All fiber-based Yb-doped high energy, high power femtosecond fiber lasers

Peng Wan,* Lih-Mei Yang, and Jian Liu

PolarOnyx, Inc., 2526 Qume Drive, Suite 17 & 18, San Jose, CA, 95131, USA
**pwan@polaronyx.com*

Abstract: Two all fiber-based laser systems are demonstrated to achieve high energy and high average power femtosecond pulsed outputs at wavelength of 1 μm. In the high energy laser system, a pulse energy of 1.05 mJ (0.85 mJ after pulse compressor) at 100 kHz repetition rate has been realized by a Yb-doped ultra large-core single-mode photonic crystal fiber (PCF) rod amplifier, seeded with a 50 μJ fiber laser. The pulse duration is 705 fs. In the high average power experiment, a large mode area (LMA) fiber has been used in the final stage amplifier, seeded with a 50 W mode locked fiber laser. The system is running at a repetition rate of 69 MHz producing 1052 W of average power before compressor. After pulse compression, a pulse duration of 800 fs was measured.

OCIS codes: (140.4050) Mode-locked lasers; (140.3510) Lasers, fiber; (140.3070) Infrared and far-infrared lasers; (320.5550) Pulses; (060.2390) Fiber optics, infrared; (060.2320) Fiber optics amplifiers and oscillators.

References and links

1. J. Limpert, N. Deguil-Robin, I. Manek-Hönninger, F. Salin, F. Röser, A. Liem, T. Schreiber, S. Nolte, H. Zellmer, A. Tünnermann, J. Broeng, A. Petersson, and C. Jakobsen, "High-power rod-type photonic crystal fiber laser," Opt. Express **13**(4), 1055–1058 (2005).
2. T. Eidam, S. Hanf, E. Seise, T. V. Andersen, Th. Gabler, Ch. Wirth, Th. Schreiber, J. Limpert, and A. Tünnermann, "Femtosecond fiber CPA system emitting 830 W average output power," Opt. Lett. **35**(2), 94–96 (2010).
3. A. Klenke, E. Seise, S. Demmler, J. Rothhardt, S. Breitkopf, J. Limpert, and A. Tünnermann, "Coherently-combined two channel femtosecond fiber CPA system producing 3 mJ pulse energy," Opt. Express **19**(24), 24280–24285 (2011).
4. A. Klenke, S. Breitkopf, M. Kienel, T. Gottschall, T. Eidam, S. Hädrich, J. Rothhardt, J. Limpert, and A. Tünnermann, "530 W, 1.3 mJ, four-channel coherently combined femtosecond fiber chirped-pulse amplification system," Opt. Lett. **38**(13), 2283–2285 (2013).
5. Z. Liu, L. Shah, I. Hartl, G. C. Cho, and M. E. Fermann, "High-energy fiber chirped-pulse amplification system based on cubicons," Proceedings of the Conference on Lasers and Electro-Optics (Baltimore, May 2005), paper CThG4.df.
6. P. Wan, L. M. Yang, and J. Liu, "156 micro-J Ultrafast Thulium-Doped Fiber Laser," SPIE Photonics West 8601–117, February 2–7, 2013, San Francisco, CA, USA.
7. J. Liu, H. Huang, and L. Yang, "High Energy Ultrafast Fiber Lasers and Applications,"(Invited Paper) 2012 OSA Laser and Tera-Hertz Science and Technology (LTST) meeting, November 1–2, 2012, Wuhan, China.
8. A. Galvanauskas, "Mode-scalable, fiber-based, chirped-pulse amplification systems," IEEE J. Sel. Top. Quantum Electron. **7**(4), 504–517 (2001).
9. F. O. Ilday, H. Lim, J. R. Buckley, and F. W. Wise, "Practical all-fiber source of high-power, 120-fs pulses at 1 micrometre," Opt. Lett. **28**(15), 1362–1364 (2003).
10. L. Shah, Z. Liu, I. Hartl, G. Imeshev, G. Cho, and M. Fermann, "High energy femtosecond Yb cubicon fiber amplifier," Opt. Express **13**(12), 4717–4722 (2005).
11. J. Liu and L. Yang, "Ns and fs Fiber Lasers," (Invited Talk), FILAS 2011, February 16–18, 2011, Turkey.
12. http://www.polaronyxlaser.com/
13. J. Liu, "Nonlinear polarization pulse shaping model locked fiber laser at one micron with photonic crystal (PC), photonic bandgap (PBG), or higher order mode (HOM) fiber," PolarOnyx Inc., US patent 7,529,278 B2(2009).
14. J. Liu and J. Xia, "All fiber laser solution for spectral broadening and pulse stretching in a chirped pulse amplification fiber system," PolarOnyx Inc., US patent 7,440,173 (2008).
15. J. Liu, "Nonlinear polarization pulse shaping mode locked fiber laser at one micron," PolarOnyx Inc., US patent 7,526,003 (2009).

#197166 - $15.00 USD Received 5 Sep 2013; revised 14 Nov 2013; accepted 21 Nov 2013; published 26 Nov 2013

1. Introduction

An ideal high energy and/or high power ultrafast fiber laser should include all fiber based seed oscillator, stretcher, and amplifiers. The connection between components (fiber combiner, gain fiber, isolators, etc.) should be done primarily by fiber splicing to provide robust operation. Free space components should be minimized. All fiber based femtosecond fiber laser has been widely accepted as a revolutionary source for a variety of applications, such as high energy physics and material micro-processing, due to its compactness, energy saving, and cost effectiveness.

However, high energy mJ and kW level femtosecond fiber lasers are still in research stage. Although average power at kW level and pulse energy at mJ level were demonstrated by using solid state seed oscillator, bulk grating stretcher, and photonic crystal fiber (PCF) rods [1–4], it is very challenging to make these hybrid approaches for practical applications due to complexity and reliability in integrating many discrete subsystem and components.

In an all fiber based femtosecond fiber laser system, due to the difficulties in handling nonlinearity accumulated in fibers and fiber amplifiers, the energy scaling has experienced significant challenges over those hybrid approaches and experimental demonstration has been limited in 100's μJ level and average power in 100 W level [5–11]. L. Shah et al. used an all fiber based chirped pulse amplification (CPA) system to boost the pulse energy to 200 μJ before compression at a wavelength of 1040 nm and pulse repetition rate of 50 kHz. The last amplifier used a 40 μm core size of PCF. After compression, pulse energy of 100 μJ was achieved with a pulse width at 650 fs and average power at 5 W [10]. In our previous work, an all fiber based CPA system was demonstrated to achieve pulse energy of 100μJ and an average power of 100W at central wavelength of 1030 nm with a pulse duration of 600 fs and repetition rate of 1 MHz [11]. An integrated pump combiner with a 35 μm core size PCF was used.

In this paper, we present the most recent progress on scaling all fiber based femtosecond fiber laser systems to achieve an average power of above 1 kW and a pulse energy of above 1 mJ respectively. Mode-locked pulses were generated directly from all fiber-based high energy/high power lasers. In the high energy experiment, an Yb-doped, ultra large-core, single-mode PCF rod, seeded with a 50 μJ chirped pulse fiber laser, has been used to boost the pulse energy to 1.05 mJ at 100 kHz repetition rate. After pulse compressor, a pulse duration of 705 fs was obtained. In the high average power experiment, a final stage large mode area (LMA) fiber amplifier, seeded with a 50 W chirped pulse fiber laser at a pulse repetition rate of 69 MHz, a has been used to produce 1.05 kW of average power before compressor. After pulse compression, a pulse duration of 800 fs was measured. Both 1.05 kW average power and 1.05 mJ pulse energy are the highest record from all fiber-based femtosecond laser systems to the best of our knowledge.

This progress is one step closer towards achieving both mJ pulse energy and kW average power in single all fiber based femtosecond fiber laser system.

2. One millijoule level femtosecond fiber laser

2.1 One millijoule experiment setup

The setup for the 1 μm high energy femtosecond laser system is shown in Fig. 1. It consists of a 50 μJ seeding laser at 1 μm, a high energy amplifier and a pulse compressor (not shown in Fig. 1). The seeding laser is a 1 μm high energy mode-locked femtosecond fiber laser, which is commercially available (Uranus series, PolarOnyx Laser Inc.) [12–15]. The laser outputs stretched pulses with pulse durations of around 1.2 ns. The laser repetition rate is tunable between 100 kHz and 2 MHz with the maximum output power of 5 W. The highest pulse energy is 50 μJ at a repetition rate of 100 kHz. The active medium in the energy amplifier is an 80 cm-long single-mode Ytterbium-doped polarization maintaining (PM) Rod-type PCF with ultra large mode area from NKT Photonics. It has a core diameter of 100 μm and a pump

#197166 - $15.00 USD Received 5 Sep 2013; revised 14 Nov 2013; accepted 21 Nov 2013; published 26 Nov 2013

cladding diameter of 285 μm. The collimated seeding laser beam is first passing an isolator, then focused and injected into the PCF by a spherical lens with a focal length of 35 mm. Reverse pumping scheme is used in this experiment. Up to 174 W, 976 nm pump power from laser diodes is injected from the other end of the PCF. The pump beam is delivered by an optical fiber with core diameter of 242 μm. Pump beam is collimated and then re-focused into the gain medium by two aspherical lenses with focal length of 11 mm. Multiple dichroic mirrors are used to protect the pump laser diodes from the possible damage due to high peak power signal wavelengths. The overall isolation is greater than 30 dB for signal wavelengths in the experiment setup. No extra cooling method is applied to the PCF Rod.

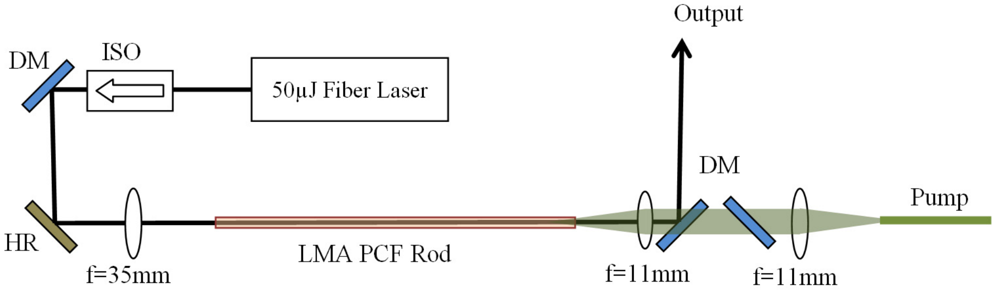

Fig. 1. Systematic diagram of 1 μm high energy fiber laser system. DM:Dichroic Mirror; ISO:Isolator.

2.2 One millijoule experiment results

The system was operated at three different repetition rates of 100 kHz, 500 kHz and 1 MHz in this experiment. When the seeding laser was set to the maximum output power level, an average power of 4.4 W was injected into the PCF. Figure 2 shows the output power and pulse energy as functions of the pump power at different repetition rates. Output power of around 105 W was obtained at all three repetition rates. And a pulse energy of up to 1.05 mJ was achieved at repetition rate of 100 kHz. Optical slope efficiencies of 68% were measured at all repetition rates.

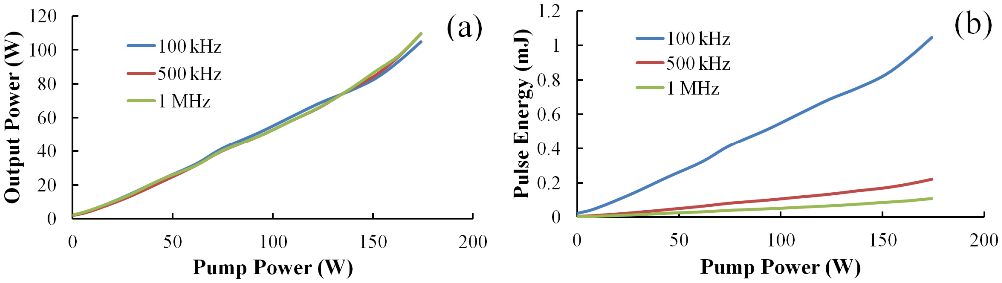

Fig. 2. (a) Output power and (b) Pulse energy as functions of pump power at various repetition rates.

Figure 3 shows the output spectra at various pulse energies. The spectrum of seeding laser was also plotted in the same figure as a comparison. The spectrum bandwidth of seeding laser was 17.5 nm, and it was slightly narrowed to 16.7 nm and 14.5 nm at amplified pulse energy levels of 0.76 mJ and 1.05 mJ respectively. This was mainly due to the gain narrowing effect. Output beam quality at the highest output pulse energy was evaluated. Beam diameters measured as functions of distance from the beam waist were plotted in Fig. 4. The best-fit M^2 values were 1.17 (parallel) and 1.27 (perpendicular).

#197166 - $15.00 USD Received 5 Sep 2013; revised 14 Nov 2013; accepted 21 Nov 2013; published 26 Nov 2013

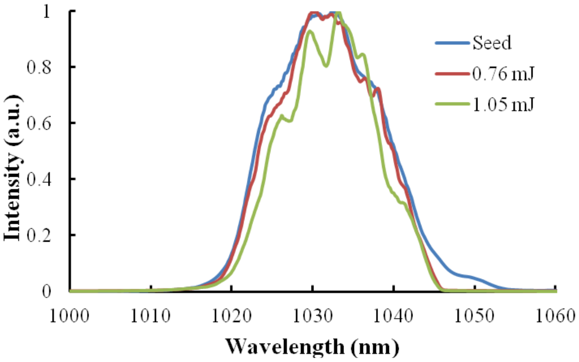

Fig. 3. Spectra of seeding laser and amplified output at various energy levels.

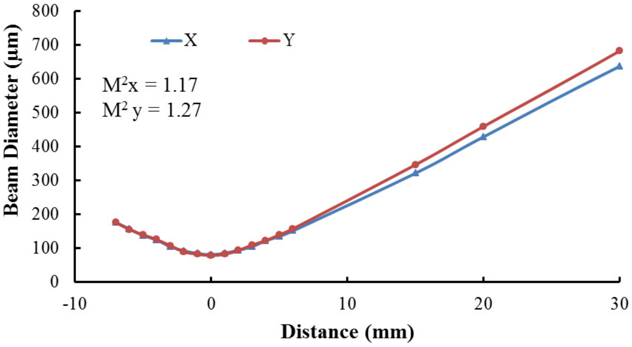

Fig. 4. M^2 measurements: Beam diameters as functions of distance from laser beam waists.

The output beam was compressed in a grating pulse compressor with a grating efficiency of 95%. After compression, a pulse duration of 705 fs was measured with the maximum amplified pulse energy of 1.05 mJ and a pulse energy of 0.85 mJ was obtained after the compressor. By improving the grating efficiency to 98%, compressed 1 mJ pulse energy can be readily achieved. The autocorrelation trace is shown in Fig. 5(a). Figure 5(b) shows the measured pulse durations at various amplified pulse energies. The pulse compressor was optimized for the highest pulse energy. Without tuning the compressor, the duration was slightly varied between 700 fs and 800 fs at all amplified pulse energy levels. By further increase pump power and control the thermal issues, femtosecond pulses with higher pulse energy (multi-mJ) are expected.

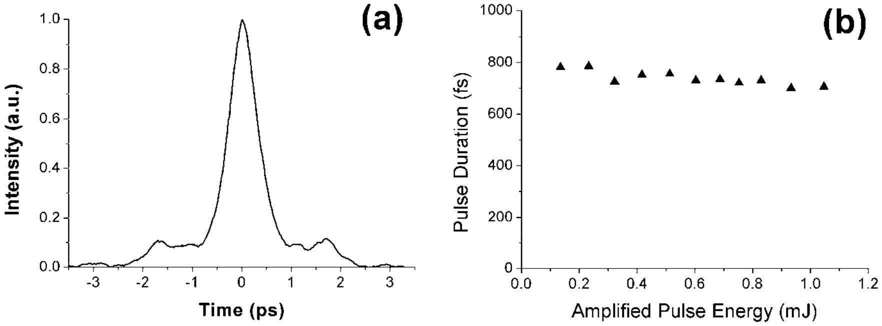

Fig. 5. (a) Autocorrelation trace of the output beam with amplified pulse energy of 1.05 mJ; (b) Output pulse durations at various amplified energy levels.

#197166 - $15.00 USD Received 5 Sep 2013; revised 14 Nov 2013; accepted 21 Nov 2013; published 26 Nov 2013

3. One kilowatt level fiber femtosecond laser

3.1 One kilowatt experiment setup

In another experiment, an all fiber based system was built to boost laser output power to 1.05 kW. The design of 1 kW fiber laser system is shown in Fig. 6. It consists of a 1 µm seeding laser and a high power amplifier based on LMA fiber. The seeding laser is a commercially available high power mode-locked femtosecond fiber laser (Uranus series, PolarOnyx Laser Inc.) [10–15]. The average power from the seeding laser is 50 W. It generates pulses with central wavelengths of 1064 nm at a repetition rate of 69 MHz. The compressor of the seeding laser is removed, thus the output pulses are stretched with pulse durations of around 1 ns. The active medium in the high power amplifier is an 8 m-long PM double cladding LMA fiber with a core diameter of 30 µm (Nufern PLMA-YDF-30/400-VIII). The gain fiber is pumped by 976 nm diode lasers with a total pump power of 1600 W. Bi-directional pumping scheme is chosen for the kW fiber amplifier. From each side of the gain fiber, 800 W, 976 nm pump power is injected into the gain fiber through a high power pump/signal combiner. A small portion of output beam is reflected by a fused silica prism for the output beam characterization.

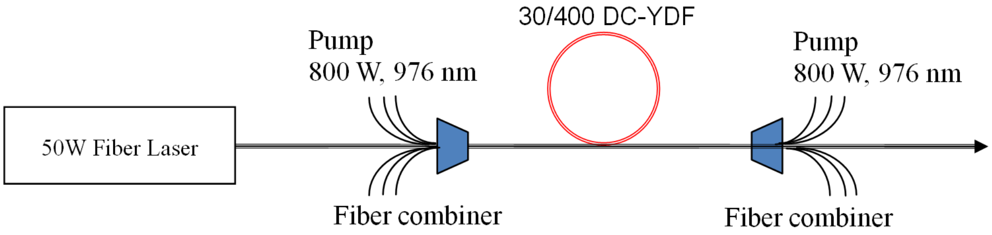

Fig. 6. Systematic diagram of 1 µm femtosecond kW fiber laser system.

3.2 One kilowatt experiment results

The seeding laser was set to the maximum output power level of 50 W. The output power as a function of pump power is shown in Fig. 7. An output power of up to 1052 W was obtained at the maximum pump power level of 1600 W, corresponding to a power conversion efficiency of 65.7%. The optical slope efficiency was measured as 70.4%.

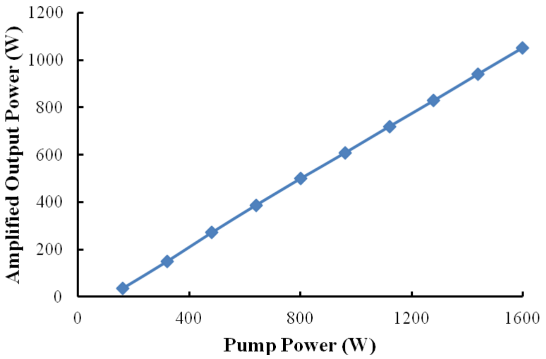

Fig. 7. Output power as function of pump power.

Figure 8(a) shows the optical spectra at output power levels of 0.5 kW and 1.05 kW respectively. The spectrum of seeding laser is also plotted in the same figure as a comparison. The spectrum bandwidth is slightly narrowed from an initial value of 4.7 nm right after seeding laser, to 3.8 nm and 3.3 nm with output power of 0.5 kW and 1.05 kW respectively,

#197166 - $15.00 USD Received 5 Sep 2013; revised 14 Nov 2013; accepted 21 Nov 2013; published 26 Nov 2013

due to the gain narrowing effect. A small portion (3.4%) of the output power was reflected by a fused silica prism, and sent to a grating compressor to perform the pulse compression. The pulse width can be optimized to around 800 fs at both 0.5 kW and 1.05 kW amplified power levels. The autocorrelation traces are shown in Fig. 8(b). Output beam quality at the highest output power was evaluated. Figure 9 is a screen shot from M^2 measurement results. The best-fit M^2 values were 1.117 (parallel) and 1.12 (perpendicular). The insert in Fig. 9 shows a beam profile image.

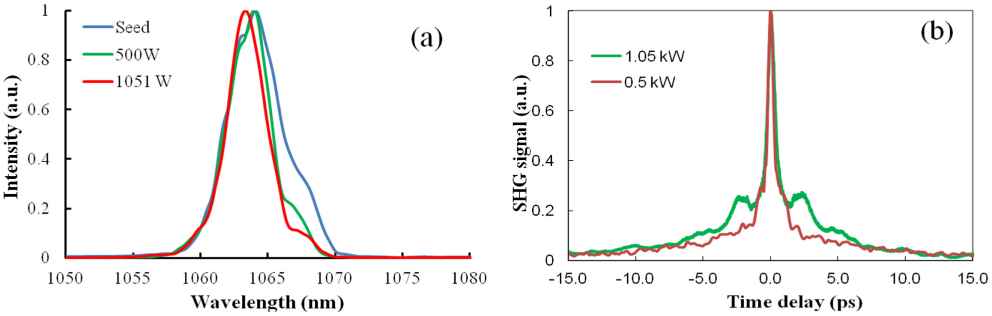

Fig. 8. (a) Spectra of seeding laser and amplified output at various power levels; (b) Autocorrelation trace of the output beam with various amplified average power.

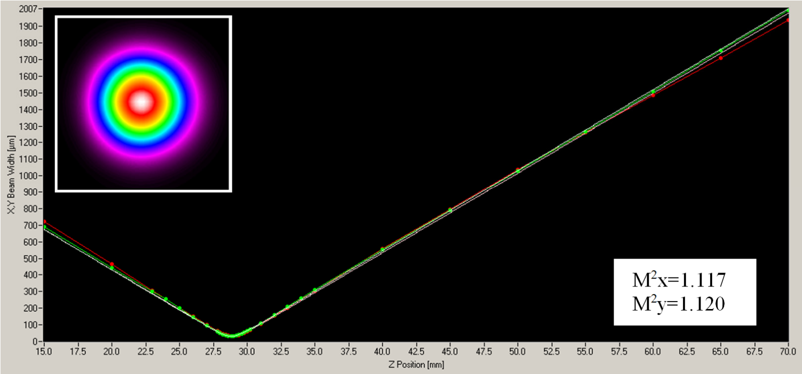

Fig. 9. Screen shot for M^2 measurements: Beam diameters as functions of distance from laser beam waists. Insert is an image of 2D beam profile.

Conclusions

In conclusion, we demonstrated two chirped pulse amplification systems to obtain mJ level high energy and kW level high average power femtosecond outputs at wavelength of 1 μm, by seeding with commercial high energy or high power femtosecond fiber lasers. In the high energy laser system, amplified pulse energy of 1.05 mJ (0.85 mJ after pulse compressor) and pulse duration of 705 fs were generated from a Yb-doped ultra large-core single-mode rod-like PCF, seeded with a 50 μJ chirped pulse fiber laser. In the high average power system, an average power of 1052 W was obtained from the final stage LMA fiber amplifier, seeded with a 50 W chirped pulse fiber laser. This work provides a breakthrough in developing a compact, stable and low cost high energy (> 1 mJ) and high power (> 1 kW) femtosecond fiber laser system. Moreover it lays out a solid foundation towards achieving simultaneous high energy (mJ) and high power (kW) all fiber based femtosecond fiber laser system.

Acknowledgment

This project is supported in part by DOE, AFOSR, and Army SBIR programs.