Yb:YAG single crystal fiber power amplifier for femtosecond sources

Xavier Délen, Yoann Zaouter, Igor Martial, Nicolas Aubry, Julien Didierjean, Clemens Hönninger, Eric Mottay, François Balembois, Patrick Georges

HAL Id: hal-00854435

https://hal-iogs.archives-ouvertes.fr/hal-00854435

Submitted on 27 Aug 2013

Yb:YAG single crystal fiber power amplifier for femtosecond sources

Xavier Délen,[1,*] Yoann Zaouter,[2] Igor Martial,[3] Nicolas Aubry,[3] Julien Didierjean,[3] Clemens Hönninger,[2] Eric Mottay,[2] François Balembois,[1] and Patrick Georges[1]

[1]*Laboratoire Charles Fabry, Institut d'Optique, CNRS, Université Paris Sud, 2 Avenue Augustin Fresnel, 91127 Palaiseau Cedex, France*

[2]*Amplitude Systemes, 6 allée du Doyen Georges Brus, Pessac 33600, France*

[3]*Fibercryst SAS, La Doua-Bâtiment l'Atrium, Boulevard Latarjet, F-69616 Villeurbanne Cedex, France*

*Corresponding author: xavier.delen@institutoptique.fr

We demonstrate a versatile femtosecond power amplifier using a Yb:YAG single crystal fiber operating from 10 kHz to 10 MHz. For a total pump power of 75 W, up to 30 W is generated from the double-pass power amplifier. At a repetition rate of 10 kHz, an output energy of 1 mJ is obtained after recompression. In this configuration, the pulse duration is 380 fs, corresponding to a peak power of 2.2 GW. The M^2 beam quality factor is better than 1.1 for investigated parameters.   © 2013 Optical Society of America
OCIS codes: 320.7090, 140.3615.

Ultrafast lasers are now a common tool for scientific and industrial applications. Over the past decade, many technological developments of diode-pumped solid-state laser systems have allowed tremendous improvements of their performance, reliability, and cost. In order to achieve high energy per pulse in the femtosecond regime, master oscillator power amplifier systems are commonly used. Regenerative amplifiers based on bulk or thin disk Yb-doped crystals can amplify ultrashort pulses to several tens of millijoules [1,2]. They can provide high gain and high output energy at a low repetition rate, but they are limited in terms of repetition rate to a few hundreds of kilohertz due to the high-voltage-driven switch speed. Ytterbium-doped optical fibers can also be used to amplify ultrashort pulses. Their high surface-to-volume ratio provides good thermal management and allows attainment of high average powers of several hundreds of watts [3]. However, the signal confinement in small-cross-section cores induces nonlinear effects, such as self-phase modulation and self-focusing, which limit the peak power and the pulse energy. Femtosecond pulses with an energy of 2.2 mJ were obtained using the well-known chirped pulse amplification technique together with large-core-diameter photonic crystal fibers [4]. Another approach consists in amplifying femtosecond pulses directly in Yb-doped crystals using multipass amplifiers without active elements. Although it requires quite complex systems, the slab geometry has proven to be a very successful approach. Up to 1.1 kW [5] average power and 20 mJ [6] energy were obtained with an Yb:YAG Innoslab amplifier. Significant improvement of the emission cross section and the thermal conductivity can be observed at cryogenic temperatures in most Yb-doped crystals. 40 mJ output energy was obtained using a cryogenic Yb:YAG double-pass amplifier [7]. However, stronger spectral narrowing at low temperatures induces longer optical pulses of several picoseconds. Finally, the single crystal fiber (SCF) concept lies between fibers and crystals and can contribute to original performance for femtosecond systems.

SCFs are long, thin crystal rods with a diameter lower than 1 mm and a typical length of a few centimeters. SCFs are designed for free-space propagation of the laser signal, as in bulk lasers together with a guidance of the pump beam, which depends on the pump brightness. This concept has recently been successfully implemented in Yb:YAG lasers and demonstrated continuous emission of 250 W from an oscillator based on a 1% doped Yb:YAG SCF pumped by a 600 W laser diode [8]. This clearly shows the potential of this approach for high-power extraction. Furthermore, Yb:YAG SCF also demonstrated high single-pass gain with very simple amplifier geometries.

In the context of ultrashort pulse amplification, SCF provides several advantages that clearly benefit the amplification of ultrashort and intense pulses. Among them, the mitigation of nonlinear effects thanks to the short length of interaction together with the large beam diameter is probably the most interesting. Also, the high gain per pass prevents the use of a regenerative amplifier and therefore significantly expands the range of operation at a high repetition rate. Consequently, Yb:YAG SCF has attracted attention as a potential simple, robust, and cost effective amplifier of ultrashort pulses. In a proof-of-principle experiment, femtosecond pulses were directly amplified from 400 mW to 12 W average power in a double-pass architecture while maintaining the duration of the 30 MHz repetition rate pulses below 400 fs [9].

In this Letter, we demonstrate a femtosecond power amplifier using a diode-pumped Yb:YAG SCF operating from 10 kHz to 10 MHz. For a total pump power of 75 W out of a fiber-coupled high-brightness laser diode, up to 30 W is generated from the double-pass power amplifier. At a repetition rate of 10 kHz, an output energy of 1 mJ is obtained after recompression.

The experimental setup is shown in Fig. 1. The seed source provides a train of stretched and amplified pulses with a repetition rate ranging from 10 kHz to 10 MHz, a maximum energy per pulse of 150 μJ, and a maximum average power of 10 W. The optical spectrum is 4.3 nm at full width at half-maximum (FWHM) and is centered around 1030 nm to match the gain bandwidth of the Yb:YAG SCF booster placed downstream after optical isolation. A 500 mm focal length lens (L1) is used to focus
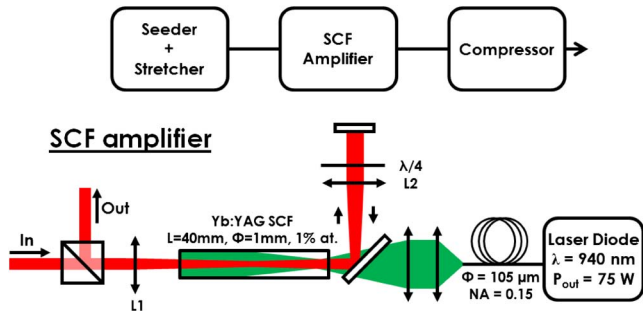
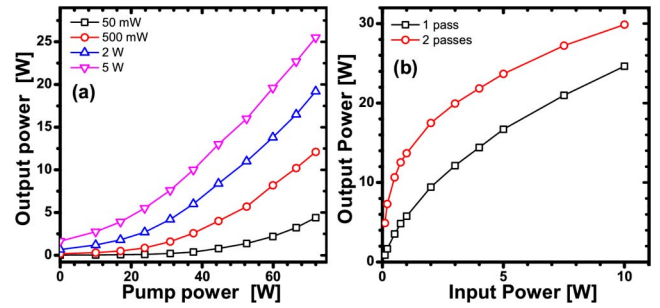Fig. 1.   (Color online) Experimental setup.

Fig. 2.   (Color online) (a) Output power before compression versus pump power for different seed powers in the double-pass configuration and (b) output power versus input power at 10 MHz in single-pass and double-pass configurations for a pump power of 72 W.

the seed beam on the crystal input facet to a measured diameter of 450 μm. The gain element is a TARANIS laser gain module from Fibercryst, integrating a 40 mm long, 1 mm diameter Yb:YAG SCF with a 1 at. % doping rate. The two crystal facets have an antireflective coating at the pump and signal wavelengths to prevent parasitic lasing and excess losses at the interfaces. The SCF mount is water-cooled at a temperature of 16 °C. The pump source is a high brightness laser diode (JOLD-75-FC-11 from Jenoptik) with side-by-side combined single emitters. It emits up to 75 W at 940 nm coupled in a fiber having a core diameter of 105 μm and an NA of 0.15. The pump fiber output is imaged inside the SCF with a magnification factor of 3.75 using two doublets with focal lengths of 40 and 150 mm. Because of the low NA of the pump beam, it is in free propagation and only weakly guided at the end of the SCF. Depending on the pump waist position, the first section of the SCF in which the pump is in free propagation is between 15 and 25 mm long. A dichroïc mirror is used to separate the incoming pump beam from the first-pass output of the signal beam. To perform a second pass of amplification into the gain module, the signal waist after the first pass is imaged on a highly reflective plane mirror using a lens (L2) operating in $f-f$ configuration. The adjustment of this imaging system is done at full pump power in order to optimize the second-pass alignment with the nominal thermal lens. The polarization is also rotated by 90° using a quarter-wave plate between the first and second pass, which allows extraction on the input polarizer.

The experiment is first operated at the maximum repetition rate of 10 MHz in order to characterize our amplifier in terms of average power extraction capability in single-pass and double-pass configurations without having to consider nonlinear effects and in particular self-focusing. Figure 2(a) shows the output power versus the pump power for 50 mW to 5 W seed power. For a low seed power of 50 mW, gains of 10 and 90 are measured in single-pass and double-pass configurations, respectively. For a 500 mW input, the output power reaches a maximum of 12 W in two passes for 72 W of pump power. In this configuration 95% of the pump power is absorbed. In a previous experiment, we obtained similar performance, but with a much higher pump power of 180 W coupled in a 200 μm core diameter fiber with an NA of 0.22 [9]. This considerable efficiency improvement is brought by the high pump brightness, which allows for a better geometrical overlap between the signal and the pump beams in the crystal section where the pump is not guided. For a seed power of 5 W, the output power

reaches 17.8 and 25.5 W for one pass and two passes, respectively. With an extracted power of 20.5 W, the optical-to-optical efficiency is 28.5% with the double-pass configuration. Moreover, the slope efficiency increases constantly with the pump power to reach almost 50%. This clearly demonstrates the potential for the use of our amplifier with higher pump powers.

Next, we study the output power of the SCF amplifier as a function of the seed power. It is worth mentioning that without injection, the output signal was not measurable with our power meter for the double-pass configuration (it is estimated to be lower than 2 mW). Consequently, the SCF can operate at very low seed power without perturbation by amplified spontaneous emission. Thanks to the high gain available in the SCF amplifier, the output power rapidly reaches the 10 W level for a seed power of 1 W [Fig. 2(b)]. As a result, the SCF is able to boost a signal between 10 and 30 W for any input signal in the range between 1 and 10 W.

To explore the flexibility in the repetition rate and thus in the energy of the Yb:YAG SCF booster, we decrease the frequency of the seed laser from 10 MHz to 10 kHz. Figure 3 shows the input energy and the output energy after two passes for different repetition rates. For high repetition rates above 100 kHz, the gain is constant and equal to 3. Between 100 and 10 kHz, the output pulse energy continuously increases to 1.3 mJ at 10 kHz, corresponding to a gain of 9.

Figure 4(a) shows the spectrum of the amplified pulses at maximum output energy (1.3 mJ). The gain-narrowing effect progressively narrows the optical spectrum, which
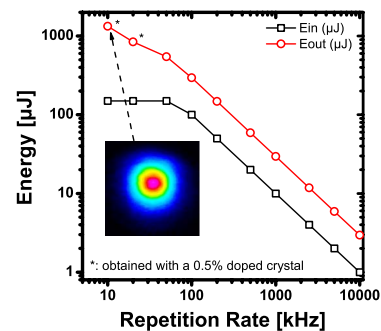

Fig. 3.   (Color online) Input and output energies after two passes versus the repetition rate. Inset: output beam profile for 1.3 mJ at 10 kHz output.
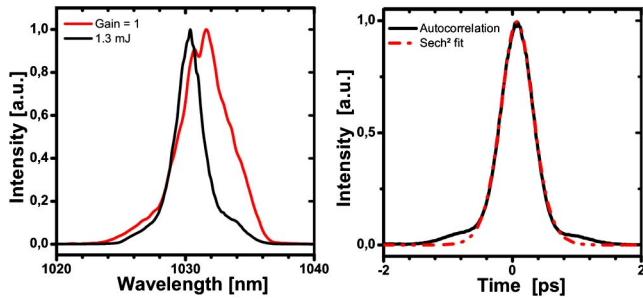
Fig. 4.   (Color online) (a) Input and output spectrum, and (b) pulse autocorrelation for 1 mJ output at 10 kHz after recompression.

FWHM decreases from 4.3 to 2.3 nm at maximum energy. Consequently, the pulse duration decreases during amplification and is calculated to be about 150 ps at 1.3 mJ, leading to an extracted peak power close to 10 MW. This peak power is remarkably high and never could have been reached in a silica-based fiber amplifier, where self-focusing usually destroys the gain medium for a peak power not higher than 4 MW. Even if it does not limit the output peak power in our case because of the short crystal length, we can also expect self-focusing in Yb:YAG, inducing a decrease of the beam size on the output facet and potential damage of the antireflective coating. Aware of this effect, we monitor the beam size on the output facet while increasing the seed power at a constant repetition rate. We do not observe any decrease of the beam size that would indicate self-focusing due to higher peak power. Furthermore, no modification of the beam profile is observed, and M^2 values below 1.1 were measured for all parameters investigated in the article (see beam profile in the inset of Fig. 3).

In order to recover the femtosecond regime, the pulses are recompressed using a transmission-grating-based compressor with an efficiency of 76%. Figure 4(b) shows the autocorrelation trace of the output pulses at a 10 kHz repetition rate and a pulse energy of 1 mJ. It has an FWHM of 590 fs, corresponding to a pulse duration of 380 fs, assuming a sech^2 pulse shape. The corresponding peak power is estimated to be in excess of 2.2 GW after taking into account the fact that more than 95% of the total energy remains in the central pulse. As expected from the gain narrowing, the pulse duration is increasing for large gain values but it remains below 550 fs. Considering the upper state lifetime of Yb in YAG and the total energy storage capacity, the output energy should continue to increase if we reduce the repetition rate below 10 kHz. However, the antireflection coating of the output

facet degrades at 1.3 mJ of extracted energy, corresponding to an energy density of 1.1 J/cm^2 on the output facet. The authors believe that this value can be increased by an order of magnitude by applying different coatings or by using a Brewster-cut gain sample.

In conclusion, we have shown that Yb:YAG SCF pumped by a high-brightness laser diode can be used as a power amplifier for a wide range of seed powers and repetition rates. Sub-550 fs pulses with excellent beam quality ($M^2 < 1.1$) have been obtained with average powers between 10 and 23 W for repetition rates ranging from 10 kHz to 10 MHz. The amplifier is also able to produce high energy pulses, the best performance being 1 mJ pulses at 10 kHz with a duration of 380 fs. Considering the versatility of this amplifier and its simplicity and compactness, the Yb:YAG SCF demonstrates a strong potential to boost femtosecond systems in the millijoule range with average powers in the several tens of watts range. Further development of SCF amplifiers will concern power scaling with higher power pump laser diodes and energy scaling with improvement of the damage threshold of the amplifier faces.

References

1. A. V. Okishev, Opt. Lett. **37**, 1199 (2012).
2. T. Metzger, A. Schwarz, C. Y. Teisset, D. Sutter, A. Killi, R. Kienberger, and F. Krausz, Opt. Lett. **34**, 2123 (2009).
3. T. Eidam, S. Hanf, E. Seise, T. V. Andersen, T. Gabler, C. Wirth, T. Schreiber, J. Limpert, and A. Tünnermann, Opt. Lett. **35**, 94 (2010).
4. T. Eidam, J. Rothhardt, F. Stutzki, F. Jansen, S. Hädrich, H. Carstens, C. Jauregui, J. Limpert, and A. Tünnermann, Opt. Express **19**, 255 (2011).
5. P. Russbueldt, T. Mans, J. Weitenberg, H. D. Hoffmann, and R. Poprawe, Opt. Lett. **35**, 4169 (2010).
6. M. Schulz, R. Riedel, A. Willner, T. Mans, C. Schnitzler, P. Russbueldt, J. Dolkemeyer, E. Seise, T. Gottschall, S. Hädrich, S. Duesterer, H. Schlarb, J. Feldhaus, J. Limpert, B. Faatz, A. Tünnermann, J. Rossbach, M. Drescher, and F. Tavella, Opt. Lett. **36**, 2456 (2011).
7. K. Hong, J. T. Gopinath, D. Rand, A. M. Siddiqui, S. Huang, E. Li, B. J. Eggleton, J. D. Hybl, T. Y. Fan, and F. X. Kärtner, Opt. Lett. **35**, 1752 (2010).
8. X. Délen, S. Piehler, J. Didierjean, N. Aubry, A. Voss, M. Abdou Ahmed, T. Graf, F. Balembois, and P. Georges, Opt. Lett. **37**, 2898 (2012).
9. Y. Zaouter, I. Martial, N. Aubry, J. Didierjean, C. Hönninger, E. Mottay, F. Druon, P. Georges, and F. Balembois, Opt. Lett. **36**, 748 (2011).