

Amplification of 1 ps pulses at 1.053 μm in a Ti:Al₂O₃ regenerative amplifier

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We demonstrate the operation of a Ti:Al₂O₃ regenerative amplifier tunable around 1 μm . Gains up to 10⁸ at 1.053 μm without any spectral narrowing are obtained. This amplifier is designed for use in terawatt picosecond lasers.

Recent application of the chirped pulse amplification (CPA) technique [1] to the optical domain [2] has made it possible to exploit the storage capability of solid-state laser media with ultra-short pulses. For instance, using Nd:glass amplifiers, 1 ps pulses have been amplified to the joule level leading to peak powers in the 1–20 TW range [3–5]. Until now, the final pulse duration was limited by spectral narrowing during the amplification process [6]. A careful examination of the laser system reveals that the greatest percentage of narrowing occurs in the regenerative amplifier used in these systems. Typically, the pulse experiences a net gain of 10⁸–10⁹ after having passed through the regenerative amplifier. Beyond the regenerative amplifier, the pulse is amplified by only a factor of 10³–10⁴. Thus, to significantly increase the final pulse bandwidth the spectral narrowing due to the regenerative amplifier must be eliminated.

In order to address this problem we have built a Ti:Al₂O₃ regenerative amplifier tuned to match the peak wavelength of Nd:glass. Ti:Al₂O₃ has a much broader bandwidth than Nd:glass and is capable of amplifying 100 fs pulses to the millijoule level. This makes the Ti:Al₂O₃ regenerative amplifier the ideal front end for high power, Nd:glass systems.

The gain of Ti:Al₂O₃ peaks at 790 nm and most of the experiments have been conducted around this

wavelength [7–10]. We have recently shown that tunable subpicosecond pulses can be obtained around 1 μm using an actively mode-locked Ti:Al₂O₃ laser [11]. We will show here that, despite its low gain in this spectral region, Ti:Al₂O₃ is still suitable for amplification of picosecond or femtosecond pulses up to the millijoule level. The saturation fluence of Ti:Al₂O₃ at 1.053 μm is estimated to be 4 J/cm², which is comparable to that of Nd:glass [11]. The damage threshold of this crystal is estimated to be 10 J/cm² for a 10 ns pulse. Pumping at conservative values around 5 J/cm², we can expect a gain of 2 per pass in the crystal which is sufficient for efficient amplification.

The configuration of the regenerative amplifier used in this experiment is shown in fig. 1. The resonator is 1.3 m long and uses two high reflectors coated for 1.053 μm . Their radii of curvature are 0.5 m and 1 m. This choice of a short radius of curvature decreases the misalignment sensitivity of the resonator and allows large beam sizes on critical elements. A single Pockels cell (Medox Electro-Optics) oriented to give a quarter wave of static birefringence and a thin film polarizer are used to trap a pulse in the resonator and to cavity dump it. We have tried several Ti:Al₂O₃ crystals with different dopant levels and observed similar results with all of them. We will report the results obtained with a 1.7 cm long Brewster end cut crystal (Crystal Systems). The crystal is end pumped through one of the mirrors. Its absorption coefficient is 1.4 cm⁻¹. The amplifier is

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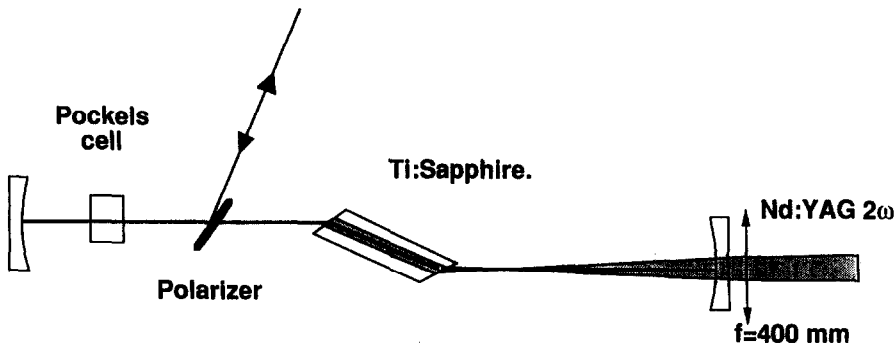


Fig. 1. Regenerative amplifier set-up.

pumped by the second harmonic of a single-mode Q -switched Nd:YAG laser (QUANTEL S.A.). The pump beam is focused 8 cm in front of the crystal by a 400 mm focal length lens. No damage on the crystal was observed for pump energies up to 40 mJ. We have measured the pump beam profile at different positions in the cavity and estimate the pump fluence to be 2 J/cm^2 on the crystal. Because of inhomogeneities in the pump beam we had to keep the fluence at this value in order to avoid damage. At 40 mJ pump energy the uninjected build-up time is around $1 \mu\text{s}$ and the energy of the cavity dumped pulse is 1.2 mJ. The spectrum of the free-running (or uninjected) amplifier is given in fig. 2. Its width is 8 nm which is 6 times that of our Nd:glass regenerative amplifiers. That means that 100 fs pulses can be amplified without experiencing any spectral narrowing. In our $\text{Ti:Al}_2\text{O}_3$ we have found that the lim-

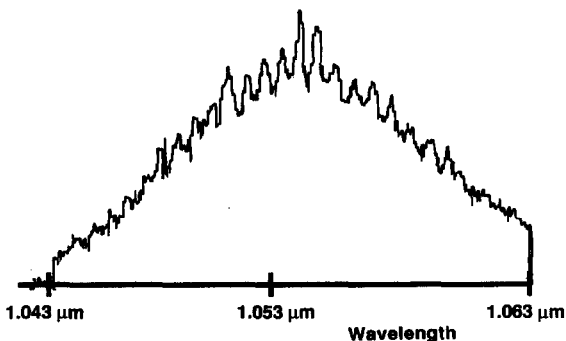


Fig. 2. Spectrum of the pulse produced by the regenerative amplifier in the free-running mode (i.e. uninjected). The modulation seen on the spectrum is due to electrical noise in the detector.

iting element is no longer the gain medium but the thin film polarizer. The single pass bandwidth (fwhm) of this device was measured to be 50 nm and the central wavelength of the transmission curve was found to be dependent on the angle of incidence on the polarizer. The amplifier can be tuned from 950 nm to 1075 nm by rotating the polarizer.

We have used this $\text{Ti:Al}_2\text{O}_3$ regenerative amplifier in a 1 ps, 1 J laser source. This terawatt system has already been described elsewhere [3]. The oscillator used in our source is an actively mode-locked Nd:YLF laser producing 30–40 ps pulses which are spectrally broadened in an optical fiber. After temporal stretching with a 1200 l/mm grating pair [12] the pulse is sent to a Nd:glass regenerative amplifier and then double-passed through both a 9 mm and a 16 mm Nd:glass amplifier. A second identical grating pair is used to recompress the pulse after amplification [13]. The Nd:glass regenerative amplifier limits the amplified spectrum to 1.5–2 nm [3,4,14]. Typical spectra of the pulses before and after the Nd:glass regenerative amplifier are shown in fig. 3. A factor of 3 reduction of the pulse spectrum width is observed for an input spectrum fwhm of 4 nm and an output energy of 3 mJ. The same comparison between input and output spectra in the case of the $\text{Ti:Al}_2\text{O}_3$ regenerative amplifier is given in fig. 4. Absolutely no spectral narrowing is observed. The output energy and build-up time are respectively 1 mJ per pulse and 800 ns at a pump energy of 40 mJ. The energy of the pulse entering the amplifier is 100 pJ. The repetition rate is fixed at 20 Hz by the Nd:YAG laser pumping the $\text{Ti:Al}_2\text{O}_3$ crystal. The stability of the amplified pulses is typ-

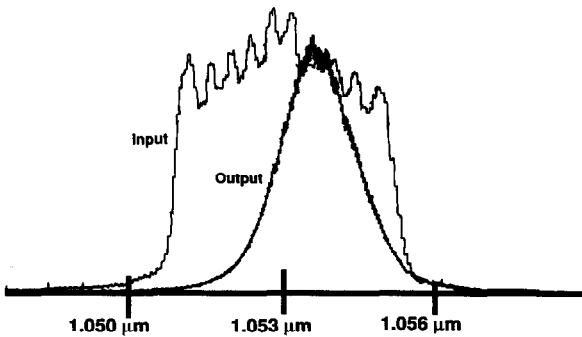


Fig. 3. Spectrum of the pulses injected in the Nd:glass regenerative amplifier (fwhm is 4 nm) and spectrum of the same pulses after amplification in the Nd:glass regenerative amplifier (fwhm is 1.8 nm).

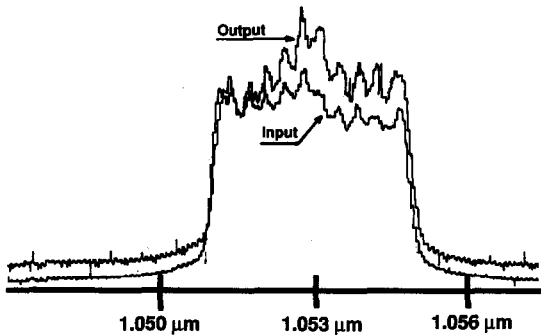


Fig. 4. Spectrum of the pulses injected in the Ti:Al₂O₃ regenerative amplifier (fwhm is 4 nm) and spectrum of the same pulses after amplification in the Ti:Al₂O₃ regenerative amplifier (fwhm is 4 nm).

ically 20% peak to peak and most of the instabilities come from energy fluctuations and beam wandering of the pump laser.

After amplification in the Ti:Al₂O₃ regenerative amplifier we recompressed the pulses. A single shot autocorrelator [15,16] was used to record the pulse autocorrelation function. As the amplified spectrum is now almost perfectly square (see fig. 4) the pulse shape can be approximated by a $\sin^2 t/t^2$ function. With this assumption the pulse duration was 1 ps and the time-bandwidth product was 1.08. This compares favorably with the theoretical pulse duration of 850 fs and time-bandwidth product of 0.89 for a square spectrum. As expected for a $\sin^2 t/t^2$ shape the pulse contrast (intensity ratio between the peak and

the wings) was not as good as with a gaussian profile. In order to obtain a better contrast one has to introduce a pulse-cleaning stage. Various methods of pulse cleaning have been proposed including using nonlinear properties of optical fibers [17,18], spectral windowing [19] or spectral shaping [14]. Using a combination of these methods a 10^{-5} contrast ratio has been demonstrated [20]. This device is currently being introduced between our oscillator and our regenerative amplifier.

In summary we have demonstrated a Ti:Al₂O₃ regenerative amplifier working at 1.053 μm . This amplifier has several advantages over previous Nd:glass regenerative amplifiers. First, it does not exhibit any spectral narrowing for a 4 nm spectrum and should be capable of amplifying pulses as short as 100 fs. Second, it can be tuned to perfectly match the wavelength of any oscillator in the 950–1075 nm range. We believe that further improvements of terawatt systems will include the production of shorter pulses from the oscillator followed by amplification in the kind of regenerative amplifier described here. With such a system one should be able to amplify 100 fs pulses to the joule level at 1.053 μm .

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