New generation of high average power industry grade ultrafast Ytterbium fiber lasers

Alex Yusim[1], Igor Samartsev, Oleg Shkurikhin, Daniil Myasnikov, Andrey Bordenyuk,
Nicholai Platonov, Vijay Kancharla, Valentin Gapontsev
IPG Photonics Corp., 50 Old Webster Rd, Oxford, MA, USA 01540

ABSTRACT

We report an industrial grade picosecond and femtosecond pulse Yb fiber lasers with >100 µJ pulse energy and hundreds of Watts of average power for improved laser machining speed of sapphire and glass. This highly efficient laser offers >25% wall plug efficiency within a compact 3U rackmountable configuration plus a long >2m fiber delivery cable. Reconfigurable features such as controllable repetition rate, fine pulse duration control, burst mode operation and adjustable pulse energy permit the customer to tailor the laser to their application.

Keywords: Fiber laser, ultrafast laser, picosecond laser, femtosecond laser, chirped pulse amplification, micromachining

1. INTRODUCTION

Recent advances in scaling the pulse energy and the average power of ultrafast pulse fiber lasers have led to the significant progress in commercializing this technology [1-4]. Ultrafast lasers were research lab devices requiring significant upkeep and adjustment. Over the years, more rugged ultrafast pulse laser architectures have been developed such that these lasers are now used in medical and industrial applications. One of the most monolithic, efficient, compact and power scalable architectures uses fiber laser technology. CW fiber lasers have been scaled to tens of kilowatts with high reliability [5,6]. Pulsed fiber lasers with pulse durations as short as 0.5ns and as long as 50ms are widely used for applications in material processing and in many cases can achieve as good or better performance as ultrafast pulse lasers [7]. Ultrafast pulse lasers with pulse duration less than 20 ps are well suited to applications that require a small heat affected zone and small kerf such as micromachining. Transparent materials can be machined with these lasers due to the process of multiphoton absorption [8]. Machining of materials such as Gorilla® Glass and sapphire is one application that is of interest for the mobile phone industry. Machining speed is of high importance for this application requiring optimization of pulse energy and average optical power for top performance. In this paper, we present an industrial ultrafast fiber laser scalable to hundreds of Watts and hundreds of microjoules for glass and sapphire machining.

2. GENERAL CONFIGURATION

The ultrafast fiber laser system presented in this paper is a Master Oscillator Power Amplifier configuration utilizing the very well known technique of Chirped Pulse Amplification (CPA) developed in mid-1980s for the optical frequencies [9]. Our CPA system consists of a tunable chirped Fiber Bragg Grating (FBG) pulse stretcher and a Volume Bragg Grating (VBG) pulse compressor for compactness and ruggedness. Stretching of optical pulses with a Bragg reflector was demonstrated in 1994 by Rottwitt et al [10,11]. Since then further optimization of the Bragg reflectors and active fiber in CPA systems has yielded average powers greater than 250W and more than 1 mJ pulse energy [12,13]. The master oscillator in our system is a mode locked fiber laser with broad bandwidth and pulse energy >2nJ. The fiber amplifier consists of a number of amplifier stages separated by isolators for ASE suppression. The fiber lengths of the active and passive fibers are minimized and fibers with larger mode field diameters are used throughout the fiber amplifier to reduce self-phase modulation (SPM) and stimulated Raman Scattering (SRS). Large mode area polarization maintaining fiber with mode area of 850 μm^2 is used for the final amplification stage. An AOM is utilized for pulse picking. The general laser configuration is shown in Figure 1.

---

[1] ayusim@ipgphotonics.com; phone +1 (508) 373-1179; www.ipgphotonics.com

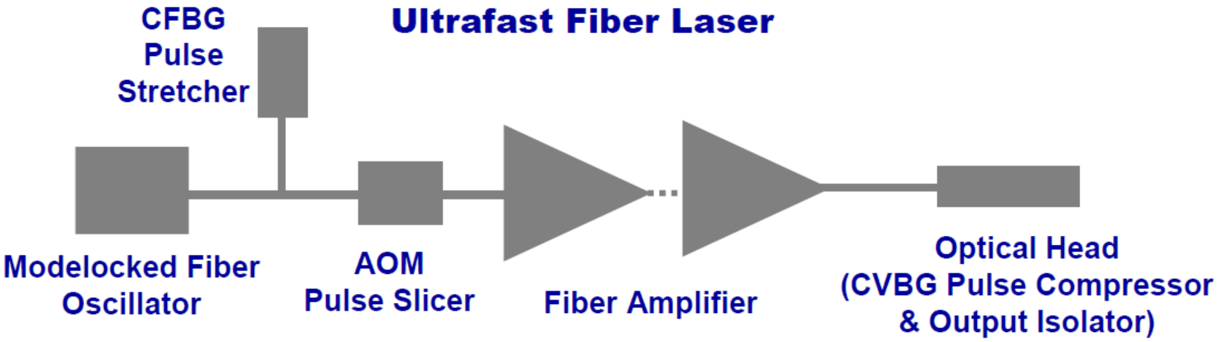


Figure 1. Sample schematic of an ultrafast fiber laser. Similar or identical configurations are used for all experimental data.

The ultrafast fiber laser almost wholly consists of polarization maintaining fiber based components that are spliced into a monolithic configuration. This includes an all-fiber based modelocked master oscillator, a Fiber Bragg Grating pulse stretcher, and a fiber amplifier all based on IPG patented technology. The remaining components are fiber pigtailed with telecom-grade reliability and tested for long term high power handling. The pulse compressor and the output isolator are the only free space optical components. These are located in the compact optical head situated at the end of a flexible armored metal cable which houses the active fiber. Water cooling removes extraneous heat for high mechanical stability and reliability.

Lasers with average output power up to 100W are commercially available. These are housed in a 3U rackmountable laser driver with a touch screen front panel display as shown in Figure 2. A flexible metal umbilical cable exits this driver from the rear. The cable is terminated with an optical head from which the laser beam exits. The laser driver has RS-232 as well as ethernet communication ports. Customers may apply a TTL signal to switch the laser at speeds up to 500 kHz and generate a single pulse or any other integer number of pulses on demand. Pulse energy can be controlled in a number of different ways. The average power is adjusted through the front panel, RS232, or ethernet. The repetition rate can be set from 10 kHz to 5 MHz. In addition, analog pulse energy control is available via 2 methods. The simpler method is to adjust the pump power, but this is effective only up to 20 kHz. Since transient gain dynamics may produce unwanted artifacts, we implemented a second analog modulation scheme that keeps the inversion constant to eliminate these artifacts. This method is also used for TTL on/off modulation for the same purpose.

Figure 2. Photograph of the industrial grade ultrafast fiber laser. The 3U Rackmountable chassis with an output fiber cable and an optical head for up to 100W average output power is shown.

The AOM synchronized to the seed laser provides some important functionality. The AOM in our system is a pulse slicer and the repetition rate is adjusted by pulse picking with an integer divisor. The adjustment of the repetition rate is shown in Figure 3. The repetition rate can be inputted from the front panel display, RS232, or ethernet. The pulse energy is limited automatically by software for the entered repetition rate. The AOM also performs the burst mode functionality by adjusting the window size for the number of pulses requested. The number of pulses in a burst may be entered by the user. The pulses inside the burst are separated by the oscillator repetition rate which is ~35MHz for the seed laser used in Figure 4. Modifying the seed laser cavity length can provide the required pulse separation. The total burst pulse energy is limited by the number of pulses in the burst and is automatically adjusted higher with greater number of pulses in a burst in a linear manner.

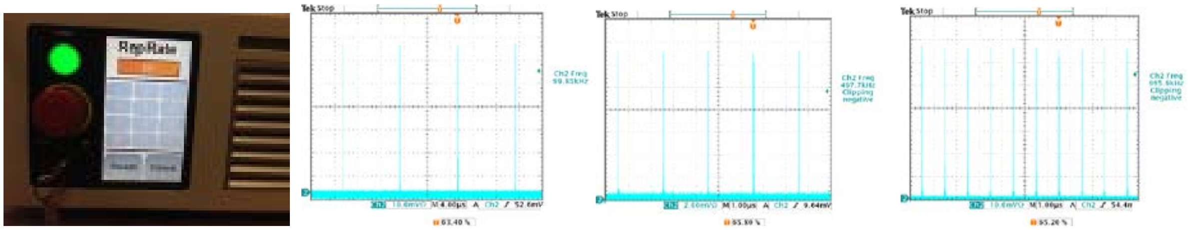


Figure 3. Adjustment of the output repetition rate of the ultrafast pulse laser through the touch screen front panel display.

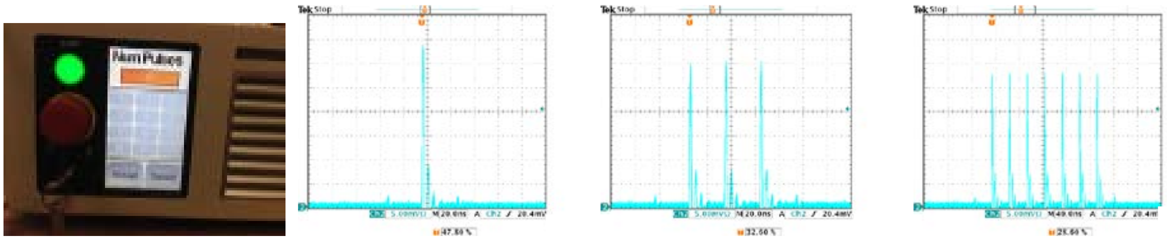


Figure 4. Adjustment of the number of pulses in a burst of the ultrafast pulse laser through the touch screen front panel display in kHz.

This ultrafast pulse laser has extensive control including the pulse energy delivered to the work piece and when the pulse is delivered. The pulse can be specified using a few different methods. Setting the average power, the repetition rate, and number of pulses in a burst determines energy per pulse. This is set using a number of different interfaces including RS232, ethernet, or front panel. In addition, analog control permits adjustment of the average power/pulse energy during the machining process at speeds up to 20 kHz limited by our present electronics.

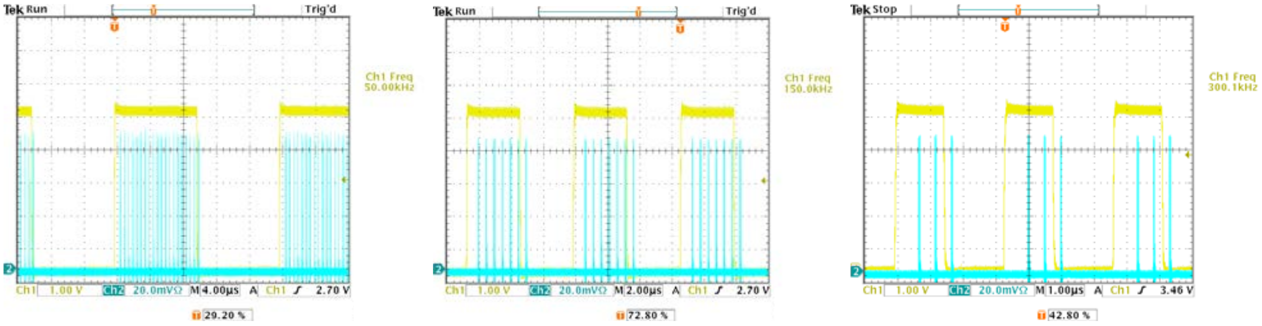


Figure 5. Customer controlled gating functionality is shown. A 2 MHz pulse train is gated by the user with an on/off gate at 50 kHz (right), 150 kHz (center), and 300 kHz (Left). The gate is the yellow trace and the output pulses is the blue trace.

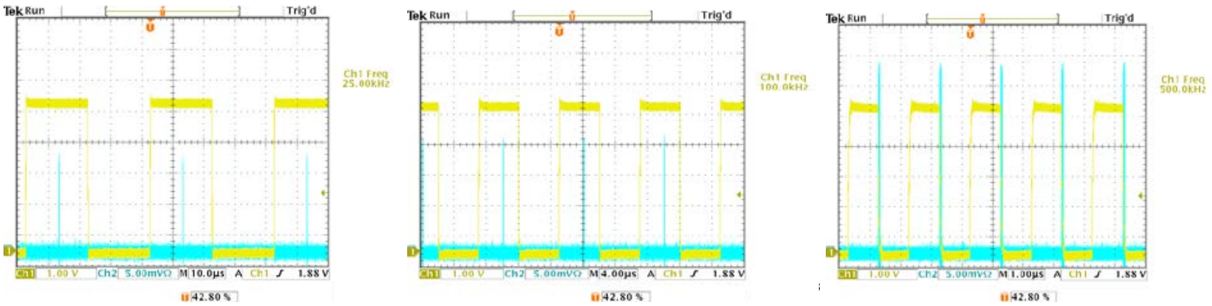


Figure 6. Customer controlled gating of a single pulse is shown. A 2 MHz pulse train is gated by the user with an on/off gate at 25 kHz (right), 100 kHz (center), and 500 kHz (Left). The gate is the yellow trace and the output pulses is the blue trace.

The pulses are provided on demand through a gate controlled by the user at speeds up to 500 kHz. This permits one to deliver a single pulse, a train of pulses, or a train of pulse bursts to the work piece (Figures 5 and 6). The pulse energy of the first to the last pulse is finely controlled by correcting transient gain dynamics for any inversion changes. This is shown in Figure 7. A second seed laser at a wavelength within the gain of the amplifier and outside the reflection spectrum of the VBG is launched after the AOM either through the FBG pulse stretcher or through a coupler. The power of this secondary seed laser is controlled such that the gain for the modelocked pulses is finely tuned. In one configuration the secondary laser is on when the gate is in the off state and reverse when the gate is in the on state. The AOM on the other hand is configured such that it blocks the modelocked pulses when the gate is in the off state. It is possible to suppress changes in inversion and changes in the gain as the laser pulses are turned off or on as needed. The secondary seed laser power is adjusted as conditions change with regards to output power, repetition rate, and burst mode to suppress any gain transients. The amplified secondary seed laser power is dumped behind the VBG and is contained completely within the chassis. In another configuration, this secondary laser can be turned on concurrently with the modelocked laser in order to deplete the gain and perform the function of analog power control by varying the power of the secondary laser. Since this secondary laser can be a diode, the power of the laser can be adjusted at high speeds correcting any transients.

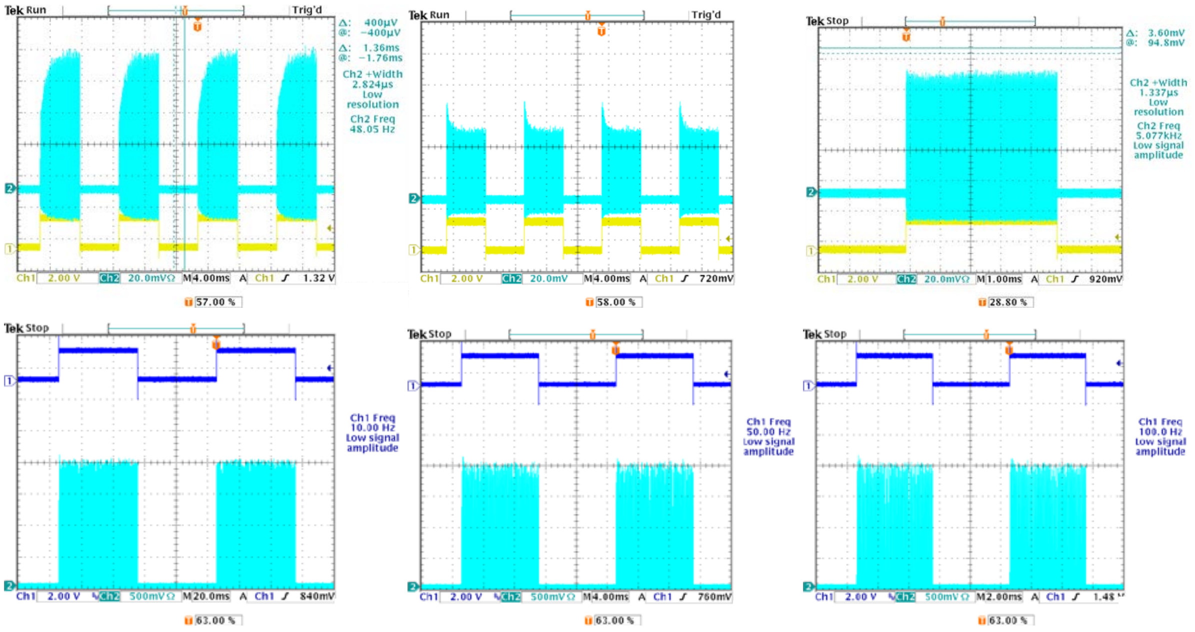
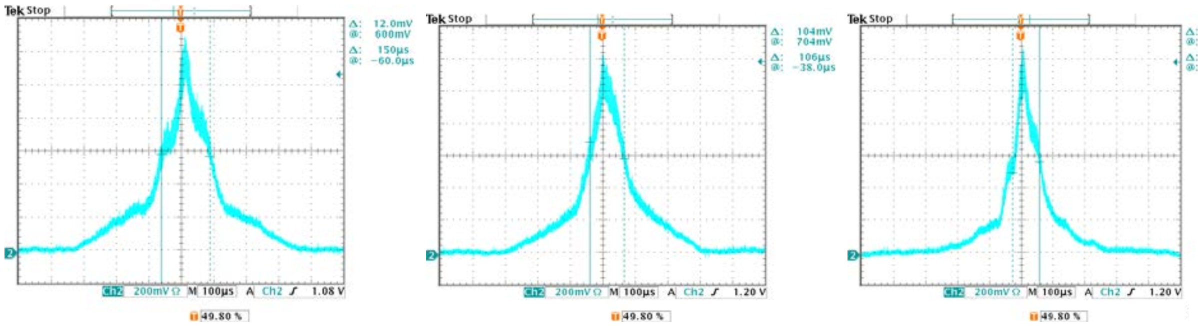
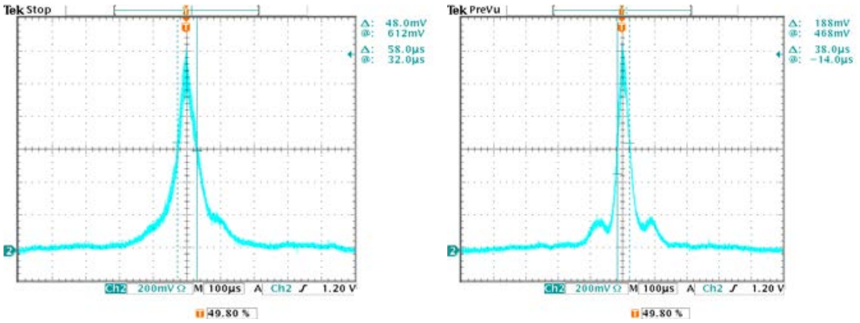


Figure 7. The top 3 oscilloscope traces demonstrate the fine inversion control for 300kHz pulse train gated with 100Hz TTL signal (yellow) by adjusting the secondary seed laser. The bottom 3 oscilloscope traces are 10Hz, 50Hz, and 100Hz TLL gate (dark blue) and the 300kHz pulse train (light blue). The secondary laser is coupled through a PM 20/80 fiber coupler.

Tunable pulse duration is another function of this laser. The pulse duration can be tuned by the user from 0.5ps to 5ps through an analog voltage applied through a connector on rear panel. The tuning of the pulse duration can be as fast as 100 µsec for fast reconfiguration of the machining process. Another application for this feature is pre-compensation of the dispersion that may be introduced from the optics in the beam path and the material that is machined. The pulse duration adjustment is shown in Figure 8 for tuning from 3.1ps to 750 fs.



3.1 ps (0 V) **2.2 ps (1V)** **1.7 ps (2V)**



1.2 ps (3 V) **750 fs (4 V)**

Figure 8. The autocorrelation traces shown above are a representation of different pulse durations controlled by the user through an analog voltage. Any voltage from 0-4V may be applied to finely control the pulse duration. The pulse duration are calculated assuming hyperbolic secant pulse shape.

3. POWER SCALABLE ULTRAFAST FIBER LASERS

Ultrafast lasers are finding applications in a number of industries requiring a wide spectrum of pulse energies and average powers. Ophthalmology and micromachining applications require low average powers and moderate pulse energies. For example, corrective eye surgery using a few hundred femtosecond laser requires only a few microjoules at most and cataract surgery requires up to 20 µJ with average powers of less than a few watts. Micromachining applications typically use less than 50 µJ pulse energy and relatively low average power to avoid overheating the material and increasing the heat affected zone and kerf. For other applications such as glass and sapphire cutting, higher average powers and pulse energy increase the speed of the machining process. These applications can require up to 100 W average power or more and greater than 50 µJ. Yet, other applications require higher pulse energies up to couple hundred microjoules with lower average powers. It is therefore necessary to have a highly flexible laser system configuration to cover the many applications.

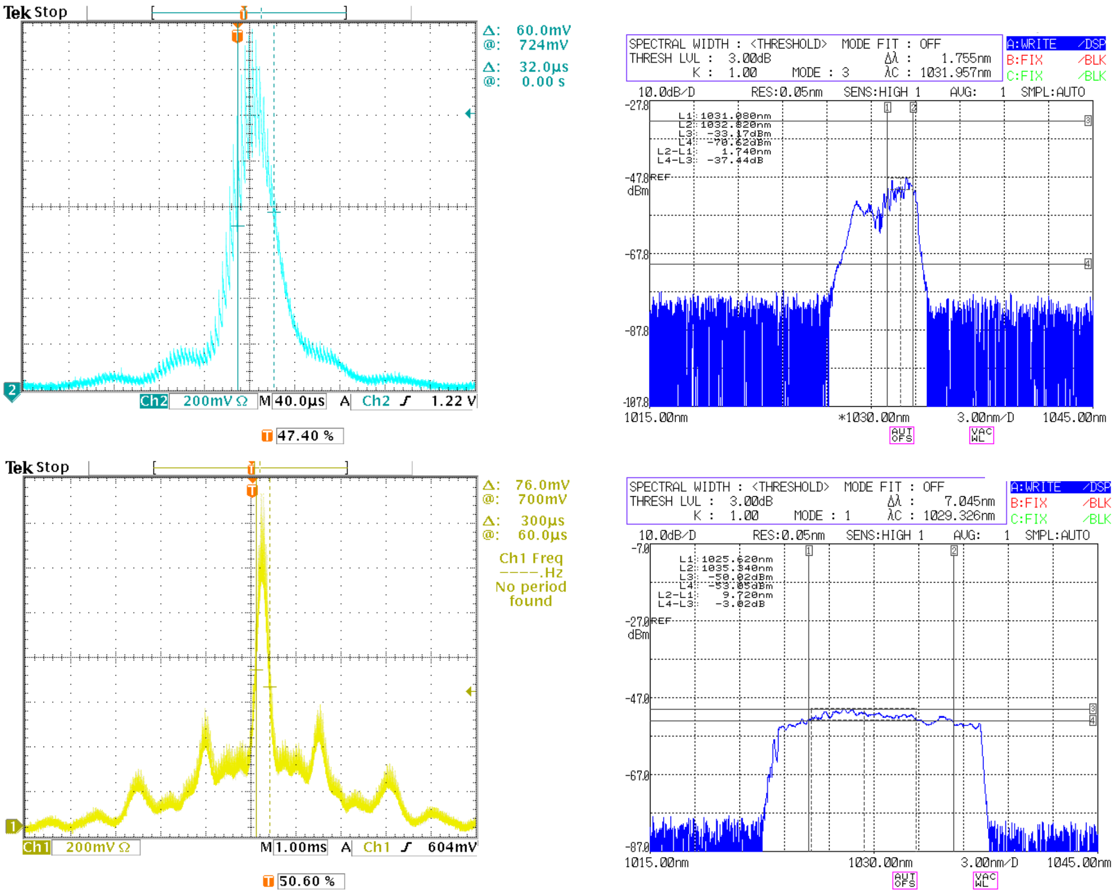


Figure 9. Autocorrelation trace for the ultrafast pulse laser with 10 µJ and 3W average power. The autocorrelation trace has a calibration factor of 32ps/ms multiplied by 0.648 for hyperbolic secant pulse shape resulting in pulse width of 650 fs (Top Left). The output spectrum with spectral width of 1.75nm FWHM for the 650fs pulse laser (Top Right). Autocorrelation trace for the ultrafast pulse laser with 10 µJ and 1W average power. The autocorrelation trace has a calibration factor of 2ps/ms multiplied by 0.648 for hyperbolic secant pulse shape resulting in pulse width of 390 fs (Bottom Left). The output spectrum with spectral width of ~7nm for the 390fs pulse laser (Bottom Right).

3.1 Moderate Pulse Energy and Low Average Powers Ultrafast Fiber Lasers

Femtosecond lasers with moderate pulse energies have been developed using nearly the same configuration as for the high average power and high pulse energy laser systems. The laser is air cooled due to lower power consumption at these lower average power levels. Sub-picosecond pulses are achieved without the usage of nonlinear pulse duration compensation. Figure 9 shows two sets of results. For the first set, the pulse duration is 650 fs assuming a hyperbolic secant pulse shape. The spectral width is 1.75nm centered at 1032 nm. This is shown in Figure 9a and 9b respectively. The pulses are transform limited with the time bandwidth-product of 0.32. The pulse energy is 10 µJ and the average power is 3W. To achieve shorter pulses, more bandwidth is required. The second set of results shown in Figure 9c and 9d are the output autocorrelation and the much wider output spectrum respectively. The spectral width is 7 nm centered at 1030 nm. The pulse duration is 390 fs assuming hyperbolic secant pulse. The pulse energy is 10 µJ and the average power is 1W for 100 kHz repetition rate. The autocorrelator calibration factor is 2 ps/ms for 100kHz repetition. The autocorrelation scan shows additional side structure due to the nonlinear portion of the chirp introduced by self phase modulation. Reducing the nonlinear interaction, sometimes referred to as the B-Integral, can further help suppress this effect without the use of nonlinear dispersion compensation techniques [14].

3.2 Higher Average Power with Higher Pulse Energy Ultrafast Fiber Laser

We developed fiber lasers with less than 20 ps and average powers up to 100 W. The laser configuration is similar to the low power version with a few exceptions. The lasers for these power levels are water cooled. Even though air cooling is possible due to the high >25% wall plug efficiency, the heat dissipation through water cooling helps to increase the ambient temperature range. The optical head is also water cooled to remove any residual heat for improved mechanical stability during the machining process. Pulse energy up to 150 µJ was attained. In Figure 10, we show the output autocorrelation traces for 100 kHz rep rate for up to 15 W average output power. Greater than 95% of the energy is within 20 ps up to 150 µJ, and the pulse duration is less than 5 ps full width half maximum. In Figure 11, we show the output autocorrelation traces for 300 kHz rep rate for up to 30 W average output power. The pulse duration is less than 3 ps at full width half maximum. Greater than 95% of the energy is within 20 ps up to 100 µJ.

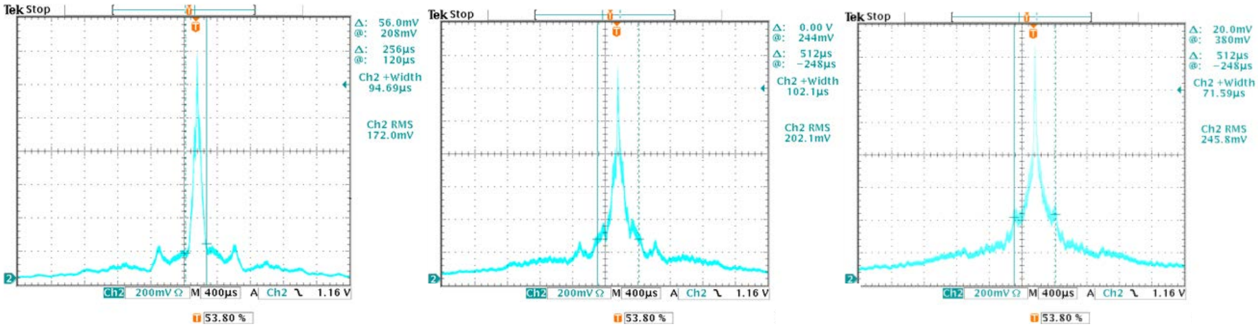


Figure 10. Autocorrelation traces for 5W average power and 50 µJ pulse energy (left), 10W and 100 µJ (Center), and 15W and 150 µJ (Left). The calibration factor is 32ps/ms. Assuming hyperbolic secant pulse shape, the pulse durations are less than 5ps FWHM and >95% of the energy is within 20ps for up to 150 µJ.

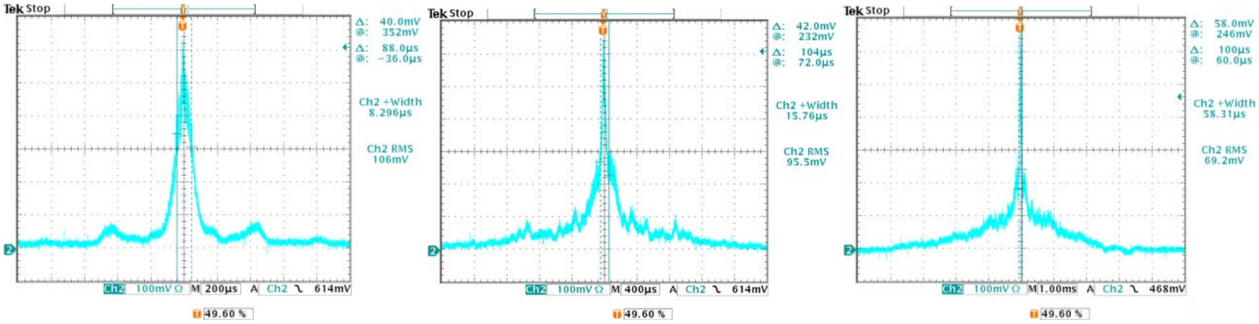


Figure 11. Autocorrelation traces for 10W average power and 33 µJ pulse energy (left), 20W and 67 µJ (Center), and 30W and 100 µJ (Left). The calibration factor is 32ps/ms. Assuming hyperbolic secant pulse shape, the pulse durations are less than 3ps FWHM and >95% of the energy is within 20ps for up to 100 µJ.

In Figure 12 below, we show the autocorrelation trace, the M^2, and the output power versus pump power curve for a 100W fiber laser. The pulse duration is 7.5 ps FWHM and M^2 was ~1.3. The optical to optical conversion efficiency is greater than 53% at 100W output power. The repetition rate is 2 MHz corresponding to 50 µJ of pulse energy.

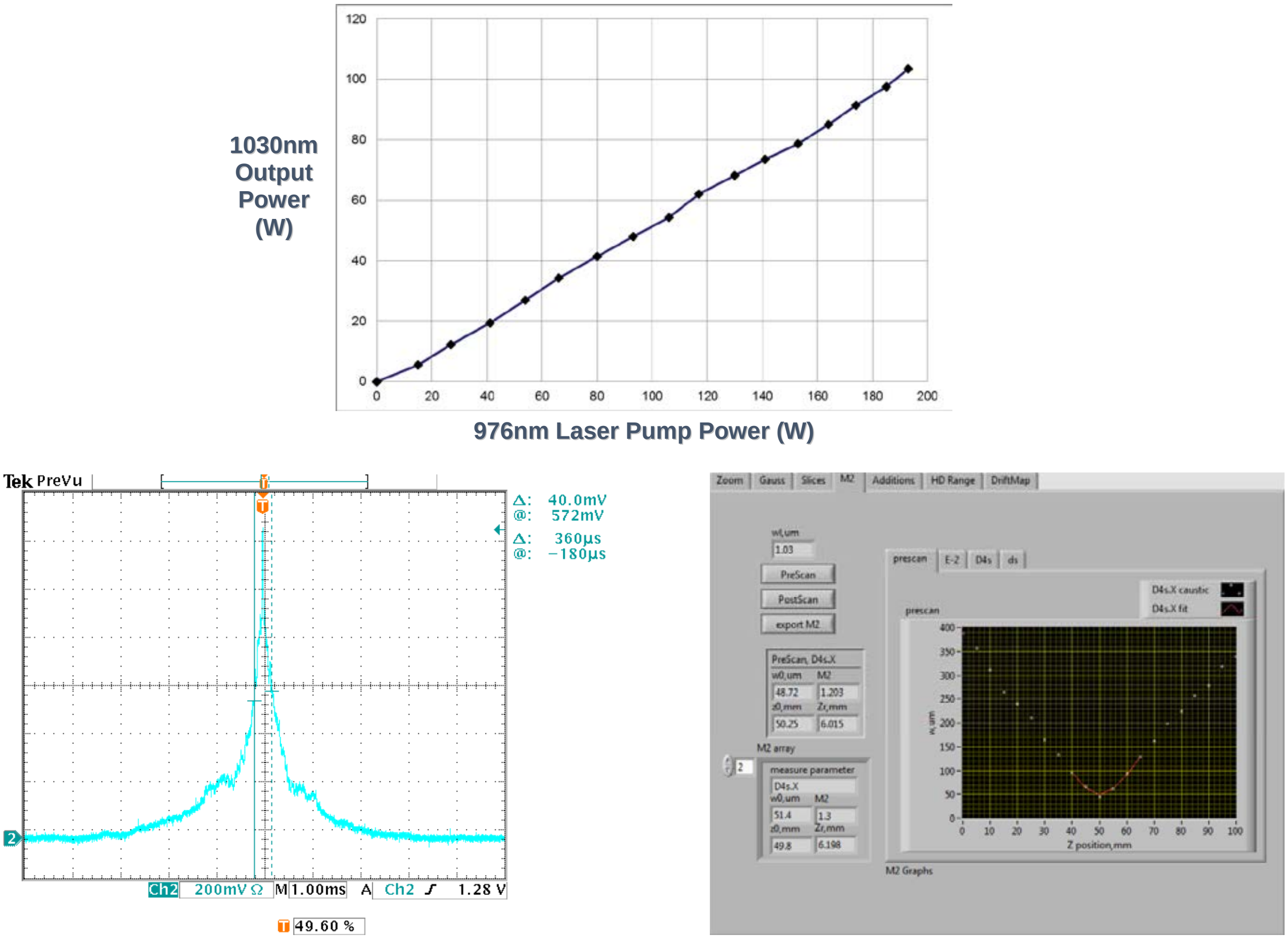


Figure 12. Output Power versus pump power for 100 W ultrafast fiber laser. Autocorrelation traces corresponding to 7.5ps pulse duration for 100 W average power and 50 µJ pulse energy (bottom left). The M^2 = 1.3 at 100 W output power level (Bottom Right).

3.3 Further Average Power Scaling of the Ultrafast Fiber Laser

Further power scaling for an ultrafast fiber laser is demonstrated. We initially tested the amplified stretched pulses without pulse compression, achieving 391W output with 0.5 ns stretched pulses at 2MHz repetition rate, shown in Figure 13. The optical to optical slope efficiency is 86%. The fiber platform used is very similar to IPG's CW single mode multi-kilowatt fiber laser systems. We expect further average power scaling is possible. In our first attempt for pulse compression, we used the chirped VBG from Optigrate to reach 143W output and 70 µJ, 7.5 ps pulses at which point the VBG was damaged. Output average power of the compressed optical pulses versus pump power is shown in Figure 14. We also include the autocorrelation trace for ~140W output power corresponding to 7.5 ps. We attribute the damage of the VBG to facet cleanliness. We estimate that we should reach greater than 250W average output powers assuming a typical conversion efficiency through the VBG and through the other components in our laser system for our next attempt using the VBG pulse compressor. We also plan on using a standard Traecy grating compressor for comparison purposes.

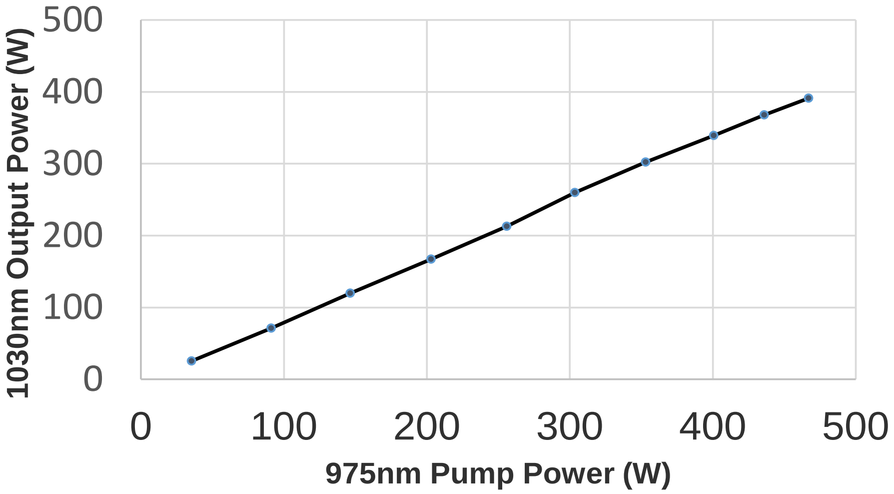


Figure 13. Output power versus pump power for 0.5ns stretched optical pulses at 2 MHz repetition rate without pulse compression. Slope efficiency is 86%.

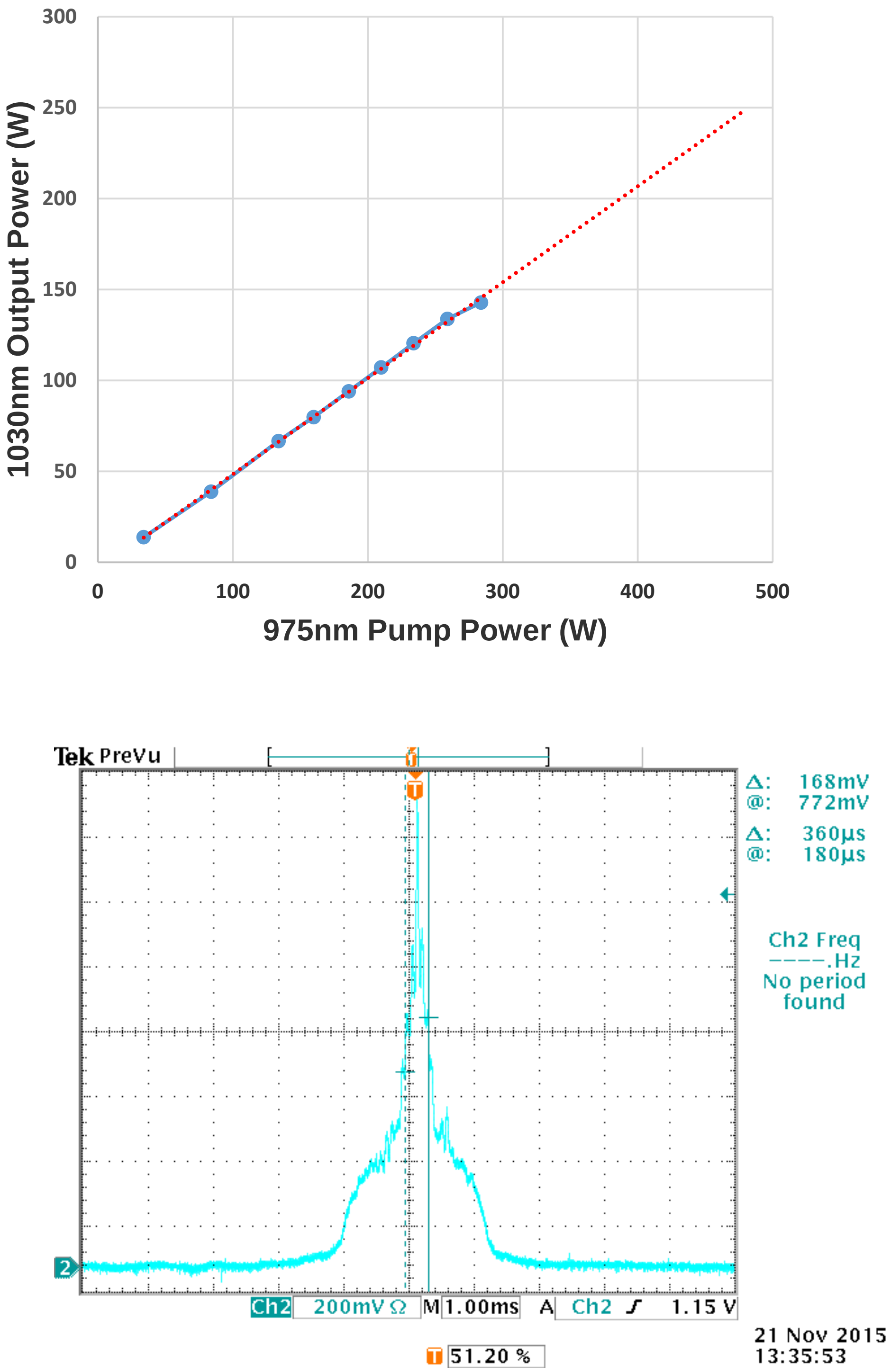


Figure 14. Output power versus pump power for compressed optical pulses up to ~143W output power (top plot in blue) and the extrapolation to 250W output power (top plot in red). The autocorrelation plot at ~140W output corresponds to 7.5 ps and 70 µJ pulse energy (bottom plot).

4. GLASS AND SAPPHIRE CUTTING USING ULTRAFAST FIBER LASER

We tested the laser with average output power of 50 W for cutting sapphire (see Figure 15). We made grooves and cut windows optimizing the laser parameters for speed. The cut speed increased with pulse energy and average power as shown in Figure 16 and Figure 17. Testing is ongoing for the optimum pulse energy and average power for best cut quality as well as the highest speed.

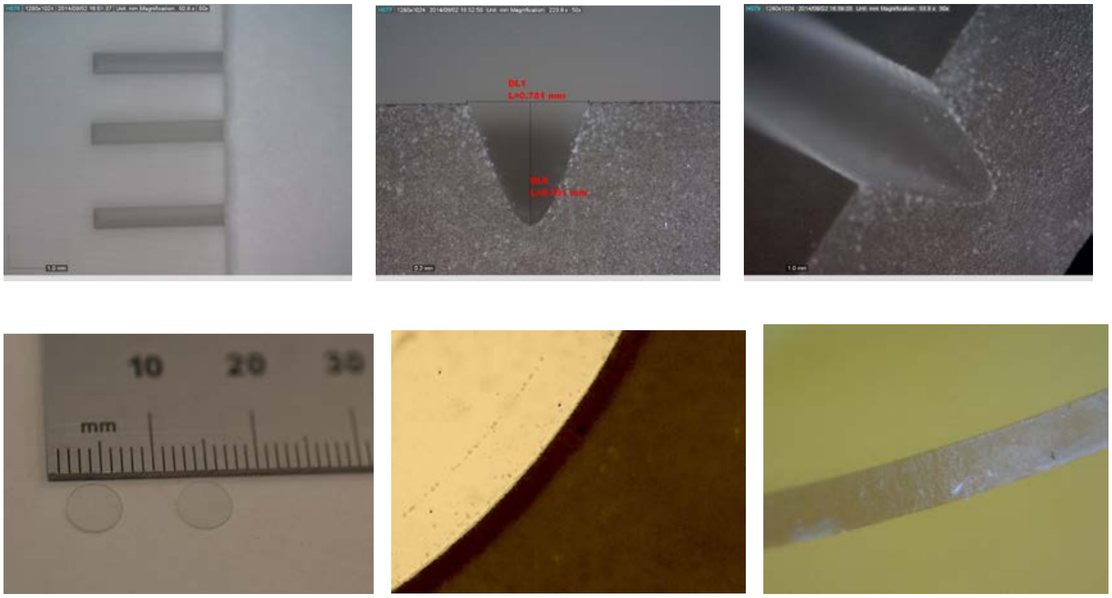


Figure 15. Cutting grooves in sapphire is shown in the top 3 photographs. Cutting sapphire windows is shown in the bottom 3 photographs.

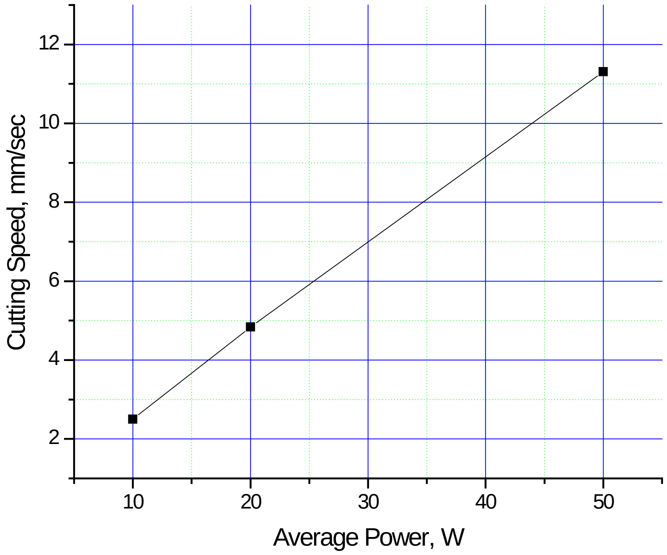


Figure 16. Cutting speed versus average power is shown in the graph above to cut through a 0.3mm window. The pulse energy was kept constant at 50 µJ while increasing the average power by increasing the repetition rate.

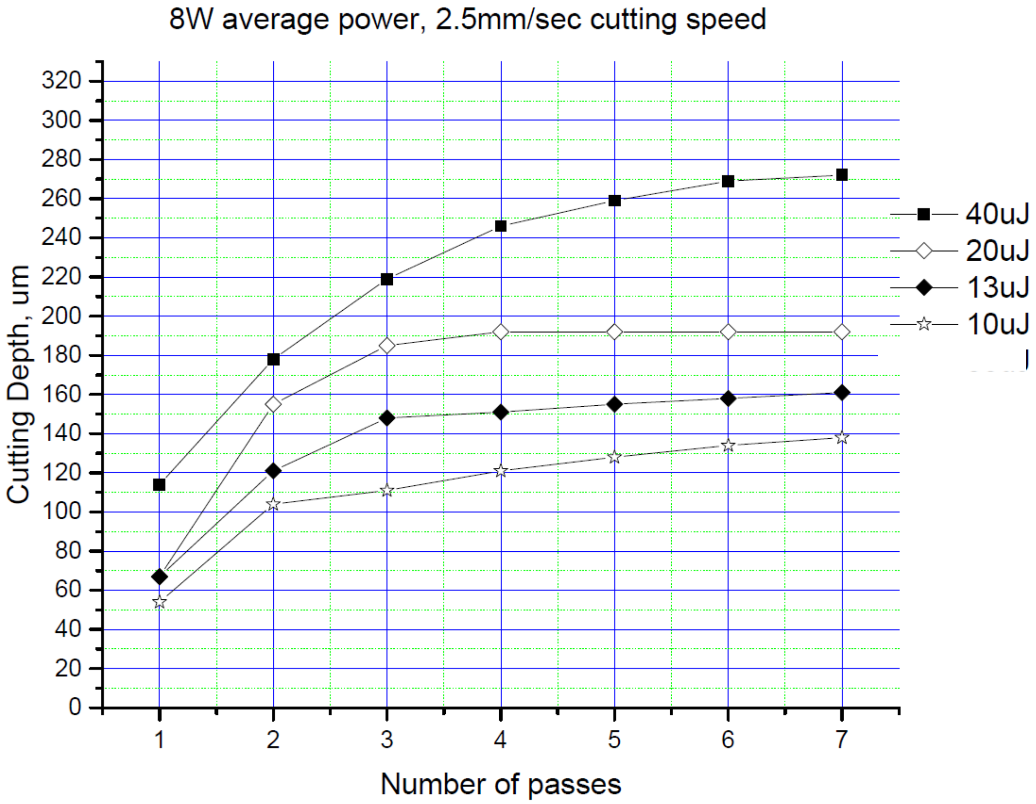


Figure 17. Cutting depth versus pulse energy is shown in the graph above for different number of passes without changing the beam waist location on the work piece. The average power was kept constant at 8 W while increasing the pulse energy by decreasing the repetition rate.

5. CONCLUSION

Ultrafast fiber laser systems are an optimum tool to fulfill the requirements for an industrial application of glass and sapphire cutting. Our highly scalable architecture with respect to average power and pulse energy permits the user to optimize the machining speed and the cut quality of these materials. We have shown up to 150 µJ pulse energy per pulse and up to 143W output power in a compact, efficient fiber laser system generating less than 20ps pulses. Further scaling of average power up to 250W is possible in a similar configuration.

6. ACKNOWLEDGEMENT

We would like to extend our appreciation to the Conference Programs and Proceedings Department of the SPIE, as well as to the Committee of the SPIE LASE Conference. We would like express gratitude for the tireless work provided by Justin Barsalou, Joe Antas, and Cesar Arambula, and Alexey Podvyaznyy in resolving many of the technical issues. We would also like to thank Anton Drozhzhin, Armen Sevian, and Bruce Jenket for their work on fiber Bragg design and mechanical packaging. In addition, we would like to thank Oleksyi Andrusyak for his consultation on volume Bragg grating design. Finally, we would like to extend our appreciation to Alexey Glebov and Vadim Smirnov from Optigrate in their assistance with volume Bragg gratings.

REFERENCES

[1] A. Yusim, I. Samartsev, A. Bordenyuk, V. Gapontsev, " New generation of industry grade ultrafast Ytterbium fiber lasers", 16th Int. Conf. Laser Optics in St. Petersburg, Russia (2014).

[2] T. Eidam, S. Hanf, E. Seise, T. V. Anderson, T. Gabler, C. Wirth, T. Schreiber, J. Limpert, A. Tunnermann, "Femtosecond fiber CPA system emitting 830 W average output power", Opt. Lett. 35 (2), 94 (2010).

[3] P. Wan, L. Yang, J. Liu, "All fiber-based Yb-doped high energy, high power femtosecond fiber laser", Opt. Exp. 21 (24), 29854 (2013).

[4] Y. Zaouter, F. Guichard, C. Hoenninger, E. Mottay, M. Hanna, P. Georges, " High average power 600 µJ ultrafast fiber laser for micromachining application", J. Laser Appl, 27, S29301 (2015).

[5] V. Gapontsev, V. Fomin, A. Yusim, "Recent progress in scaling of high power fiber lasers at IPG Photonics", SSDLTR, 142 (2009).

[6] V. Fomin, V. Gapontsev, E. Shcherbakov, A. Abramov, A. Ferin, D. Mochalov, "100 kW CW fiber laser for industrial application", 16th Int. Conf. Laser Optics in St. Petersburg, Russia (2014).

[7] M. Mendes, V. Kancharla, C. Porneala, X. Song, M. Hannon, R. Sarrafi, J. Schoenly, D. Sercel, S. Dennigan, R. VanGemert, J. Bickley, J. Sercel, "Laser machining with QCW lasers", ICAELO #M406 (2014).

[8] J. Sercel, J. Bickley, J. Stearns, "ULTRAFAST LASERS: Picosecond laser micromachining produces high –quality results", Laser Focus World, 10 (2012).

[9] D. Strickland, G. Mourou, "Compression of amplified chirped optical pulses", Opt. Commun.56, 219 (1985).

[10] K. Rottwitt, M. J. Guy, A. Boskovic. D. U. Noske, J.R. Taylor, R Kashyap, "Interaction of uniform phase picosecond pulses with chirped and unchirped photosensitive fiber Bragg gratings", Elec. Lett. 30 (12), 995 (1994).

[11] A. Boskovic, J. R. Taylor, R. Kashyap, "Forty times dispersive broadening of femtosecond pulses and complete recompression in a chirped fibre grating", Opt. Com. 8 (1995).

[12] L. Glebov, V. Smirnov, E. Rotari, I. Cohanoschi, L. Glebova, O. Smolski, J. Lumeau, C. Lantigua, A. Glebov, "Volume-chirped Bragg gratings: monolithic components for stretching and compression of ultrashort laser pulses", Opt. Eng. 53(5), 051514 (2014).

[13] M. Rever, S. Huang, V. Smirnov, E. Rotari, I. Cohanoshi, L. Glebov, A. Galvanauskas. "200W, 350fs fiber CPA system enabled by chirped-volume-Bragg-gratings and chirally-coupled-core fiber technology", Proc. SPIE 7580, Fiber Lasers VII:Technology, Systems, and Applications, 75800Y (2010).

[14] J. Limpert, F. Roser. D. N Schimpf, E. Seise, T. Eidam, S. Hadrich, J. Tothhardt, C. J. Misas, A. Tunnermann, "High repetition rate gigawatt peak power fiber laser systems: challenges, design, and experiment", IEEE J. Quant Elec. 15 (1), 159 (2009).