen at 1.5 m (red), broadening at 25 m (dark blue) extending to 2350 nm, and cutting back of broadening at 50 m (light blue) to 2250 nm.

1.5 m, respectively. Figure 5 shows the evolution of the continuum from the onset of broadening due to occurrence of modulation instability in the fiber at 1.5 m length, smoothing and red shifting to 2300 nm at 10 m length, and reaching a maximum wavelength of 2350 nm at 25 m length. At 50 m, the maximum wavelength reduces to 2300 due to the $>0.03$ dB/m absorption of silica beyond $\sim$2300 nm.

Given the very simple setup utilized in these experiments, the spectral broadening induced by this $Q$-switched oscillator with 6 kW peak power compares favorably to that of Kulkarni *et al.* [14] who used multistep amplification to generate $>15$ kW peak power and multistage spectral broadening processes for mid-IR generation beyond 4 $\mu$m.

We have demonstrated $Q$-switching in a Tm-doped PCF laser for the first time, and we have investigated the potential of this unique laser source as a pump for supercontinuum generation. The combination of single mode, large mode area, polarization purity, broad spectral tunability, and large extractable energies make Tm-doped PCF an excellent candidate for fiber lasers producing high peak power pulses at the 2 $\mu$m wavelength.

The authors acknowledge the support of the Department of Defense (DOD) High Energy Laser Joint Technology Office (JTO) through the Multidisciplinary Research Initiative (MRI) program (contract #W911NF-05-1-0517), the State of Florida, and the European Commission through project IMPROV (Grant Agreement number 257894).

## References

1. O. Schmidt, J. Rothhardt, T. Eidam, F. Röser, J. Limpert, A. Tünnermann, K. P. Hansen, C. Jakobsen, and J. Broeng, Opt. Express **16**, 3918 (2008).
2. D. Creeden, M. Jiang, P. A. Budni, P. A. Ketteridge, S. D. Setzler, Y. E. Young, J. C. McCarthy, P. G. Schunemann, T. M. Pollak, P. Tayebati, and E. P. Chicklis, Proc. SPIE **6952**, 69520S (2008).
3. N. Simakov, A. Hemming, S. Bennetts, and J. Haub, Opt. Express **19**, 16 (2011).
4. G. Frith, T. McComb, B. Samson, W. Torruellas, M. Dennis, A. Carter, V. Khitrov, and K. Tankala, in *Advanced Solid State Photonics*, OSA Technical Digest Series (Optical Society of America, 2009), paper WB5.
5. A. F. El-Sherif and T. A. King, Opt. Commun. **218**, 337 (2003).
6. M. Eichhorn and S. D. Jackson, Opt. Lett. **32**, 19 (2007).
7. C. C. C. Willis, L. Shah, M. Baudelet, P. Kadwani, T. S. McComb, R. A. Sims, V. Sudesh, and M. Richardson, Proc. SPIE **7580**, 758003 (2010).
8. Y. Tang, L. Xu, Y. Yang, and J. Xu, Opt. Express **18**, 22964 (2010).
9. W. Shi, E. Petersen, Q. Fang, K. Kieu, A. Chavez-Pirson, N. Peyghambarian, and J. Yu, in *Lasers, Sources, and Related Photonic Devices*, OSA Technical Digest Series (Optical Society of America, 2012), paper FTh4A.1.
10. N. Modsching, P. Kadwani, R. A. Sims, L. Leick, J. Broeng, L. Shah, and M. Richardson, Opt. Lett. **36**, 3873 (2011).
11. M. Eichhorn and S. D. Jackson, Opt. Lett. **33**, 1044 (2008).
12. T. Schreiber, F. Roser, O. Schmidt, J. Limpert, R. Iliew, F. Lederer, A. Petersson, C. Jacobsen, K. Hansen, J. Broeng, and A. Tunnermann, Opt. Express **13**, 19 (2005).
13. T. S. McComb, R. A. Sims, C. C. C. Willis, P. Kadwani, V. Sudesh, L. Shah, and M. Richardson, Appl. Opt. **49**, 6236 (2010).
14. O. P. Kulkarni, V. V. Alexander, M. Kumar, M. J. Freeman, M. N. Islam, F. L. Terry Jr., M. Neelakandan, and A. Chan, J. Opt. Soc. Am. B **28**, 2486 (2011).