JLMN-Journal of Laser Micro/Nanoengineering Vol. 1, No. 3, 2006

High Power Femtosecond Fiber Chirped Pulse Amplification System for High Speed Micromachining

Lawrence SHAH and Martin E. FERMANN

IMRA America, Inc., 1044 Woodridge Avenue, Ann Arbor, Michigan, USA, 48105
lshah@imra.com

The need for improved precision in a wide variety of micromachining applications has driven scientific interest in ultrashort pulse lasers. Despite numerous demonstrations of reduced heat effect and improved processing quality, the utility of such lasers has been limited by the heavy demands placed upon laser performance. In addition to high contrast laser pulses with minimal pulse-to-pulse fluctuation, an ultrashort pulse laser must provide near diffraction-limited beam quality and robust long-term laser operation with high repetition rate for high processing speeds. We report here on a research prototype, high power femtosecond fiber chirped pulse amplification system. The system produces compressed pulses with energies >50 μJ at >15 W with $M^2 < 1.4$. The use of cubicon pulses, i.e. stretched pulses with cubical spectral and temporal shape, enables pulse compression to <500 fs with >1000:1 temporal contrast despite significant self-phase modulation during amplification corresponding to a nonlinear phase delay of ~6π. As a demonstration of high speed femtosecond micromachining, we drill and cut 0.5-mm thick metal, semiconductor and dielectric targets.

DOI: 10.2961/jlmn.2006.03.0005

Keywords: cubicon pulse, fiber laser, ultrashort pulse laser, high repetition rate, micromachining

1. Introduction

Increasing demand for high speed ultra-precise materials processing has motivated many recent developments throughout the laser industry. Early examples of improved precision using sub-picosecond laser pulses [1, 2], demonstrated the promise of such laser systems for a wide range of applications. However, to date, commercial applications using ultrashort laser pulses are extremely specialized. The improved precision of ultrashort pulse lasers has generally been offset by their cost, low average power, and poor reliability; thus industrial acceptance has been limited.

In recent years, there have been many improvements in femtosecond laser reliability and increased sales volumes will lead to reduced system costs; however a more basic challenge is increasing laser average power in order facilitate high volume processing. Since the late 1980s ultrafast laser processing has been investigated primarily in scientific facilities using Ti:Sapphire lasers. While Ti:Sapphire lasers are capable of producing sub-100 fs laser pulses >100mJ, it becomes prohibitively difficult to scale the average power much beyond 10 W.

Given the stringent requirements for a reliable, nearly diffraction-limited, high average power ultrashort pulse laser system, it is not surprising that there is increasing interest in femtosecond fiber lasers. While average powers of 131 W have been demonstrated [3], high energy pulse amplification in fibers is inherently limited by nonlinearities associated with the long propagation lengths and high laser intensities.

We have previously reported on a cubicon Yb-FCPA system producing 550 fs pulses with >50 μJ energy and >5 W power after compression [4]. Here we show power scaling to >15 W after compression, as limited by the the gold-coated compressor grating. As a demonstration of the utility of this laser, high speed femtosecond machining of metal, semiconductor and dielectric targets is presented.

2. Review

For ultrafast lasers, it is generally not possible to sustain system nonlinearity corresponding to a B-integral >π [5]. In bulk solid-state systems, the most obvious effect of surpassing the B-integral limit is nonlinear self-focusing leading to beam distortion and/or disruption of cavity stability [4]. In fibers, the transverse mode field distribution is determined by the structural waveguide which is significantly less sensitive to thermal lensing, mechanical vibration, or nonlinear spatial beam distortions. Instead, excessive nonlinearities in fibers result in optical wave-breaking which prevents optimal pulse recompression [5, 6].

In order to obey the B-integral limit, most high-energy sub-picosecond pulse laser systems employ chirped pulse amplification (CPA) [7]. Fiber CPA was first demonstrated in an Er-fiber system producing 440 fs pulses at 46 mW with 1.4 nJ/pulse [8]. The development of double clad fiber (DCF) amplifiers allowed the use of lower brightness diodes resulting in significant increases in output power [9, 10]. However, output pulse energy remained limited by the high nonlinearity of single-mode fibers. The demonstration of single-mode propagation in large mode area (LMA) fibers [11] and improvements in LMA and DCF fiber designs made it possible to produce compressed pulse energies >100 μJ in Er/Yb-[12] and Yb-[13] doped fibers. However these systems are subject to the B-integral limit of ~π. Operating beyond this limit significantly increases the minimum compressed pulse duration, as shown in ref. 14 where the pulse duration was 450 fs for 20 μJ compressed output pulse energy but increased to ~5 ps for 100 μJ pulse energy.

The practicality of such "conventional" fiber CPA systems is limited because they rely on matched bulk-grating stretchers and compressors which are extremely sensitive to alignment stability. In particular, fiberized stretchers significantly improve the compactness and robustness of fiber CPA systems [15, 16]. However it is generally not possible to compensate for the positive third-order dispersion (TOD) of the fiber stretcher using a grating-based compressor, thus after compression there tends to be a significant amount of uncompensated TOD which degrades pulse quality.

3. Cubicon Fiber Amplifier

3.1 Exceeding the B-Integral Limit

It is possible to exceed the B-integral limit in fibers by avoiding optical wave-breaking, which occurs when self-phase modulation (SPM) and group-velocity dispersion (GVD) create a frequency shift which overtakes the spectral wings of the pulse. Anderson et al. theorized that, for the propagation of pulses with a parabolic spectral distribution in a normal dispersion fiber, SPM and GVD generate new frequency components with linear frequency chirp [17]. As long as the gain bandwidth exceeds the spectral bandwidth, during amplification both the spectral amplitude and spectral width increase without changing the shape of the pulse thereby avoiding optical wave-breaking. Self-similar amplification of parabolic pulses, also know as similaritons; has produced clean sub-100 fs compressed pulses for levels of SPM much greater than π [17, 18] and at powers >15 W [19]. However output pulse energy has been limited to the ~1 μJ level by the bandwidth of available amplifier fibers. As the spectral bandwidth approaches the gain bandwidth, the additional frequency components cannot be amplified and self-similarity is lost.

Cubicon amplification combines the characteristics of conventional fiber CPA and similariton amplification. Like similaritons, cubicons amplify self-similarly enabling operation beyond the B-integral limit. Unlike similariton, cubicons are highly chirped pulses with cubical temporal and spectral distribution. As a result, cubicons have two key advantages. First, cubicons are stable for nonlinear phase shifts »π, even in the presence of gain narrowing, allowing the generation of clean sub-picosecond pulses with >10 μJ pulse energy [20, 4]. Second, the action of SPM on the cubic pulse shape induces negative TOD during amplification which can be used to compensate the TOD mismatch between stretcher-compressor. It has been shown experimentally that, in a properly designed fiber system, nonlinearity can be used to improve output pulse quality [4, 20-22].

3.2 Laser System Performance

A cubicon system is shown schematically in Fig. 1. The fiber integrated polarization-maintaining (PM) front-end consists of an oscillator, stretcher, preamplifier, and a fiber-coupled acousto-optic modulator (AOM) downcounter. The PM Yb-fiber oscillator, described elsewhere [23], has 45 MHz repetition rate and 1035 nm center wavelength. A length of single-mode fiber stretches the pulses to ~500 ps before pre-amplification in a PM single-mode Yb-fiber. A fiber couple downcounter reduces the repetition rate to 100-300 kHz before the power amplifier.

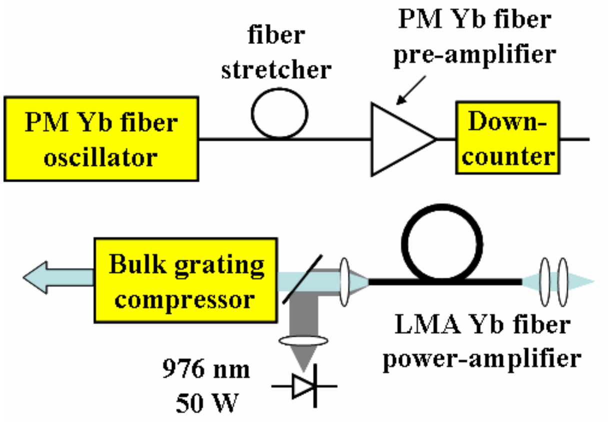

Fig. 1 Schematic of cubicon Yb fiber chirped pulse amplification system

The power amplifier is a counter-directionally pumped 3-m long Yb fiber with a 40 μm core diameter with an output M^2 of <1.2. The slope efficiency of the power amplifier is >70% and the system optical efficiency is ~33%, producing 16 W compressed from 48 W of diode power. The maximum achievable output energy is limited to ~200 μJ before compression by the ~30 J/cm^2 damage threshold of the fiber facet. Clean pulses were produced with 200 kW peak power during amplification corresponding to ~6π of SPM. Fig. 2 shows the optical efficiency of the system and autocorrelation traces for compressed pulse energies from 10 to 50 μJ at 300 kHz. A representative spectral trace, shown in the inset, has a characteristic cubicon shape with a Δλ of 5 nm (FWHM). The autocorrelation trace for 50 µJ corresponds to a 400 fs pulse (FWHM) and shows little evidence of pulse breakup from SPM.

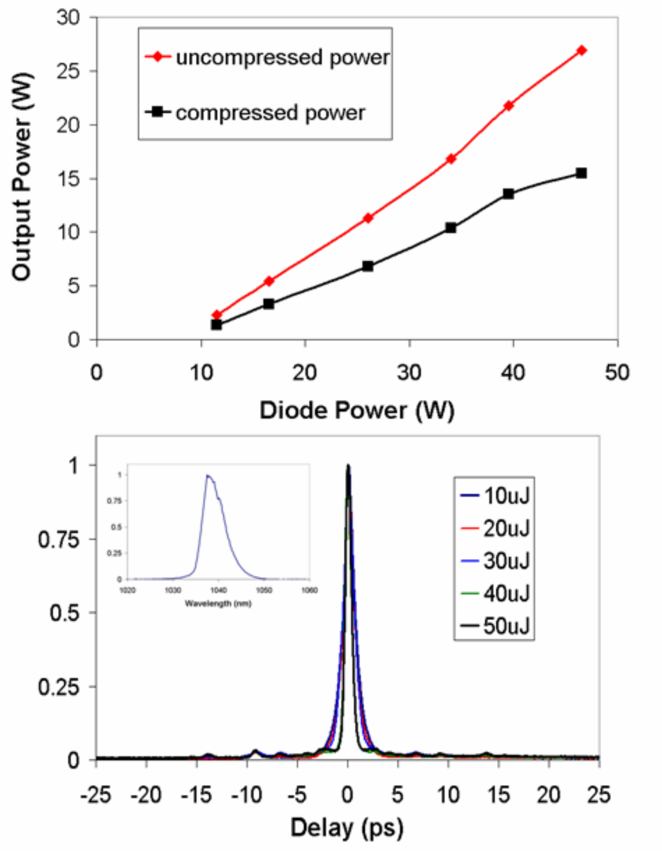

Fig. 2 System efficiency and autocorrelation of traces at 300 kHz

4. Micromachining Examples

As stated previously, scalable average power allows for scalability of processing speed. In order to investigate material removal rate, trenches were cut into several materials using 50 µJ, 400 fs laser pulses focused with a 100 mm achromatic doublet to a diameter of ~30 µm. Given these parameters, the fluence and intensity on target are estimated to be 7 J/cm^2 and 17.5x10^{12} W/cm^2, respectively.

Fig. 3 shows top-down and edge-on views of a ~30-µm wide cut made through 0.5-mm thick aluminum. With an incident laser repetition rate of 200 kHz and an average cut speed of 1.5 mm/s, the volume material removal rate is ~2.2x10^{-2} mm^3/s. Fig. 4 shows an example of a 40-µm wide and 75-µm deep trench cut into sapphire at an average speed of 2.5 mm/s with 200-kHz laser repetition rate, with a corresponding material removal rate of ~3.7x10^{-3} mm^3/s.

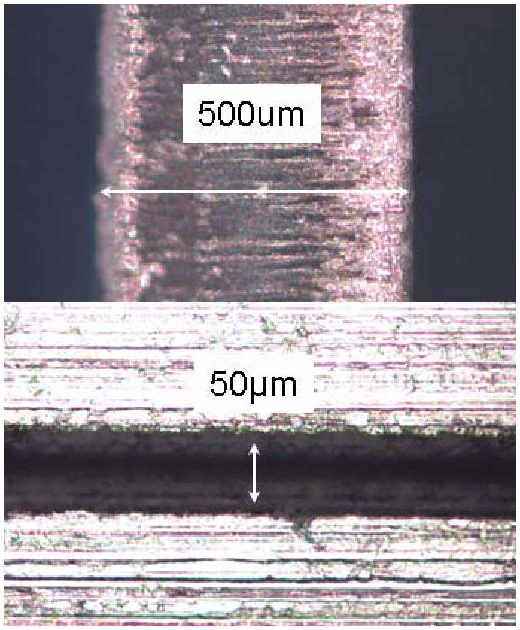

Fig. 3 Edge-on and top-down images of trenches cut into 500-µm thick aluminum using 400 fs, 50 µJ pulses at 200 kHz.

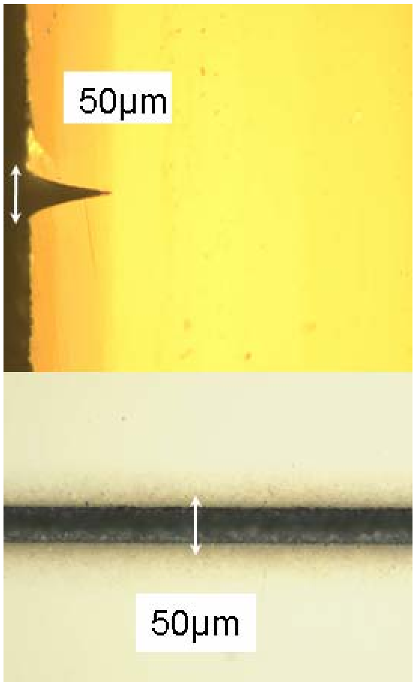

Fig. 4 Cross-section and top-down images of trenches cut into 500-µm thick sapphire using 400 fs, 50 µJ pulses at 200 kHz.

As an illustration of the importance of pulse energy and laser repetition rate on processing speed, below are several examples of scribe and break processing of 700-µm thick borosilicate glass. As shown in Fig. 5a) and d), clean breaks could be achieved using 50 µJ pulses at 200 kHz with 50-mm/s scan speed or 50 µJ pulses at 300 kHz with 75-mm/s scan speed. Unsatisfactory breaking occurred when using 50 µJ pulses at 200 kHz with 75-mm/s scan speed or 35 µJ pulses at 300 kHz at 75 mm/s, as shown in Figs. 5 b) and 5 c). Generally, we have found cleave quality is dependent upon scribe depth [25, 26]. Here we find for a scribe width of ~40 µm, a scribe depth of >60 µm is required for a smooth cleave. Previously, using 500 fs, 10 µJ pulses at 100 kHz, we achieved similar cleave quality at 2.5-mm/s scan speed producing a scribe ~7.5-µm wide and 50-µm deep [26]. These initial results indicate that there is a nearly linear correlation between the processing speed and the laser pulse energy and repetition rate. This is contrary to observations of heat accumulation [27]; however there are a wide range of factors such as scribe shape, material properties, and thermal stresses that are likely to be important in this application but are beyond the scope of this work.

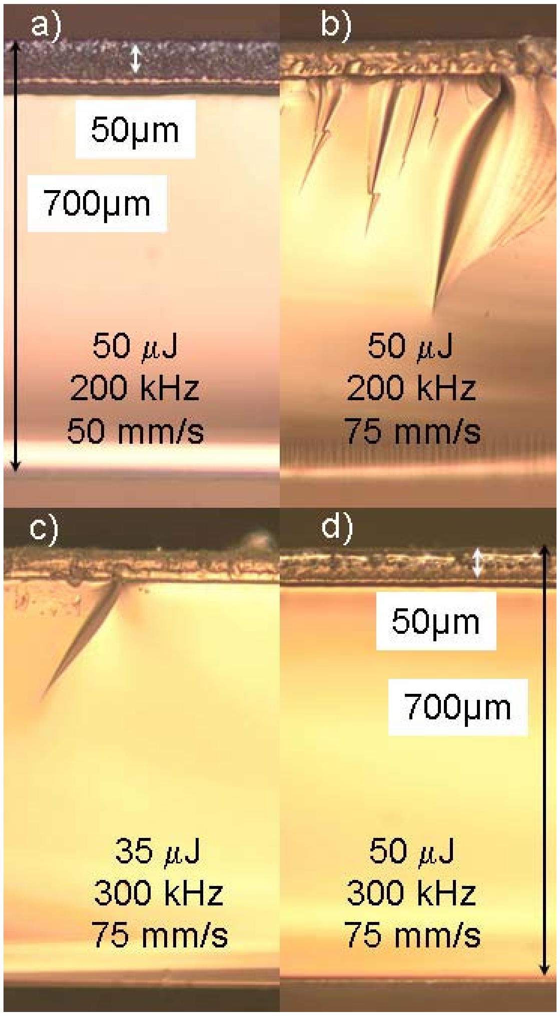

Fig. 5 Images of glass edges after scribing and breaking of 700-µm thick borosilicate glass using 400 fs pulses

5. Conclusions

One of the major limitations on ultrashort pulse laser processing speed has been average power. Here we describe a femtosecond fiber system producing 50 µJ, 400 fs laser pulses at 15 W, and show several micromachining examples demonstrating high speed processing. These initial results demonstrate that the combination of ultrashort pulse duration, high pulse energy, and high average power allow for a new regime of high speed micromachining. As such, more research is required to investigate the influence of laser parameters on processing and relate this to the performance of conventional laser during machining.

Since the current limitation on further average power scaling is the gold-coated compressor grating, the use of alternative grating technologies such as high power transmission gratings enable compressed average powers »100 W [3]. By providing high energy femtosecond pulses at high average power through an efficient and robust modular fiber architecture, cubicon fiber amplifiers offer a path to perform high speed industrial applications.

References

[1] C. Momma, B.N. Chichkov, S. Nolte, F. van Alvensleben, A. Tunnermann, H. Welling, and B. Wellegehausen, "Short-pulse laser ablation of solid targets," Opt. Commun. **129**, 134-142 (1996).

[2] X. Liu, D. Du, and G. Mourou, "Laser ablation and micromachining with ultrashort laser pulses," IEEE J. Quantum Electron. **33**, 1706-1716 (1997).

[3] F. Roser, J. Rothhard, B. Ortac, A. Liem, O. Schmidt, T. Schreiber, J. Limpert, and A. Tunnermann, "131 W 220 fs fiber laser system," Opt. Lett. **30**, 2754 (2005).

[4] L. Shah, Z. Liu, I. Hartl, G. Imeshev, G.C. Cho, and M.E. Fermann, "High energy femtosecond Yb cubicon fiber amplifier," Opt. Express **13**, 4717-4722 (2005).

[5] A.E. Siegman, *Lasers* (University Science Books, Sausalito, CA 1986).

[6] G.P. Agrawal, *Nonlinear Fiber Optics*, 3rd edition (Academic, San Diego, CA 2001).

[7] D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," Opt. Commun. **56**, 219-221 (1985).

[8] M.L. Stock and Gerard Mourou, "Chirped pulse amplification in an erbium-doped fiber oscillator/erbium-doped fiber amplifier system," Optics Comm. **106**, 249 (1994).

[9] J.D. Minelly, A. Galvanauskas, M.E. Fermann, D. Harter, J.E. Caplen, Z.J. Chen, and D.N. Payne, "Femtosecond pulse amplification in cladding-pumped fibers," Opt. Lett. **20**, 1797 (1995).

[10] L. Zenteno, "High-power double-clad fiber lasers," J. Lightwave Tech. **11**, 1435-1446 (1993)

[11] M.E. Fermann, "Single-mode excitation of multimode fibers with ultrashort pulses," Opt. Lett. **23**, 52-54 (1998).

[12] J.D. Minelly, A. Galvanauskas, D. Harter, J.E. Caplen, and L. Dong, "Cladding-pumped fiber laser/amplifier system generating 100 μJ energy picosecond pulses," Conference on Lasers and Electro Optics 1997, CFD4.

[13] A. Galvanauskas, G.C Cho, A. Hariharan, M.E Fermann, and D. Harter, "Generation of high-energy femtosecond pulses in multimode-core Yb-fiber chirped-pulse amplification systems," Opt. Lett. **26**, 935-937 (2001).

[14] T. Schreiber, F. Roser, J. Limpert, A. Liem, S. Hofer, H. Zellmer, M. Will, S. Nolte, and A. Tunnermann, "High repetition rate, high energy, fiber CPA for materials processing," Conference on Lasers and Electro Optics 2005, CFH3.

[15] I. Hartl, G. Imeshev, Z. Liu, Z. Sartania, and M.E. Fermann, "In line Yb fiber master oscillator power amplifier generating stretched 20 μJ pulses with up to 140 kW peak power," Conference on Lasers and Electro Optics 2005, CThPDA10.

[16] J. Limpert, T. Clausnitzer, A. Liem, T. Schreiber, H.-J. Fuchs, H. Zellmer, E.-B. Kley, and A. Tunnermann, "High-average-power femtosecond fiber chirped-pulse amplification system," Opt. Lett. **28**, 1984-1986 (2003).

[17] D. Anderson, M. Desaix, M. Karlsson, M. Lisak, and M.L. Quiroga-Teixeiro, "Wave-breaking-free pulses in nonlinear optical fibers," J. Opt. Soc. Am. B. **10**, 1185 (1993).

[18] M.E. Fermann, "Self-similar propagation and amplification of parabolic pulses in optical fiber," Phys. Rev. Lett. **84**, 6010 (2000).

[19] J. Limpert, T. Schreiber, T. Clausnitzer, K. Zollner, H.-J. Fuchs, E.-B. Kley, H. Zellmer, and A. Tunnermann, "High-power femtosecond Yb-doped fiber amplifier," Opt. Express **10**, 628-638 (2002).

[20] Z. Liu, L. Shah, I. Hartl, G.C. Cho and M.E. Fermann, "The Cubicon Amplifier," Photonics West 2005 postdeadline paper.

[21] S. Zhou, L. Kuznetsova, A. Chong, and F.W. Wise, "Compensation of nonlinear phase shifts with third-order dispersion in short-pulse fiber amplifiers," Opt. Express **13**, 4869-4877 (2005).

[22] T. Schreiber, F. Röser, O. Schmidt, B. Ortac, C. Nielsen, J. Limpert, and A. Tünnermann, "Influence of pulse shape in SPM limited high-energy chirped pulse fiber amplifier systems," to be published in Conference on Lasers and Electro Optics 2006, CThR4.

[23] I. Hartl, G. Imeshev, L. Dong, G. C. Cho and M. E. Fermann, "Ultra-compact dispersion compensated fiber oscillators and amplifiers," Conference on Lasers and Electro Optics 2005, CThG1.

[24] J.M. Bovatsek, F. Yoshino and A.Y. Arai: Proc. of the 6th International Symposium on Laser Precision Microfabrication (LPM2005).

[25] J. Bovatsek, A. Arai, F. Yoshino and Y. Uehara: "Fiber Laser III: Technology, Systems and Applications", Proc. of SPIE Vol. 6102-01 (2006).

[26] F. Yoshino, J. Bovatsek, A. Arai, Y. Uehara, to be published in the Proceedings of the 4th International Congress on Laser Advanced Materials Processing 2006, Tu1-7.

[27] S. Eaton, H. Zhang, P.R. Herman, F. Yoshino, L. Shah, J. Bovatsek, and A.Y. Arai, "Heat accumulation effects in femtosecond laser written waveguides with variable repetition rate," Opt. Express **13**. 4708-4716 (2005).

(Received: May 16, 2006, Accepted: October 10, 2006)