Diode-pumped Nd:glass kilohertz regenerative amplifier for subpicosecond microjoule level pulses

Alan Braun, Xinbing Liu, Gerard Mourou, Daniel Kopf, and Ursula Keller

A diode-pumped Nd:fluorophosphate regenerative amplifier was developed. Chirped seed pulses were amplified to 24 μJ at repetition rates to 1 kHz and to 5 μJ at a 10-kHz repetition rate. On compression, 850-fs pulses were obtained. White-light continuum generation was observed when these pulses were focused into a glass sample. Furthermore, based on a rate equation analysis, the effects of the gain material lifetime on the pulse energy at high repetition rates are discussed. © 1997 Optical Society of America

Key words: Laser-diode pumping, continuous-wave pumping, regenerative amplifier, Nd:glass, chirped-pulse amplification.

1. Introduction

With the maturation of high-power laser-diode technology, direct laser-diode pumping of solid-state material is allowing the generation of ultrashort laser pulses in a compact and cost-effective system. For ultrafast lasers, direct diode pumping may replace argon–ion, krypton-ion, and *Q*-switched solid-state pump lasers for both mode-locked oscillators and regenerative amplifiers. Excellent results have been obtained from diode-pumped mode-locked oscillators in Cr:LiSAF, Cr:LiSGAF, and Nd:glass. Sub-100-fs pulses have been obtained from diode-pumped Kerr-lens mode-locked (KLM) oscillators in Cr:LiSAF[1,2] and Cr:LiSGAF,[3] and, recently, 18-fs pulses were reported from a diode-pumped KLM Cr:LiSAF laser.[4] Furthermore, with an antiresonant Fabry–Perot semiconductor saturable absorber (A-FPSA) and soliton mode locking, 100-fs pulses were generated in diode-pumped Nd:glass (silicate, phosphate, and fluorophosphate)[5] and sub-50-fs pulses were obtained in Cr:LiSAF.[6]

In the area of diode-pumped regenerative amplifiers, however, most of the development has been for pulses in the picosecond domain. In an 11-ps pulse, 90 μJ were extracted from a Nd:YLF regenerative amplifier when pumped with a 2-W single-strip laser diode.[7] More recently, when pumped with a microlensed 15-W laser-diode array, 750 μJ were extracted from a Nd:YLF regenerative amplifier seeded with 15-ps pulses.[8] Both of these systems operated around a 1-kHz repetition rate. Based on a side-pumped geometry, 2.5 mJ were obtained from a Nd:YLF cavity when pumped with two 60-W quasi-cw laser diodes when seeded with 20-ps pulses.[9] This system operated at a 20-Hz repetition rate. Furthermore, based on a two-stage erbium-doped fiber amplifier,[10] 2 μJ of energy were obtained for repetition rates as high as 10 kHz, and on compression 1.8-ps pulses were measured.

Recently, however, a cw diode-pumped Cr:LiSAF regenerative amplifier was reported,[11] pushing diode-pumped amplifiers into the femtosecond regime. This system amplified 200-fs pulses to 2.6 μJ with repetition rates as high as 25 kHz. With cw pumping, the steady-state inversion is limited by the material lifetime for a given pump power. This inversion, when the repetition rate of the amplifier is less than the fluorescence decay rate, is given simply by

$$N = R\tau, \tag{1}$$

where N is the total stored inverted energy, R is the pump power, τ is the material lifetime, and assuming a quantum efficieny η_Q of 1. Therefore the material lifetime must be large so that a sufficient stored energy (and small-signal gain) is obtained with modest

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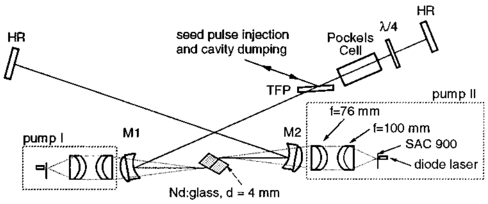

Fig. 1. Schematic of the diode-pumped regenerative amplifier. Mirror 1 (M1) and mirror 2 (M2) have a 10-cm radius of curvature. The Nd:glass and TFP (thin-film polarizer) were at Brewster's angle and a low-loss KD*P Pockels cell crystal was used. HR, high reflector.

pump powers. The Cr:LiSAF system, with an upper-state lifetime of 67 μs, stored roughly 60 μJ of energy when pumped with 900 mW of diode power. This amplifier can be compared with a cw-pumped Ti:sapphire regenerative amplifier.[12] Because of the small upper-state lifetime of Ti:sapphire (3 μs), 15 W of argon–ion power is needed to store a similar amount of energy.

Nd:glass, with a strong absorption band at 800 nm, would be a good material for a diode-pumped amplification system. Because of the long upper-state lifetime (hundreds of microseconds), Nd:glass can store large amounts of energy from a cw pump source. Also, Nd:glass has a sufficient bandwidth to support subpicosecond pulses. Because of the large saturation fluence of glass ($\sim 7\ \mathrm{J/cm^2}$), however, an efficient multipass amplifier would be difficult to design and operate safely as the damage threshold of optical coatings is on the same order as the saturation fluence. Therefore a low-loss regenerative amplifier cavity is an optimum way to efficiently extract the stored energy. Even with pulse fluences below the saturation fluence, a low-loss regenerative amplifier can efficiently extract the stored energy by making many round-trip passes.

Through chirped-pulse amplification, a diode-pumped regenerative amplifier based on Nd:glass (fluorophosphate) has been developed that produces 850-fs pulses with energies ranging from 24 μJ through 1 kHz to 5 μJ at 10 kHz. This system can be used for laser surgery and micromachining applications where pulses with a temporal duration of a few hundred femtoseconds are desired. Also, these pulses can have spectroscopic uses in which, through continuum generation, a relatively simple, short-pulse white-light source is needed.

2. Regenerative Amplifier

The design of the regenerative amplifier was based on the configuration of a diode-pumped mode-locked Nd:fluorophosphate oscillator.[5] The cavity was transformed from a mode-locked oscillator to a regenerative amplifier when the dispersion-compensating prisms were substituted with a polarizer/Pockels cell combination and the mode-locking saturable absorber was replaced with a high-reflecting mirror (Fig. 1). As Nd:glass has an absorption peak at 800 nm, it can naturally be diode pumped. This cavity was pumped from both sides of the glass by a 1.2-W laser diode (SDL-2360, 804 nm) each with an emitting facet of dimension 100 μm × 1 μm. A cylindrical microlens (SAC-900) was mounted close to the emitting facet to collimate the strongly divergent light from the plane perpendicular to the junction. The pump beam profile had roughly equal dimensions after the collimating microlens. The output of the diode/cylindrical lens combination was then imaged with spherical optics into the glass media. The 4-mm-thick Nd:glass slab absorbed 60% of the pump light. For ease of alignment, the Pockels cell (Medox Electro-Optic) was set with an initial zero-wave birefringence, and a separate quarter-wave plate was inserted into the cavity.

Because of the long upper-state lifetime, Nd:fluorophosphate has the potential for large energy storage. A simple estimate of the maximum energy available for extraction can be obtained. Within the lifetime of 500 μs ($1/\tau \sim 2$ kHz), the total energy absorbed from the diodes into the pump band was 600 μJ. However, because the emission from the diode in the plane parallel to the junction was 20 times over diffraction limited ($M_x^2 \sim 20$), its Rayleigh range was 20 times less than that of the cavity mode. In the plane perpendicular to the junction, the pump beam exhibited single-mode behavior. Therefore the divergence of the pump beam in the plane parallel to the junction was larger than the divergence of the cavity mode beam, giving a pump volume that was roughly four times larger than the cavity mode volume. Hence the maximum expected extracted energy, taking into account the modal overlap, the loss of photon energy from pump to lasing transition, and assuming a quantum efficiency of $\eta_Q = 1$, would be 120 μJ.

A. Q Switching

The Pockels cell was used to Q-switch and cavity dump the energy from the amplifier at repetition rates varying from 100 Hz to 10 kHz. Without injection, the amplifier was Q switched with a pulse buildup time of 1.25 μs. This buildup time increased for repetition rates beyond 1 kHz because this switching rate exceeded the lifetime emission rate. At a 100-Hz repetition rate, the cavity-dumped Q-switched pulse contained 30 μJ of energy with a 2-nm bandwidth centered at 1.058 μm. A simulation of the Q-switched pulse buildup, including saturation effects, was calculated to determine the small-signal gain coefficient. Based on this fit, an initial single-pass small-signal gain of 1.14 and a single-pass loss of 2.5% was obtained. Furthermore, from the theory of Lowdermilk and Murray,[13] the amplified pulse fluence was calculated to be 0.88 $\mathrm{J/cm^2}$.

B. Pulse Amplification

To amplify a short pulse, a chirped-pulse amplification system[14] was built around the regenerative amplifier (Fig. 2). The amplifier was seeded with

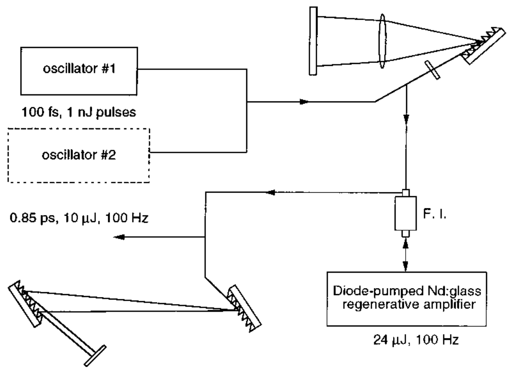

Fig. 2. Experimental setup. F. I., Faraday isolator. Oscillator #1, 1-μm KLM Ti:sapphire oscillator; oscillator #2, diode-pumped mode-locked Nd:glass oscillator. Seed pulses were generated from oscillator 1. However, for an all diode-pumped system, oscillator 2 could be used.

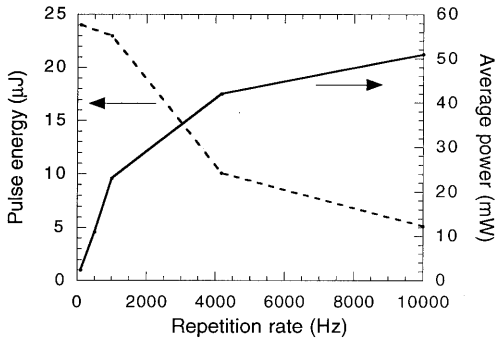

Fig. 3. Experimental data showing the extracted energy per pulse and average power as a function of amplifier repetition rate. The repetition rate was determined by the Pockels cell switching rate.

pulses generated from a KLM Ti:sapphire oscillator (Coherent Mira) tuned to the central wavelength supported in the regenerative amplifier. To avoid intensity-dependent effects in the amplifier, the pulse was chirped temporally prior to amplification. We stretched the injected pulse to roughly 500 ps by a standard grating pair-lens stretcher using 1740-lines/mm gratings. A Faraday isolator system was placed after the stretcher to isolate the amplifier from the stretcher and oscillator. The stretched pulse was injected into the amplifier by a reflection from the thin-film polarizer (TFP) and became trapped in the cavity after the Pockels cell was switched from zero-wave to a quarter-wave of birefringence. The amplifier was seeded with approximately 100 pJ of energy. For repetition rates below 1 kHz, the buildup time of the amplified-injected pulse was 800 ns, which corresponded to approximately 84 round trips through the cavity. At the peak of the buildup, after the inversion had been depleted and the gain was equal to the loss, the Pockels cell was switched to a half-wave and the amplified pulse was ejected from the cavity. With switching rates to 1 kHz, the cavity-dumped pulse contained 24 μJ of energy. At this energy level, the fluence inside the glass reached approximately 0.5 J/cm^2, below the saturation fluence of the fluorophosphate, 7 J/cm^2. Figure 3 shows how the average power and energy per pulse varied with the repetition rate. The pulse-to-pulse stability was more than 3%. As the switching rate approached 10 kHz, the average power approached that obtained in cw operation with a 1% output coupler, and the pulse energy decreased toward 5 μJ due to the amplification rate exceeding the fluorescence lifetime rate.

The switching efficiency was measured to be 90% due to a lack of perfect discrimination by the TFP. This resulted in the ejection of several postpulses following the main cavity-dumped pulse, the first with approximately 10% the energy of the main pulse. These postpulses decreased in energy to a few nanojoules within a few round trips. Furthermore, as no pulse selector was used before or after the regenerative amplifier, there was a constant background power level coming from the oscillator mode-locked train. With only one pulse selected to be amplified, the rest of the mode-locked train was rejected by the regenerative amplifier and was propagated through the rest of the laser system. This background power level was 3 mW after the Faraday isolator. This background level was subtracted from the data before we plotted Fig. 3. Both the background power level and postpulses could be eliminated with a suitable electro-optic pulse selector.

The cavity-dumped pulse was then sent to a grating pair compressor that was matched to the stretcher. Subpicosecond pulses were obtained as is shown by the autocorrelation trace in Fig. 4. Assuming a Gaussian pulse shape, the deconvolved pulse width was 850 fs. The throughput of the compressor was 40%, and at a 1-kHz repetition rate, the pulse energy after compression was 10 μJ. When these pulses were focused into a centimeter-thick piece of glass (by use of between a 6-cm and 17-cm focal length lens), white-light generation was observed. To our knowledge, this was the first observation of continuum generation from a directly diode-pumped amplification system.

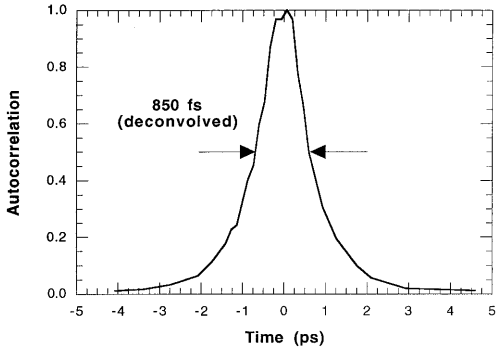

Fig. 4. Autocorrelation of the compressed pulse. The amplification system supported 850-fs pulses.

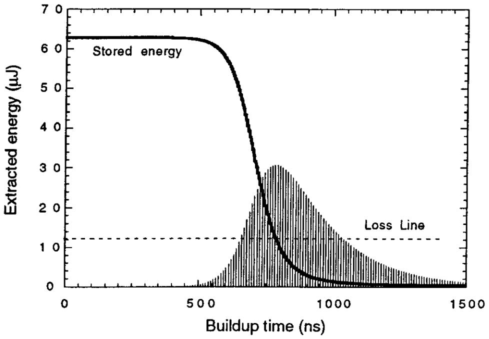

Fig. 5. Simulation results of pulse amplification in a regenerative amplifier. The solid curve shows the extraction of the inverted energy. At the peak of the amplification, where the pulse would be ejected from the cavity, there is still 12 μJ of energy stored within the cavity mode volume.

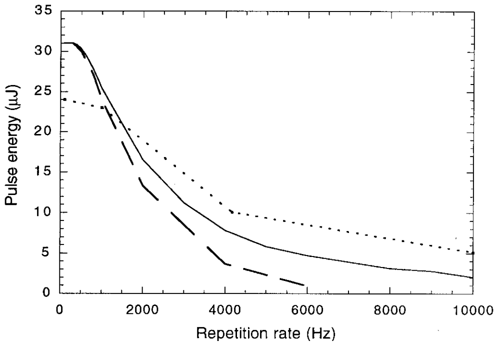

Fig. 7. Effects of cw pumping on the amplified pulse energy. The dashed and solid curves are based on numerical simulations. The dashed curve shows the pulse amplification when the initial inversion is set to zero. The solid curve includes the residual stored energy. This case fits well with the experimental data points (dotted curve) at the higher repetition rates.

3. Simulation Results

With use of a simplified set of pulse amplification rate equations,[15] interesting lifetime effects based on cw pumping of regenerative amplifiers are obtained. A fortunate characteristic of Nd:glass, with a fluorescence decay rate of 2 kHz, is that these lifetime effects are in a range that can be observed experimentally. Figure 5 shows the pulse buildup and the inversion decay in the regenerative amplifier. At the peak of the pulse buildup, where the gain is equal to the loss, the pulse is ejected from the cavity. At this time there is still a significant amount of residual energy stored in the gain volume. In this simulation, there is approximately 12 μJ of energy left within the cavity mode volume. For the case of pulse pumping, this inversion will decay toward zero before the arrival of the next pump pulse. However, in the case of cw pumping, the residual inversion is the initial stored energy seen by the pump. This effect can be seen in the pumping-rate equation. The equation governing the creation of the inversion when the cavity Q is low is given by

$$\partial N(t)/\partial t = R - N(t)/\tau, \tag{2}$$

where $N(t)$ is the number of atoms in the upper laser level per unit volume, R is the pump rate per unit volume, and τ is the material lifetime. Equation (2) can be solved to give

$$N(t) = R\tau[1 - \exp(-t/\tau)] + N_0 \exp(-t/\tau). \tag{3}$$

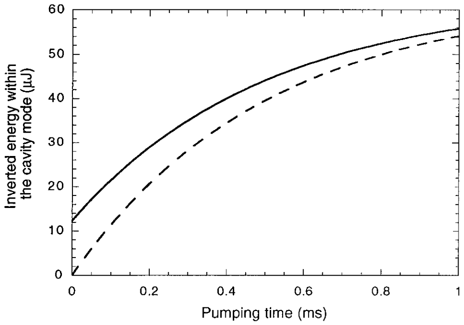

Fig. 6. Buildup of the inversion. The solid curve is with an initial inversion, the dashed curve is with no initial inversion. Both cases converge to the steady-state inversion. However, at short pumping times (high repetition rate of amplification), the difference in inverted energy is significant.

For the case of pulse pumping, where the time between pump pulses is greater than τ, the second term on the right-hand side goes to zero. However, for cw pumping, N_0 will add to the final $N(t)$, leading to a larger value of the small-signal gain than would otherwise be expected. Figure 6 shows how the inversion builds up with $N_0 = 0$ (dashed curve) and with the inclusion of a residual stored energy (solid curve). For long pumping times (low repetition rate of amplification) both curves converge to the steady-state value $R\tau$, independent of the initial inversion N_0. For repetition rates faster than the fluorescence decay rate, the effect of N_0 is significant. This can be seen in Fig. 7 where the experimentally obtained amplified pulse energy is plotted with the output of the simulation versus amplifier repetition rate. For the case of $N_0 = 0$ (dashed curve), above 6 kHz the pulse is amplified to only a few nanojoules, and beyond 7 kHz the initial small-signal gain does not exceed the loss. However, for the case including the residual N_0 (solid curve), a few microjoules of energy is still extracted at repetition rates above 8 kHz. This also agrees with the pulse energies achieved experimentally. At repetition rates below the fluorescence decay rate, the simulated pulse energies converge to the steady-state value. These lifetime effects may become important when new cw diode-pumped regenerative amplifiers are designed.

4. Conclusions

A diode-pumped Nd:fluorophosphate regenerative amplifier was developed to amplify subpicosecond pulses to the 20-μJ energy level. Better overlap between the cavity mode and pump mode volumes will help to improve the overall extraction efficiency and achieve a few hundred microjoules of energy per pulse, given the same pump power.[16] This system may be able to be scaled to the millijoule level before serious thermal effects would become a problem.

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