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An alexandrite pumped Nd:glass regenerative amplifier for chirped pulse amplification

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An alexandrite pumped, Nd:glass regenerative amplifier is demonstrated. This amplifier has been used with chirped pulse amplification to produce millijoule, picosecond pulses. Using this technique the overall gain bandwidth of glass systems can be conveniently extended, as demonstrated here. This method is also applicable to other broadband materials such as Cr:LiSrAlF$_6$.

For many high field physics studies a laser source capable of producing intensities of 10^{17} W/cm^2 or greater is necessary. Ideally, such a laser source should be compact and simple so that it is at once reliable and manageable. In order to make the laser as compact as possible it is extremely desirable to use solid-state amplifier materials because of their energy storage capability. If this energy can be safely extracted in an ultrashort pulse (1 ps or less) tremendous peak powers can be obtained with relatively modest optical energy requirements. For instance, a 3 TW system based on a 60 fs pulse only requires 200 mJ [1]. The combination of a short pulse, and the energy storage capability of the amplifier results in a very compact, high intensity laser source.

The difficulty, of course, is safely extracting this energy from the amplifier in an ultrashort pulse. Because of the pulse duration, the peak power becomes significant very early in the amplification process. Thus, nonlinear effects become important and can result in catastrophic damage to the amplifier (e.g., whole beam self-focusing). This problem is avoided by temporally stretching or chirping the pulse prior to amplification [2]. Normally this is accomplished through the use of a dispersive grating pair. A 100 fs pulse can be stretched more than 10000 times with standard size optical elements [3]. After stretching, the pulse is amplified to the desired energy level, then recompressed to its Fourier transform limit. The compression stage is also a grating pair arranged to provide the opposite sign of group velocity dispersion introduced by the stretcher. It is important throughout the stretching, amplification, and compression process that the spatial and temporal integrity of the pulse be maintained to the highest level possible. This results in the shortest, highest-contrast (peak intensity-to-background intensity) pulses and most focusable beams.

The advantages of using Nd:glass as the amplifier include the fact that large rods of high optical quality can be fabricated, making it possible to produce near diffraction-limited beams which are critically important for achieving the greatest intensities on target. The technique of chirped pulse amplification used in conjunction with Nd:glass has produced peak powers in the 20–30 TW range [4,5] using large amplifier chains. More compact systems have been shown to produce up to 10 TW [6].

The two major limitations with Nd:glass amplifiers are narrow bandwidth, and poor thermal characteristics. In order to overcome the bandwidth limitations, we use a Ti:Al_2O_3 regenerative amplifier (centered at 1.053 μm) [11] to amplify the chirped pulse from the pJ to the 1 mJ level. The 1 mJ pulse is then amplified through a series of flashlamp pumped Nd:glass amplifiers. The present laser configuration produces 400 fs, 640 mJ pulses at a 0.03 Hz repetition rate.

Although the Ti:Al_2O_3 regenerative amplifier has successfully eliminated the gain narrowing over the first 10^9 orders of amplification, we still experience approximately a 30% reduction in bandwidth over the last 10^3 orders of amplification in our glass amplifiers. (Ti:Al_2O_3 is not used to amplify the pulse beyond the mJ level since the Ti:Al_2O_3 gain cross section at 1 μm is too small to make scaling to higher energies practical with this material in this wavelength regime.) To address this problem, and simultaneously increase the repetition rate of the system we have begun investigating alexandrite pumped, Nd:glass amplifiers.

The viability of this technique has first been demonstrated by building an alexandrite pumped Nd:glass regenerative amplifier. By laser pumping, the pump energy is efficiently deposited and extracted. The pump-to-lasing modes are more closely matched, reducing the thermal load of the amplifier when compared to analogous flashlamp pumped systems. Based purely on geometric considerations we can expect an increase in repetition rate of 4–5 times that of a similar flashlamp pumped amplifier. It is important to remember, however, that we are merely reducing the net heat load and that effects such as thermal birefringence and distortion are still important considerations. Further, the poor thermal characteristics of glass ultimately limit its usefulness as a high repetition rate CPA system. Other materials such as alexandrite, Ti:Al_2O_3, and Cr:$LiSrAlF_6$ all have superior thermal conductivity and are better suited for high repetition rate applications. For the thermal characteristics of amplifier glasses, laser pumping therefore merely enables us to more effectively optimize the repetition rate of the system given these limitations.

Finally, it should be mentioned that this method can also be easily employed with different glass types, which means that the overall gain bandwidth of the system can be conveniently extended by using multiple glasses within a single resonator and/or amplifier [6,8].

We have opted to use alexandrite as the pump laser for several reasons. It has a relatively long fluorescent lifetime (120 μs) which means it is easily flashlamp pumped. It has good thermal conductivity and large crystals of alexandrite are now available for high average power applications. When alexandrite is allowed to free run it produces pulses on the order of 50–100 μs duration. This pulse duration is readily integrated by glass which typically has a lifetime of > 200 μs. This type of free running alexandrite laser has been shown to produce 5–15 joules per shot in a smooth, multimode beam. The long pulse duration, tremendous energy per pulse, combined with the smooth spatial beam profile make alexandrite an excellent pump source. To date we have pumped our glass samples with fluences greater than 300 J/cm^2 without damage. This should be compared to laser pumping Ti:sapphire with 10 ns, 532 nm pulses from frequency doubled *Q*-switched Nd:YAG. Typically, damage occurs at the 3–10 J/cm^2 level.

It is also important to notice that the peak wavelength (750 nm) of alexandrite lies within the absorption band of Cr:$LiSrAlF_6$ [10]. Cr:$LiSrAlF_6$ is a broadband material with a demonstrated tunability over the 760–1000 nm wavelength range. Thus, it is an excellent candidate for the generation and amplification of femtosecond pulses.

In fig. 1 we show the transmission characteristics of a one cm sample of a Nd:phosphate glass rod. Strong absorption bands at the alexandrite pump wavelengths (720–800 nm) are present. In fig. 2 both the calculated and measured small signal, single pass gain at 1.053 μm for the same sample is presented. The discrepancies between measured and calculated gain fall within the error due to uncertainties in both the pump beam size and energy per pump pulse. This figure demonstrates that high gains can be obtained in very small glass rods using alexandrite as the pump source. High gains are important in regenerative amplification in order to minimize spectral narrowing effects. By resorting to smaller rods, B-integral effects are reduced. Also, since the pump is tunable, the absorption length can be easily adjusted by tuning the exciting wavelength. This is an additional plus in effective heat removal.

We have built a regenerative amplifier pumped by

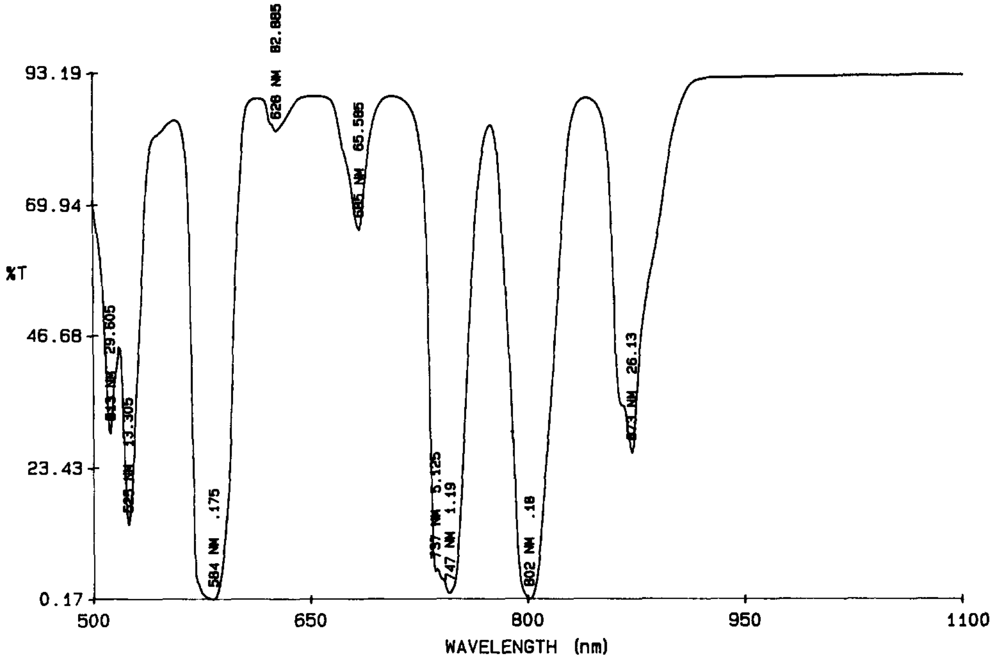

Fig. 1. Transmission of Nd:phosphate glass versus wavelength.

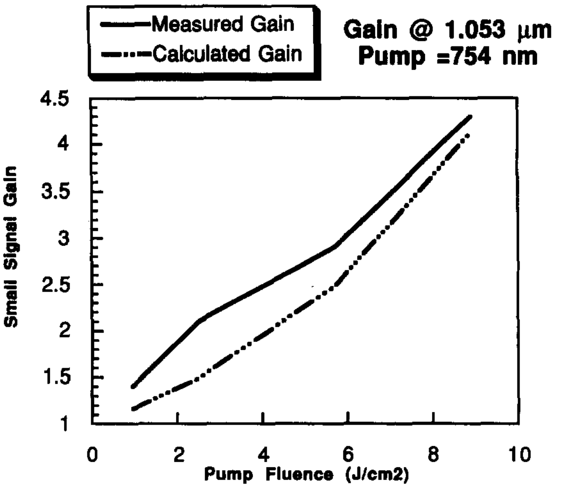

Fig. 2. Measured and calculated gain for the LG-760 glass sample for a pump wavelength of 754 nm.

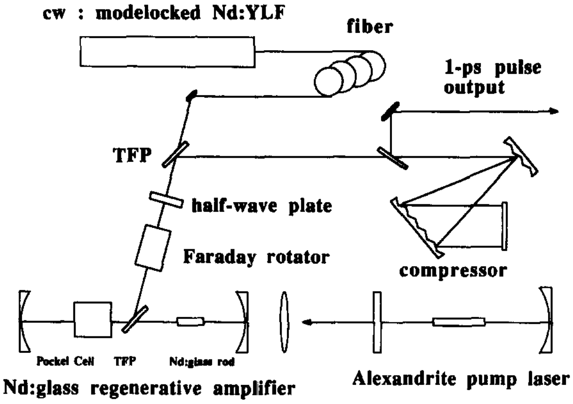

Fig. 3. Layout for the alexandrite pumped, Nd:glass regenerative amplifier for the chirped pulse amplification experiments.

the alexandrite as illustrated in fig. 3. The alexandrite laser used as our pump source, is a dual flashlamp pumped head that uses a 6.35×100 mm^2 rod. The resonator for the pump laser consists of a flat 20% output coupler and a +4 m high reflector. A birefringent filter is added to the resonator when tuning the pump laser is necessary. For this experiment, no birefringent filter was used, and with the rod heated to 65°C the free running wavelength was 754 nm. The output of the pump laser is directed through a combination waveplate and polarizer which is used to control the amount of energy delivered to the regenerative amplifier. The pump pulse is focused by a 750 mm lens into the 1 cm glass rod through one of the cavity end mirrors as shown. The cylindrical glass rod was not AR coated, and was therefore slightly tilted to avoid etaloning. The mirrors were off the shelf items and were not AR coated for the pump wavelength. A thin film polarizer, and a Pockels cell oriented to give a static quarter wave of birefringence are used to *Q*-switch, and cavity dump the amplifier. With a pump pulse energy of 100 mJ (measured just in front of the glass rod) the build up time of the amplifier was 300 ns. The 1.053 μm pulse is cavity dumped after a fixed number of round trips when the energy has reached 5–7 mJ. The rod was mounted in a copper heat sink which was maintained at room temperature. The free running spectrum of the regenerative amplifier was measured to be 1.6 nm fwhm (see fig. 4). We are presently replacing the rod with a 1 cm brewster cut version to reduce intracavity losses. By lowering the losses the pulse can be cavity dumped earlier and spectral narrowing effects further reduced.

As a demonstration of the viability of this laser we have amplified picosecond pulses in this system. The output of a cw mode-locked Nd:YLF laser was sent through a 1 km fiber to generate added bandwidth and stretch the pulse prior to amplification. The pulse spectrum out of the fiber measured 3.7 nm fwhm. (A preferred source of short pulses for this type of application would be Ti:sapphire [7] or a fiber laser [9]. Neither of these sources were available for this experiment.) After amplification to the millijoule level, the pulse spectrum narrowed to 1.6 nm, and was slightly pulled in frequency, so that it was centered on the peak frequency of the amplifier. The amplified pulse spectrum was virtually identical to that shown in fig. 4. After amplification the pulse was recompressed to 1 picosecond using a grating pair. The single shot autocorrelation of the compressed, amplified pulse is shown in fig. 5. The gratings were 1700 lines/mm and arranged in a double pass configuration. As these gratings were not intended for this application, the efficiency of the grating compressor was 10%. It should be noted that a 66% throughput can be expected from the grating compressor [6].

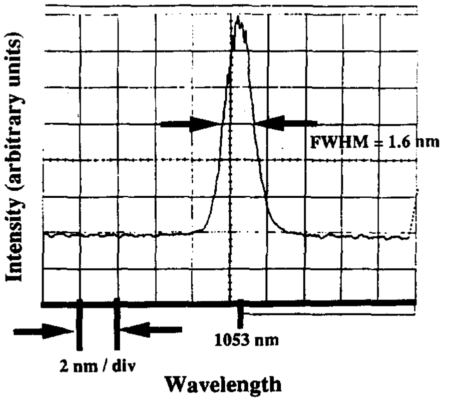

Fig. 4. Spectrum of the *Q*-switched, cavity-dumped amplifier. The fwhm is 1.6 nm.

We have also combined different glass types to extend the overall gain bandwidth of the amplifier. A 1 cm piece of silicate Q-242 glass was added to the regenerative amplifier. This glass was end pumped with 200 mJ per pump pulse (measured external to the cavity) through the resonator end mirror closest to the Pockels cell. The spectrum of the amplifier (fig. 6) now measures 3.1 nm fwhm. Greater experimentation and investigation of combinations of different glass types is necessary to further increase the bandwidth. As stated earlier, one of the advantages of laser pumping is that high gains are possible with minimal amounts of material. This is advantageous in this case also, where several glass types are being combined to extend the gain bandwidth. The gain in multiple (greater than two) rods can be precisely controlled in a convenient, compact geometry. In contrast, this is much more difficult, if not completely impractical, to do with a flashlamp pumped system.

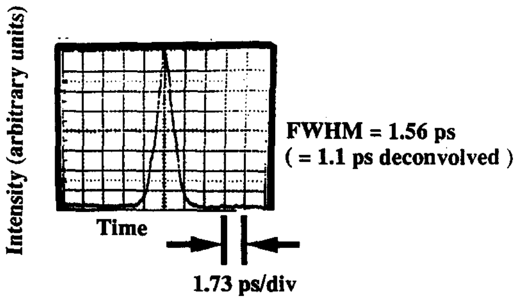

Fig. 5. Single shot autocorrelation trace of the amplified, compressed pulse. The fwhm is 1.1 ps, gaussian assumed.

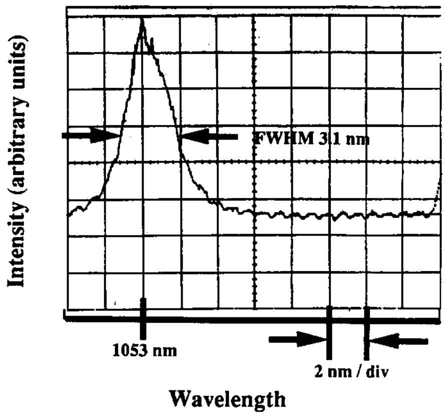

Fig. 6. Spectrum of the amplifier with the combination of Q-242 and LG-760 glasses. The fwhm is 3.1 nm.

Finally, several very important features of this method should be noted. For the regenerative amplifier used in the chirped pulse experiment, only 100 mJ of up to 15 J of available pump light was used. This means that multiple amplifiers can be pumped with a single alexandrite source. Therefore, amplification to the joule level is possible with a single, simple pump source.

Future work includes extending this technique so that it is compatible with our present Ti:Al_2O_3/Nd:glass system. A series of alexandrite-pumped glass amplifiers could be used to amplify the 1 mJ output of the Ti:Al_2O_3 regenerative amplifier. Obviously, this involves scaling the amplifier size. Due to damage considerations the amplifiers are not run at the saturation fluence of the material. It is this damage number that determines the scaling of the aperture size as we increase the pulse energy. Typically, the glass amplifiers are designed to run at ~2 J/cm^2 for a 1 ns pulse. (The saturation fluence of glass is 5 J/cm^2.) The multimode nature of the alexandrite laser is such that it has a smooth, supergaussian profile which is necessary for producing a homogeneous gain profile. We are presently investigating the effects of gain guiding with such profiles in order to ensure the production of near diffraction limited beams [15]. Further, the more efficient energy deposition made possible by laser pumping should also allow us to increase the repetition rate of our laser beyond its present level of 0.03 Hz .

As mentioned previously, this technique can also be used with other types of gain media. We are currently using our alexandrite to pump other broadband materials such as Cr:$LiSrAlF_6$ [12–14] and are obtaining similar results. We have amplified chirped pulses from a self-modelocked Ti:Al_2O_3 oscillator from the 2 pJ level to up to 20 mJ with a single Cr:$LiSrAlF_6$ regenerative amplifier. In a long pulse configuration we have obtained 50 mJ in a 50 ns pulse from an alexandrite pumped Cr:$LiSrAlF_6$ oscillator. This output has been further amplified to 200 mJ in a single pass alexandrite pumped Cr:$LiSrAlF_6$ amplifier [16].

In summary we have demonstrated a powerful, and efficient means of pumping glass for high peak power laser applications. The free running alexandrite laser makes an excellent pump source. It is capable of producing 5–15 J per shot in a 50–100 μs pulse. This long pulse duration and smooth spatial profile, allow us to easily laser pump Nd:glass with large fluences to achieve high gains, without the risk of damage. By combining different glass types the overall gain bandwidth of the system has been extended.

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