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Multi-pass confocal ultra-short pulse amplifier

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We present the results obtained in the design and construction of an amplifier system for ultrashort optical pulses. The system is based on the chirped pulse amplification technique (CPA). In this technique, the pulse to be amplified is first stretched in time to lower its peak power; in the next step, the pulse is amplified and it is finally compressed in time to approximately its original duration. Our amplifier stage is very simple, using only 2 spherical mirrors in a confocal configuration to make 8 passes of the signal pulse through the amplifying medium, a 5mm long Ti:Sapphire rod. We report obtaining output pulses with an energy of several μJ.

Keywords: Femtoseconds; amplifier; pulse-compression; stretcher.

Presentamos los resultados obtenidos en el diseño y construcción de un sistema para amplificar pulsos ópticos ultracortos. El sistema está basado en la amplificación de pulsos con modulación temporal de la frecuencia (CPA por sus siglas en inglés). En esta técnica los pulsos a ser amplificados primero son estirados en el tiempo, después se amplifican y finalmente se recomprimen casi hasta recuperar a su duración original. En la etapa amplificadora usamos un diseño muy simple que utiliza solo dos espejos esféricos dispuestos en una configuración confocal que nos permite hacer 8 pasos de la señal por el medio amplificador y una barra de Ti:Zafiro de 5mm de largo. Hasta el momento hemos obtenido pulsos con una energía de varios μJ.

Descriptores: Femtosegundos; amplificador; comprsion de pulsos; estirado de pulsos.

PACS: 42.60; 42.65

1. Introduction

When a sufficiently high peak power laser interacts with a material, we can observe nonlinear effects caused by the high field to which the electrons and atoms in the material are exposed; and the stronger the field is, the higher the order of the nonlinear effects we can observe. Thus, development of high peak power lasers plays an important role in the research of material nonlinear optical response, material processing (ablation), index-shaping, etc. opening new regimes for light-matter interactions [1–3]. Lasers producing femtosecond pulses can deliver peak powers of several kilowatts per pulse, corresponding to pulse energies in the nJ range, which is enough to observe certain nonlinear effects. Peak power levels, as high as terawatts (J per pulse), can be obtained by further amplifying these pulses in a single laboratory tabletop system. This has been possible after the demonstration of the chirped pulse amplification (CPA) technique, in 1985 [4], allowing higher efficiency in the energy extraction for short pulse amplifiers and boosting the development of high peak power pulsed lasers.

A CPA system consists of three stages, stretcher, amplifier and compressor. In this work, we mainly focus on the amplifier stage, for which there are two main configurations: regenerative and multi-pass. The regenerative configuration is basically a laser cavity, which uses a Pockels cell to couple the pulses in and out of the cavity after a given number of round trips. This design uses many different components and the alignment is critical, besides having some problems with the amplified spontaneous emission (ASE).

The multi-pass design only uses spherical or flat mirrors to redirect the signal and make a certain number of passes through the amplifying medium. The number of elements in the configuration is minimal and the alignment is easier than in the regenerative case. Many configurations have been proposed for multi-pass amplifiers [5–7]. In this article, we present a very simple configuration, using 2 spherical mirrors in a confocal multi-pass amplifier design for chirped pulse amplification. In this amplifier we make 8 passes through the amplifying medium, a 5 mm long Ti:Sapphire. The system works at a 10 Hz repetition rate, this limitation coming from the pump laser, which is a low repetition rate frequency doubled Q-Switch Nd:YAG laser. Typically, this type of configuration uses 4 spherical mirrors [6] of slightly different radii of curvature to induce a displacement of the signal beam and obtain the multiple passes. With our configuration, we obtain this displacement by means of the refraction from a window placed at the Brewster angle in the path of the signal beam. The use of only two mirrors in our configuration further simplifies the alignment of this multi-pass set-up.

2. Chirped Pulse Amplification

The amplification of ultrashort pulses is not a straightforward task. Due to the high peak power developed through the amplification of these pulses, it is possible to cause damage or undesired non-linear effects such as self-focusing, filamentation or self-phase modulation in the amplifier material and distort the temporal or spatial profile of the pulses. To overcome this situation, D. Strickland *et al.* [4], adapted a tech-

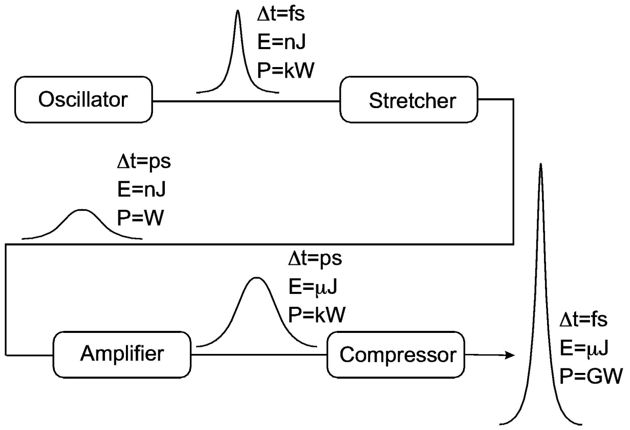

FIGURE 1. Schematics of a chirped pulse amplification system, showing the duration and energy level of the signal at the different stages of the system.

nique used in radar systems to the optical regime. This technique consists in stretching the pulse in time, typically, between $10^3 - 10^4$ times before amplifying it. The stretched pulses have therefore a much lower peak power, allowing a high amplification without the undesired effects. Finally, the amplified pulses are recompressed to their original duration (transform limited pulses), resulting in very high peak power pulses. A scheme of a typical CPA system is shown in Fig. 1.

In a CPA system, there are basically three components: a stretcher, an amplifier and a compressor; the first and latter components are basically the same for all CPA systems. For the amplifier stage there are two commonly used designs: multi-pass and regenerative. The multi-pass setup shows a lower ASE due to the low amount of material dispersion introduced by this configuration compared to that of the regenerative design. On the other hand, the regenerative amplifier has a higher efficiency because of a better overlap between the signal and the pump beams.

To stretch the pulse, a positive group velocity dispersion is added to the spectral components of the pulse, delaying the blue components relative to the red components, so the output is a stretched and positively chirped pulse. Different designs have been proposed to achieve this [8–10], most of them use a pair of diffraction gratings in an anti-parallel configuration, and a telescope with 1x magnification placed between them to invert the sign of the dispersion from the gratings. A second pass is introduced to increase the stretching factor and avoid the spatial separation of the pulse wavelength components (spatial chirp). This design is usually folded by placing a mirror at the confocal spot of the telescope, allowing to use only one lens and one grating in the setup, making it more compact and easier to align.

As said before, the amplifier stage has two basic designs, multi-pass and regenerative. In the regenerative design [11], the amplifier is basically a laser cavity. The pulse is injected into the amplifier through a combination of a thin film polarizer, Pockels cell and a wave plate. After a large number of round trips in the cavity, the pulse is extracted by switching the Pockells cell, causing the pulse to be reflected out of the cavity at the thin film polarizer. This design needs to have a low gain per pass configuration to prevent ASE from building up and depleting the gain before being extracted by the signal. Because of the low gain, more passes are needed to extract the energy efficiently, adding a lot of dispersion to the pulse and making it harder to recompress. It, however, has a very good efficiency because the overlap between the gain and the pump modes is almost total. We can also consider as a disadvantage the fact that this type of amplifier uses many components, requiring a fast switching (∼3-4 ns) Pockels cell, and a careful alignment of the mirrors to form the cavity.

In the multi-pass configuration, a set of mirrors is arranged such that the pulse passes a number of times (usually 4 to 8 times) through the amplifying medium which is pumped longitudinally by a pulsed laser. Due to the small number of passes through the gain medium, the added dispersion to the pulse is low, allowing the amplification of pulses which can be recompressed to very short durations (a few tens of femtoseconds). The ASE that could be present can be almost completely eliminated because the design does not allow it to build up fast. But, since the paths of the signal and pump beams are not collinear, the efficiency is not very good (compared to that of the regenerative amplifier) for this type of amplifier. The different variations encountered in the literature differ mainly in the type of mirrors used and the geometry of the cavity. Some use flat mirrors to guide the beam in the amplifier through the gain medium, but this means the number of passes increases the number of mirrors used in the set-up. Simpler designs use spherical mirrors in a confocal configuration, having two or four mirrors; the confocal geometry makes the beam cross the confocal spot of the setup, where the amplifying medium is located and the number of passes is only limited by the size of the mirrors and the spot size on them. Usually both designs are used in conjunction with a regenerative amplifier acting as pre-amplifier and a multi-pass amplifier as the power-amplifier.

The final stage of the system is the compressor [12], ideally it cancels exactly the group velocity dispersion introduced by the stretcher. However, in a CPA system, further dispersion of various orders is introduced by the components of the system, like the Pockells cell, the amplifying medium, possible aberrations in the stretcher, and lenses used to manipulate the size of the beam. This extra dispersion of various orders can be partially compensated with the standard compressor design. To obtain the shortest pulse possible out of the system, more sophisticated compressor and stretcher designs which can compensate for higher order dispersion, terms, must be used [13–15].

3. Experimental Set-up and Results

The experimental setup for the amplifier is shown in Fig. 2. The oscillator is a home made Ti:Sapphire Kerr-lens mode-locked laser, delivering 67 fs (FWHM) pulses at a repetition rate of 70 MHz, with ≈4 nJ of energy per pulse. The autocorrelation trace and spectrum of the pulses are shown in Fig. 3. The spectrum width is 24 nm (FWHM), and the product $\Delta\nu\Delta\tau \approx 0.814$. Considering a $sech$ pulse profile, the ideal value is 0.315, meaning that the pulses coming out of the oscillator have some residual chirp which could not be compensated in the oscillator cavity. For this given spectrum, the calculated transform limited pulse duration should be ≈26 fs.

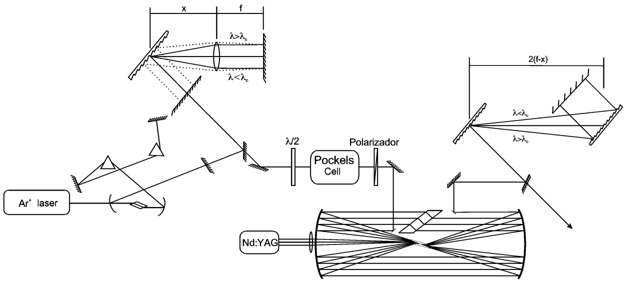

FIGURE 2. This is the experimental setup built in the laboratory. Here we can see the set-ups for the source, stretcher, amplifier and compressor.

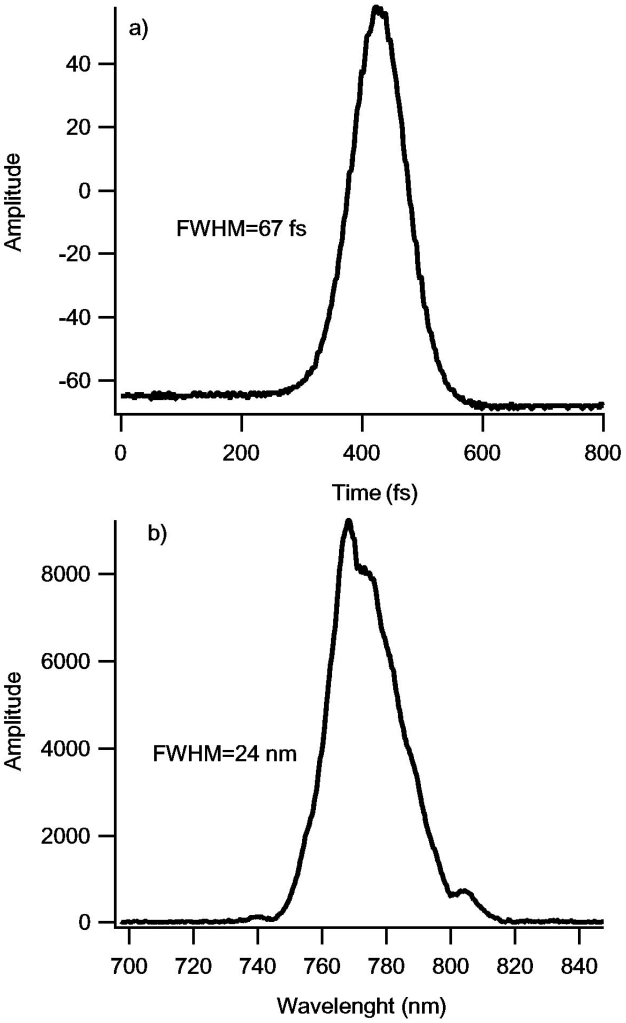

FIGURE 3. a) Autocorrelation of the input pulse to the sistem, the pulse duration is 67 fs FWHM. b) Spectrum of the input pulse, the width is 24 nm FWHM.

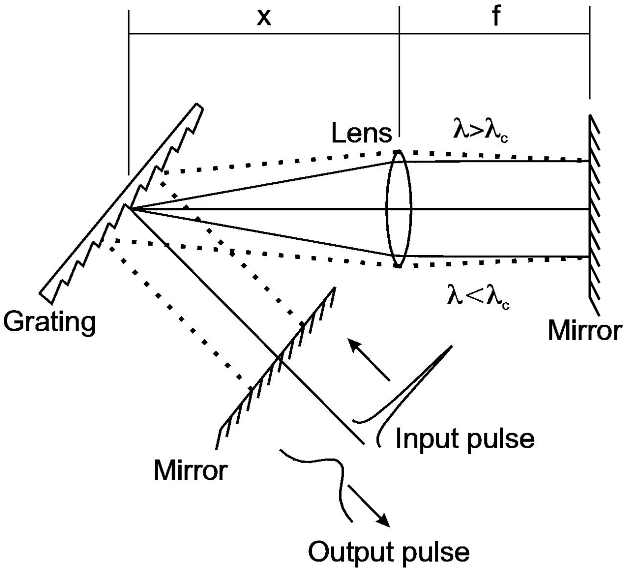

FIGURE 4. The stretcher set-up uses a single diffraction grating, a lens and a mirror to fold the configuration. A second mirror is used to make a second pass through the set-up, increasing the stretching factor and avoiding spatial chirp. The stretching ratio of this set-up is $\approx 2\times 10^3$.

The stretcher design is based on the Martinez-type stretcher [8, 9], see Fig. 4. It uses a diffraction grating with 1200 lines/mm and an achromatic lens, besides some mirrors to fold the configuration and make a second pass through it. The time delay between the various wavelength components of the pulse introduced by this set-up is given by [16]:

$$\Delta\tau = -\left[\frac{4\,(f-x)\,m^2\lambda}{cd^2\cos^2\theta}\right]\Delta\lambda, \tag{1}$$

where f is the focal length of the lens, x is the distance between the lens and the grating, m is the diffraction order, λ is the central wavelength, c is the speed of light, d is the groove spacing, θ is the diffraction angle for the central wavelength, and $\Delta\lambda$ is the FWHM of the pulse spectrum. For our experimental setup, we have $f = 50$ cm, $x = 24.5$ cm, $\theta = 36°$, $\lambda = 770$ nm, and $\Delta\lambda = 24$ nm, using this data we obtain a calculated stretched pulse duration of $\Delta\tau$ ≈138 ps.

In a previous experiment, we measured the stretched pulses using the same setup, the input pulses into the stretcher had a duration of 90 fs FWHM, the spectral width of these pulses was 22 nm FWHM centered at 801 nm. Using a 7 GHz bandwidth fast photodiode and a 20 GHz oscilloscope, the measured duration of the stretched pulses was 121 ps FWHM. The calculated duration using equation 1 gave 132 ps for this case, showing good agreement with the experimental data.

As the pump for the amplification stage, we use a frequency-doubled Q-switched Nd:YAG laser that produces 5 ns pulses centered at 532 nm with 20 mJ energy at a 10

Hz repetition rate. The pump is triggered using the output signal from a fast photodetector, which monitors the pulse train coming from the Ti:Sapphire oscillator. In this way, we avoid free-running operation in the amplifier which could cause damage to the amplifying rod. To synchronize the repetition rate of the signal pulses with that of the pump pulses in the amplifier, we placed a pulse picker before the amplifier to lower the repetition rate of the Ti:Sapphire oscillator pulse train from 70 MHz to 10 Hz. The pulse picker consists of a $\lambda/2$ wave plate to rotate the polarization of the pulses 90°; next we have a Pockels cell which rotates the polarization of the pulses 90° more for a determined amount of time. After the pulse picker, a polarizer is set to allow the pulses to pass only when their polarization has been rotated by the Pockels cell. By setting the amount of time the Pockels cell is active, we can control the number of pulses that pass onto the amplifier stage. There are some applications in which having a train containing a given number of closely spaced amplified pulses could be a desirable feature [3, 17].

The amplifier, depicted in Fig. 5, is a multi-pass design that uses a pair of spherical mirrors with 1 m radius of curvature. These mirrors are placed in a confocal configuration where the distance between them is 1 m. The amplifying medium is a 5 mm long Ti:Sapphire rod (gain saturation fluence $\approx$0.9 J/cm^2) placed in the center of the confocal configuration, absorbing 90 percent of the pump energy, and the fluence of the pump at the rod is $\approx$2 J/cm^2. There is also a 5 mm thick transparent sapphire window, needed to displace the path of the pulse after each pass, and a small flat mirror for extracting the pulse from the amplifier after a certain number of passes.

The final stage is the compressor shown in Fig. 6, here we have the standard design with two 1200 lines/mm diffraction gratings and a mirror to make a second pass. The incidence angle onto the gratings has to be the same as the one used in the stretcher to match the same dispersion introduced by it. Similarly, the distance between the gratings depends on the distance used in the stretcher between the grating and the lens. However, some adjustments to the distance between the gratings and the angle of these must be made to account for all the material dispersion introduced to the pulse by the elements between the stretcher and compressor, and be able to obtain the shortest pulse possible.

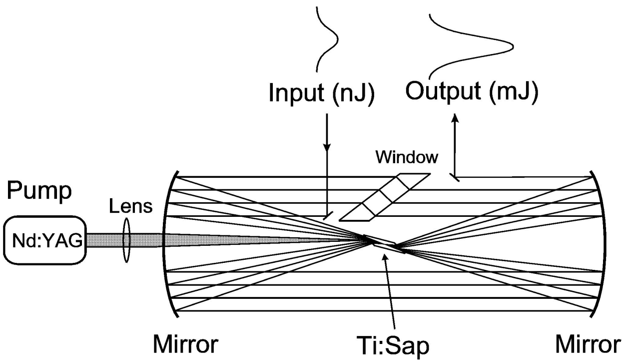

FIGURE 5. The amplifier configuration uses two spherical mirrors in a multi-pass confocal configuration to make the signal pass eight times through the amplifying medium.

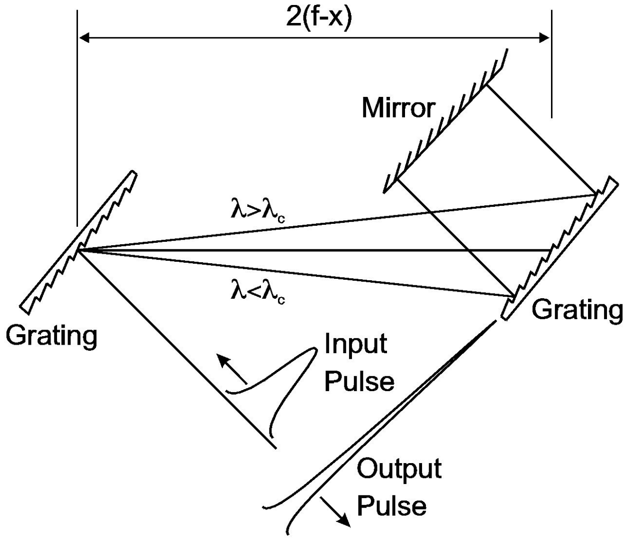

FIGURE 6. The compressor has two diffraction gratings to revert the chip introduced in the stretcher stage, and compensate for dispersion introduced by the components of the amplifier system.

In order to fine tune and optimize the compressor stage, we place a second harmonic generator (SHG) at the exit of the compressor, and measured the output power of the second harmonic signal. The results of these measurements can be seen in Fig. 7, where we have plotted the distance between the gratings of the compressor vs the power of the second harmonic signal. For a given pulse energy, the output power of the SHG is the maximal for the shortest pulse. By adjusting the distance between the gratings in the compressor, we

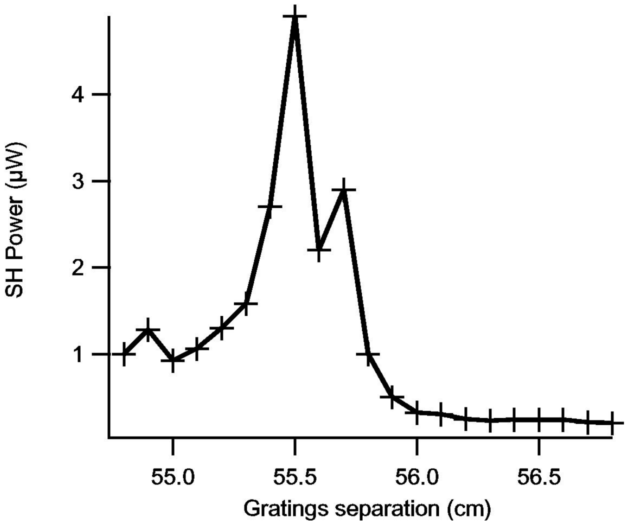

FIGURE 7. Optimization of the compressor stage. In this plot we can see how the output power of the second harmonic signal produced by the unamplified pulses varies with teh separation between the gratings of the compressor. The higher the power output the shorter the output pulse of the compressor is.

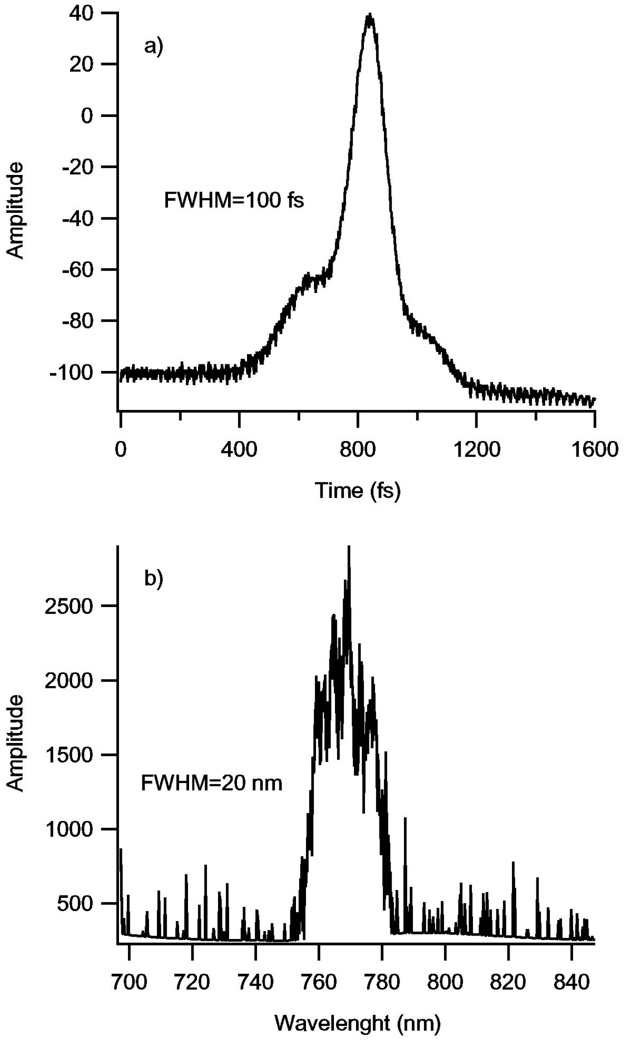

FIGURE 8. Characteristics for the unamplified pulses after passage through the whole stretcher-amplifier-compressor system. a) Autocorrelation trace. b) Spectrum.

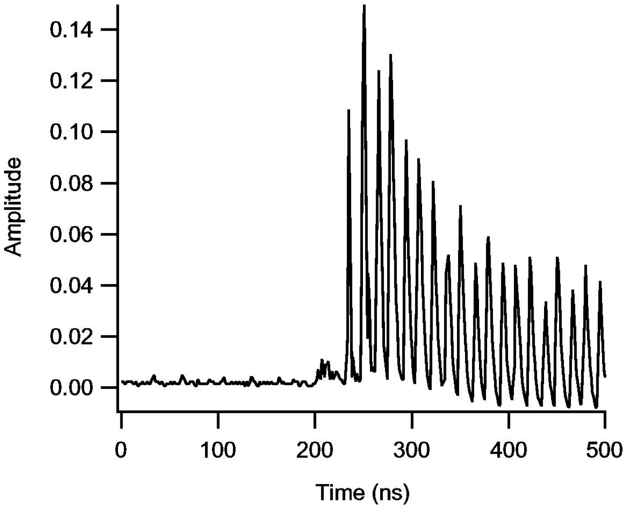

FIGURE 9. This is the train of pulses from the oscillator amplified without using the pulse picker.

compensate by shortening it, the dispersion in the pulse. These measurements are done with no amplification of the pulses, and using the pulse train at 70 MHz.

We used autocorrelator and a spectrum analyzer to measure the duration and the spectrum of the compressed pulses at the output of the system, both graphs can be seen in Fig. 8. The measured output pulse duration given by the intensity autocorrelation trace is 100 fs (FWHM), see Fig. 8a. We can also notice that the width of the output spectrum (20 nm) is narrower than that of the input spectrum (24 nm), see Fig. 8b. This is due to the size of the optics used in the stretcher and the compressor stages of the system, which can not support the whole pulse spectrum. The measurement of the pulse duration for the unamplified pulses also stands for the amplified pulse, since the dispersion introduced by the gain in the amplifier is very small (less than a femtosecond). The phase change $\varphi(\omega)$ introduced to the pulse by the amplification process is given by [18]:

$$\varphi(\omega) = \ln(G_{tot}) \frac{(\omega - \omega_0)/\Delta\omega_g}{1 + 4\left((\omega - \omega_0)/\Delta\omega_g\right)^2}, \tag{2}$$

where G_{tot} is the total gain of the amplifier, ω is the frequency at which we want to calculate the delay, ω_0 is the center of the gain profile, and $\Delta\omega_g$ is the width of the gain profile. For Ti:sapphire, the time delay between the center of the gain profile (800 nm), and a point 50 nm away is 10 fs for a gain of 10^6. In our amplifier the gain is of the order of 10^4, so the gain dispersion is not significant enough to change the pulse duration after the amplification.

The measured energy per pulse at the output for the system is 10 μJ, which gives us a total amplification factor of 2×10^4, and an average gain per pass in the amplifier of 3.45. We have observed that the gain has not been completely saturated in the amplifier, leaving room for improvement in the output energy. In Fig. 9, we can see a train of amplified pulses at 70 MHz (this is not using the pulse picker), where we can observe that the gain was not completely depleted by the first pulse switched in the amplifier. Adjustments in the beam size of the signal, and pump at the amplifier rod could potentially give us a better amplification factor. We are currently working in a variation of this configuration, where the beam path of the signal is split in two planes, reducing the angle between the pump and the signal, and increasing their overlap in the gain medium.

4. Conclusions

We have built an ultra-short pulses amplifier using the CPA technique. The pulses were amplified up to the microjoule level at a 10 Hz repetition rate. The 67 fs ultrashort pulses were stretched in time up to 138 ps before amplification. The amplifier stage was a very simple confocal design with two spherical mirrors, allowing 8 passes through the amplifying medium, and potentially more depending on the spot size of the signal on the mirrors. Finally, the pulses were recompressed to almost the original duration using a typical two grating compressor design. We believe that this system can be improved adding another amplifying stage, allowing us to achieve up to mJ pulses, and by modifying the current configuration to improve overlap between the pump and the signal.

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