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# Generation of 150-fs pulses from a diode-pumped Yb:KYW nonlinear regenerative amplifier

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**Abstract:** Generation of sub-150-fs-level pulses has been obtained from an Yb-doped crystal-based regenerative amplifier by applying an innovative amplification scheme. This scheme is based on optimization of the linear and non-linear phase during the amplification process inside the regenerative amplifier cavity. This technique with Yb:KYW allows to achieve pulse durations from diode-pumped Yb-doped regenerative amplifiers that were up to now only accessible with more complex Ti:sapphire amplifiers. With this Yb-doped tungstate crystal used in regenerative amplifiers, 145 fs pulses centered at 1026 nm with a spectral bandwidth of 14 nm at 50 kHz for an average power of 1.6 W have been generated.

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**OCIS codes:** (140.3615) Lasers, ytterbium; (140.3280) Laser amplifiers; (140.7090) Ultrafast lasers.

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## References and links

1. S. Nolte, C. Momma, H. Jacobs, A. Tünnermann, B. N. Chichkov, B. Wellegehausen, and H. Welling, "Ablation of metals by ultrashort laser pulses," *J. Opt. Soc. Am. B* **14**(10), 2716–2722 (1997).
2. D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," *Opt. Commun.* **55**(6), 447–449 (1985).
3. M. Delaigue, I. Manek-Hönninger, F. Salin, C. Hönninger, P. Rigail, A. Courjaud, and E. Mottay, "300 kHz femtosecond Yb:KGW regenerative amplifier using an acousto-optic Q-switch," *Appl. Phys. B* **84**(3), 375–378 (2006).
4. D. Nickel, C. Stolzenburg, A. Giesen, and F. Butze, "Ultrafast thin-disk Yb:KY(WO<sub>4</sub>)<sub>2</sub> regenerative amplifier with a 200-kHz repetition rate," *Opt. Lett.* **29**(23), 2764–2766 (2004).
5. P. Raybaut, F. Balembos, F. Druon, and P. Georges, "Numerical and experimental study of gain narrowing in ytterbium-based regenerative amplifiers," *IEEE J. Quantum Electron.* **41**(3), 415–425 (2005).
6. S. Ricaud, F. Druon, D. N. Papadopoulos, P. Camy, J.-L. Doualan, R. Moncorgé, M. Delaigue, Y. Zaouter, A. Courjaud, P. Georges, and E. Mottay, "Short-pulse and high-repetition-rate diode-pumped Yb:CaF<sub>2</sub> regenerative amplifier," *Opt. Lett.* **35**(14), 2415–2417 (2010).
7. E. Caracciolo, M. Kemnitzer, A. Guandalini, F. Pirzio, J. Aus der Au, and A. Agnesi, "28-W, 217 fs solid-state Yb:CaIGdO<sub>4</sub> regenerative amplifiers," *Opt. Lett.* **38**(20), 4131–4133 (2013).
8. G. H. Kim, J. Yang, S. A. Chizhov, E. G. Sall, A. V. Kulik, V. E. Yashin, D. S. Lee, and U. Kang, "High average-power ultrafast CPA Yb:KYW laser system with dual-slab amplifier," *Opt. Express* **20**(4), 3434–3442 (2012).
9. U. Buenting, H. Sayinc, D. Wandt, U. Morgner, and D. Kracht, "Regenerative thin disk amplifier with combined gain spectra producing 500 microJ sub 200 fs pulses," *Opt. Express* **17**(10), 8046–8050 (2009).
10. M. Larionov, F. Butze, D. Nickel, and A. Giesen, "High-repetition-rate regenerative thin-disk amplifier with 116 μJ pulse energy and 250 fs pulse duration," *Opt. Lett.* **32**(5), 494–496 (2007).
11. G. H. Kim, J. H. Yang, D. S. Lee, A. V. Kulik, E. G. Sall, S. A. Chizhov, U. Kang, and V. E. Yashin, "Femtosecond laser based on Yb:KYW crystals with suppression of spectral narrowing in a regenerative amplifier by spectral profiling of the pulse," *J. Opt. Technol.* **80**(3), 142–147 (2013).
12. Y. Zaouter, D. N. Papadopoulos, M. Hanna, J. Boulet, L. Huang, C. Aguerarary, F. Druon, E. Mottay, P. Georges, and E. Cormier, "Stretcher-free high energy nonlinear amplification of femtosecond pulses in rod-type fibers," *Opt. Lett.* **33**(2), 107–109 (2008).

13. D. N. Papadopoulos, Y. Zaouter, M. Hanna, F. Druon, E. Mottay, E. Cormier, and P. Georges, "Generation of 63 fs 4.1 MW peak power pulses from a parabolic fiber amplifier operated beyond the gain bandwidth limit," *Opt. Lett.* **32**(17), 2520–2522 (2007).
14. S. A. Planas, N. L. Mansur, C. H. Cruz, and H. L. Fragnito, "Spectral narrowing in the propagation of chirped pulses in single-mode fibers," *Opt. Lett.* **18**(9), 699–701 (1993).
15. J. Pouysegur, M. Delaigue, Y. Zaouter, C. Hönninger, E. Mottay, A. Jaffrès, P. Loiseau, B. Viana, P. Georges, and F. Druon, "Sub-100-fs Yb:CALGO nonlinear regenerative amplifier," *Opt. Lett.* **38**(23), 5180–5183 (2013).

## 1. Introduction

Significant progress has been made during the recent years in the development of diode-pumped femtosecond lasers based on Yb-doped materials. This achievement has enabled this technology into more and more industrial domains addressing applications such as micromachining or eye surgery [1]. Indeed, femtosecond lasers based on the chirped pulse amplification (CPA) scheme [2] have developed a growing interest since they combine ultrashort pulse duration, high pulse energy, and extreme high peak power (up to the GW-level) in a simple and reliable architecture. The use of the Yb-based laser technology has allowed addressing efficiency for the systems and high repetition rates. Industrial apparatus for the development of CPA systems with the 400-fs-range pulses have been essentially based on Yb-doped tungstate [3,4] that are mature crystals and have provided very reliable laser systems. However, the main concern has been to access shorter pulse in CPA systems by relying on the gain narrowing effect. In fact, typical femtosecond CPA systems use ultrashort pulses from the laser oscillator that are strongly temporally stretched in a positive dispersion pulse stretcher prior to amplification. This approach has enabled pulse amplification over several orders of magnitude without suffering from nonlinear effects or damage of optical components. After the amplification process, the pulses were compressed down to the femtosecond regime by means of a negative dispersion pulse compressor that compensates for the positive dispersion of the stretcher and the amplifier. Nevertheless, the main drawback concerned the spectral gain narrowing [5], which is not handled and leads to an increase of the pulse duration during amplification. In order to overcome this problem, one method consists in using innovative and atypical crystals with particular spectral properties to counteract the spectral gain narrowing and to access shorter-pulse amplifiers [6,7]. In the case of a Yb:KY(WO<sub>4</sub>)<sub>2</sub> crystal (Yb:KYW), the pulses duration of the oscillators can easily be in the 200 fs range but they moved to a typical range of 300-400 fs after amplification. Research has been carried out to resolve this problem by enhancing the effective gain bandwidth with combination of gain media with separated gain maxima and overlapping broadband gain, allowing the generation of 180-fs-level pulses [8,9]. Another solution consists to use nonlinear effects [10,11] providing limited pulse duration to 250-500fs. In these configurations, the nonlinear effects strongly affect the temporal shape leading to large pedestals. These nonlinear effects are commonly seen as deleterious effects in bulk amplifiers even though they have been employed in fiber amplifiers [12,13]. They can also be used in regenerative amplifier to generate short pulses while maintaining good temporal quality.

Yb:KYW crystals for regenerative amplifiers are already integrated in industrial systems and it would be beneficial to improve their performance by reaching a 100-150 fs range with pulses of high temporal quality. In order to reach this objective, a new method has been developed using optimized control of the linear and nonlinear effects during amplification. An essential feature of the technique is to start the amplification process with a tailored negative stretching of the seed laser. Because of the effective positive dispersion of the regenerative amplifier cavity, this leads to temporal compression during amplification, and partly to spectral compression [14] that appears to be beneficial to access nice temporal shapes after amplification. Furthermore, this technique includes spectral broadening by self-phase modulation during the last roundtrips of the amplification cycle. Due to the nonlinear effects, the technique is able to overcome spectral gain-narrowing during amplification. This leads to slightly chirped pulses of a few ps pulse duration at the output of the amplifier, which can be easily compressed with chirped mirrors or a standard compressor.

In the present article, we report on the first laser sources using this negative stretching technique on Yb:KYW regenerative amplifier. This generates the shortest pulses, to our best knowledge, from Yb:KYW amplifier with duration of 145 fs, energies of several 10  $\mu$ J, and average power of up to 1.6 W.

## 2. Experimental Setup

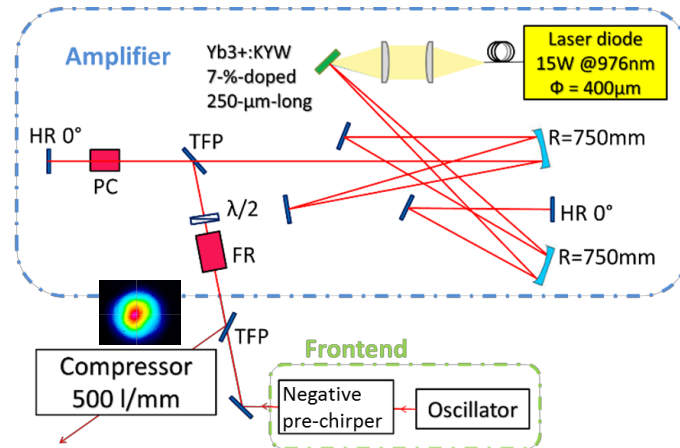


Fig. 1. Experimental Setup and amplified beam profile. HR: High Reflective Mirror. TFP: Thin Film Polarizer. FR: Faraday rotator. PC: Pockels cell.

The schematic of the laser setup is depicted in Fig. 1. The laser source consists of a compact low-power and broadband seed fiber-oscillator and a regenerative amplifier using broadband Yb:KYW. The laser oscillator delivers pulses centered at 1030 nm with a spectral bandwidth of 10 nm at 40 MHz for an average power of a few mW. Pulses are stretched to operate in negative dispersion leading to low stretched pulses of typically less than 5 ps. A 20 mm single BBO Pockels cell combined with a 2 mm thin film polarizer (TFP) are used as an optical gate to trap the pulse to be amplified with minimal losses inside the regenerative amplifier and extract it after amplification. The crystal used inside the amplifier is a 250- $\mu$ m thick 7 at% doped Yb:KYW. This crystal is used in active mirror configuration. It is longitudinally pumped with a 15-W, 400- $\mu$ m-diameter-fiber-coupled laser diode emitting at 976 nm. The pump beam is 1:1 imaged in the crystal. The cavity length is 3 m (corresponding to a round trip of 20 ns). In order to easily optimize the pulse duration, the compressor uses transmission gratings of 500 grooves per mm to compress chirped pulses with an overall efficiency of 75%.

The seed laser is negatively chirped with an amount of dispersion that is dimensioned in relation to the positive dispersion (around 0.2 ps<sup>2</sup>) that the pulses encounter in the amplifier for a build-up time of 1.8  $\mu$ s (around 90 round trips inside the amplifier). This leads to temporal compression of the pulses. When the pulse peak power is sufficient and pulse dispersion still negative, self-phase-modulation-induced spectral compression appears. The exact compensation of the dispersion occurs at the 80th round-trip in the regenerative amplifier where the energy is higher and the nonlinear effects predominant. Then, the self-phase modulation encountered by the amplified pulses compensates for gain narrowing and drastically broadens the spectrum. The non-linear-spectral compression has the advantage of “cleaning” the pulse by cutting the high-order phases that are located in the edges of the spectrum. Indeed, the nonlinear compression allows to have a nearly Fourier Transform (FT) pulse just before the spectral broadening, which is not the case when the pulse is FT at the input. In this last case, the pulse is already importantly stretched when the spectral broadening occurs. This difference plays the major role in the cleaning. On a chirped pulse the temporal intensity is directly related to the spectral shape. And, for the spectral compression case, the

spectrum is reshaped to a nicer shape and almost FT with then less uncompressible phase added during the beginning of spectral broadening.

We have after the spectral compression stage, a quasi-Fourier-transform limited pulse. This pulse appears to exhibit good spectro-temporal properties to give an excellent compressible pulse after the subsequent spectral broadening. Indeed, due to the SPM, the intensity shape has an impact on the pulse phase after the broadening and thus its compressibility.

After optimal recompression it enables the generation of ultrashort femtosecond duration even shorter than the seed pulses and far beyond the classical gain narrowing limit. In contrast to previous work exploiting nonlinear spectral pulse broadening during amplification [8], the essentially coherent character of the spectral broadening lasting only in the last amplifier phase enables the generation of compressed femtosecond pulses of excellent temporal quality without strong tails containing a significant portion of the pulse energy. Moreover, the spectral pulse compression phase allows starting with a well-shaped pulse and a flat spectral phase, which allow initiating the pulse broadening on an excellent basis.

### 3. Experimental results

In order to estimate the spectrum accessible with this amplifier in a “standard” long-stretched pulse amplifier configuration, preliminary results have been acquired without seeding. In Q-switched regime, we can obtain a spectrum of 3 nm bandwidth as shown in Fig. 2. As expected, this typical bandwidth of few nm is a relatively good representation of what is obtained in standard amplifiers developed with CPA technology using Yb:KYW leading then to 400-fs pulse duration. With the help of nonlinearities, we can improve the spectral bandwidth by almost a factor x5. For instance, with 32  $\mu$ J at the amplifier output, the generated spectrum is then around 14 nm bandwidth without parasitic ASE light observed. The shape of the spectrum exhibits a deep because of the high value of B-integral of 9 rad leading to strong SPM effect. This indeed is quite above the gain bandwidth limit for this kind of amplifier material when considering an amplification gain of more than 50 dB. In our case the main source of nonlinearities was provided by the BBO crystal and the KYW crystal where beam sizes were 1 mm and 400  $\mu$ m in diameter, respectively.

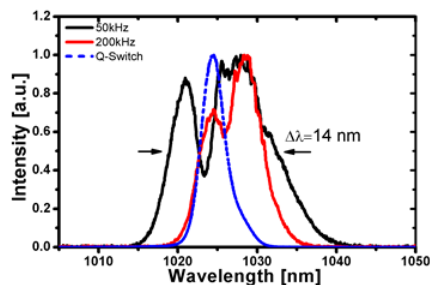


Fig. 2. Output spectrum for different repetition rate: 200 kHz (red), 50 kHz (black) and Output spectrum in Q-switched regime (dashed blue).

The shortest pulse duration was achieved at a repetition rate of 50 kHz with 1.6 W compressed average power corresponding to 32  $\mu$ J pulse energy. The autocorrelation was 200 fs after compression and it was close to the Fourier transform limit. The corresponding autocorrelation trace is shown in Fig. 3(a). By calculating the pulse duration at the Fourier limit we can estimate the duration to be around 145 fs (see Fig. 3.), leading to a time bandwidth product (TBP) of 0.58. This value is higher than for a  $\text{sech}^2$  or a Gaussian pulse mainly because of the spectral shape, which leads to the same value when Fourier transformed with a flat phase (Fig. 3). The pulse quality was beneficial with a very slight pedestal induced by uncompensated spectral phase containing less than 10% of the overall energy.

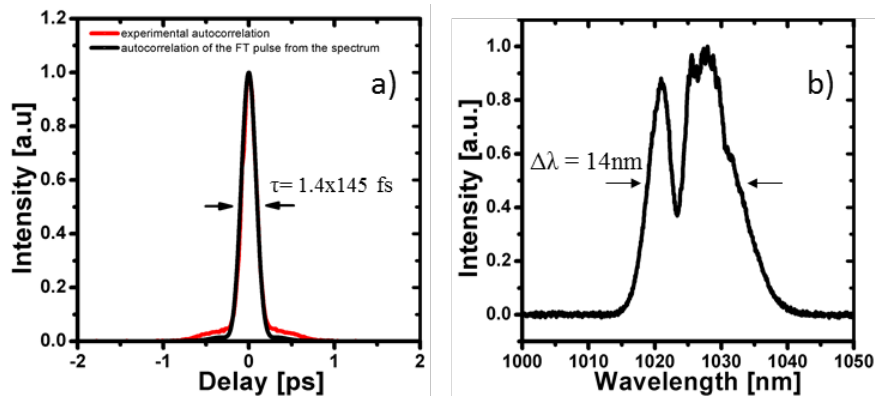


Fig. 3. Autocorrelation at 50 kHz (a) and Corresponding spectrum (b).

From 50 kHz to 200 kHz the Yb:KYW regenerative amplifier produced spectrally broadened high quality pulses for energies in the range of 10-30  $\mu\text{J}$  as shown in Fig. 4. The associated autocorrelation FWHM durations were below 300 fs leading to pulses typically in the 145-215 fs range. The average output power was between 1.6 and 2.2 W after compression. (Fig. 4(a)).

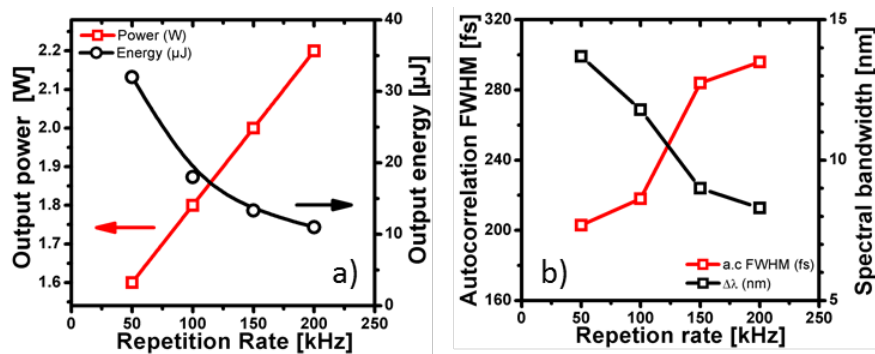


Fig. 4. (a) Average output power (red) and pulse energy (black) as a function of repetition rate – (b) Autocorrelation FWHM as a function of repetition rate.

In that span, as nonlinear effects depend on the pulse energy, the lower the repetition rate the shorter the pulses (see Fig. 4(b)). In the current setup, 32  $\mu\text{J}$  represented the maximum accessible energy (Fig. 4(a)). Afterwards, the pulse intensity in the regenerative amplifier was too high and the risk of damaging the crystal became too important to be used in a reliable system. Moreover, we observed a degradation of the spatial profile when we reached lower repetition rates. As show in Fig. 1, the beam profile at 32  $\mu\text{J}$  exhibited a perfect  $\text{TEM}_{00}$  profile. The transverse spatial beam profile was measured (Fig. 5.) showing the satisfactory quality of the beam with a  $M^2 < 1.2$  in both vertical and horizontal directions.

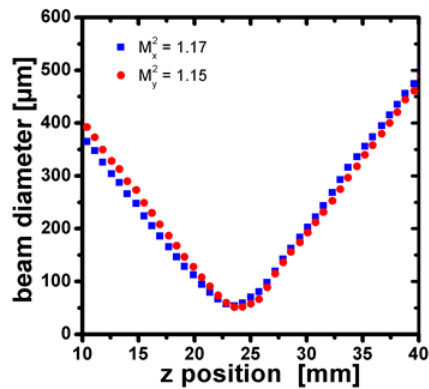


Fig. 5. Camera-based measurement of beam quality.

#### 4. Conclusion

This study demonstrated a controlled way to generate unprecedented pulse durations from an Yb:KYW-based regenerative amplifier. The parameters to control and optimize the amplified pulse duration are the management of the linear and non-linear phase prior and during the amplification cycle. With the provided experimental setup, generation of 32  $\mu\text{J}$  145 fs pulse was attained leading to a peak power of 220 MW with a gain up to 50 dB. The 150-fs-level compact diode-pumped ultrafast enables the reproduction of femtosecond results, which were up to now commercially available using much more complicated Ti:sapphire-based ultrafast lasers. It is believed that this innovative and simple femtosecond amplifier architecture is suitable for compact and reliable industrial lasers and will facilitate the penetration of this type of lasers into many market segments and laser applications. The method is transferable to even shorter pulse durations below 100 fs, e.g. using broader bandwidth gain media [15]. Moreover, this technic could be scaled to higher energy (reasonably to few 100s of  $\mu\text{J}$  level), adjusting other parameters like beam size to control the peak intensity.