

Directly diode-pumped millijoule subpicosecond Yb:glass regenerative amplifier

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An Yb:glass regenerative amplifier directly side pumped by four 20-W diodes is demonstrated. By use of a novel pumping scheme and introduction of cylindrical optics into the cavity, a free-running average output power as great as 4 W with a TEM₀₀-like mode was achieved from the bare cavity, with a 0.56 pump duty cycle. When the regenerative amplifier injected, 1-mJ 200-fs FWHM pulses were obtained following compression by use of 2-ms pump pulses and up to a 150-Hz repetition rate. © 1999 Optical Society of America

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Laser diodes have attracted great attention in diode-pumped solid-state lasers because they usually guarantee more-compact, cost-efficient, and reliable systems than do flash-lamp-pumped or gas lasers. These qualities are very important in real-world applications such as surgery and micromachining. Nd-doped glass has been demonstrated to be a feasible medium for generating subpicosecond pulses from a diode-pumped laser. A Nd:glass mode-locked oscillator that produced sub-100-fs pulses¹ and a Nd:glass chirped-pulse-amplification laser system that produced subpicosecond, microjoule-energy-level output pulses,² both directly pumped by laser diodes, have been demonstrated. This Nd:glass chirped-pulse amplification system has also been applied in corneal surgery.³ However, for some applications, such as glaucoma surgery, microjoule-level pulse energies are insufficient. Unfortunately one cannot obtain diode-pumped millijoule-energy-level lasers merely by pumping the Nd:glass harder. We need a gain medium with a longer fluorescence lifetime and a lower pump-saturation intensity for this purpose. Yb:glass has the advantages of a low quantum defect, a simple electronic structure, a long fluorescence lifetime (~2 ms), and wide, smooth absorption and emission spectra.⁴ The low pump-saturation intensity of Yb:glass at 975 nm (~4 kW/cm²) can especially benefit from diode pumping by reduction of the brightness requirement of the diodes, and the long fluorescence lifetime allows for greater stored energy. The broad absorption spectrum relaxes the tolerance of the diode output bandwidth, and the broad emission spectrum supports subpicosecond pulses. Pulses as short as 60 fs have been obtained from a diode-pumped mode-locked Yb:glass oscillator.⁵ Furthermore, by use of a regenerative amplifier, the challenge of efficiently extracting energy from a low-emission cross-section material can be met.⁶ A diode-pumped Yb:glass regenerative amplifier that produces laser pulses with as much as 50 μJ of energy at 100 Hz with a

total pump power of 1.2 W has already been demonstrated.⁷ Therefore, Yb:glass is a promising candidate for generating millijoule, subpicosecond pulses.

In this Letter we report on what are believed to be the first millijoule, subpicosecond pulses produced from a directly diode-pumped laser. A schematic diagram of the laser is shown in Fig. 1. The gain medium was a novel keystone slab of 400-μm-thick Kigre QX phosphate glass doped with 15-wt. % Yb₂O₃. A water-cooled copper mount allowed us to cool the Yb:glass through both the top and bottom faces while it was side pumped by four cw 20-W 1-cm laser-diode bars from Thomson-CSF. In most side-pumping schemes the lasing mode poorly overlaps the absorbed pump light. In our design the signal beam entered and exited at Brewster's angle through the same face of the glass, undergoing three total internal reflections within the glass. We pumped the glass with one diode at each face where total internal reflection took place to achieve good overlap between the lasing mode and the pump beam, similar to a grazing-incidence slab geometry.⁸ We added a fourth diode to the entering-exiting face of the glass to increase the total gain. Each diode emitted 975-nm light with a bandwidth of ~5 nm FWHM at an output power of 20 W and was cooled with

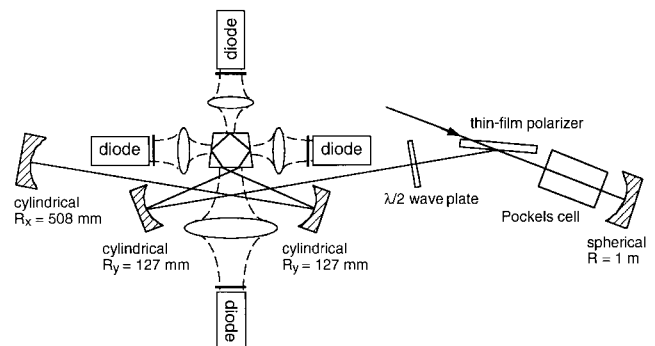


Fig. 1. Schematic diagram of the regenerative amplifier.

20 °C water. The output beam from each diode was first collimated in the sagittal plane by attachment of a 300- μm -diameter microlens to the emitting surface and then focused into the Yb:glass by an aspheric lens. Such a pumping scheme makes possible a compact and cost-effective laser system that uses readily available low-brightness high-power diodes with large tangential M^2 values (usually in the thousands), while providing an opportunity for a single-mode output beam with good mode matching between the pump and the signal beams; therefore, a high-energy TEM₀₀-like output beam is achievable.

First, a regular x-fold cavity with two spherical mirrors and two plane mirrors around the keystone, a Yb:glass gain medium, was built. The output beam from this cavity was a mixture of very high-order modes with measured M^2 values of 114 in the tangential plane and 1.3 in the sagittal plane. To match the desired TEM₀₀ lasing mode to the absorbed pump volume we used a laser cavity with an elliptical TEM₀₀ mode modified from the one suggested in Ref. 9. By use of three cylindrical mirrors and one spherical mirror, as shown in Fig. 1, the tangential M^2 value of the output beam from the bare cavity was improved from 114 to 1.7, whereas the sagittal M^2 value stayed the same, at 1.3. The output performances of these two cavity configurations with a 5% output coupler are shown in Fig. 2. To alleviate thermal effects we modulated the driving currents of the diodes with a pulse generator to control the average pump power. The highest peak power obtained from each diode after the light passed through the focusing lenses was ~ 15 W. Figure 2 shows the average output power versus the total average pump power and the corresponding peak power from each diode with 25-ms-duration 20-Hz pump pulses. As shown in Fig. 2, the output power from the cavity with cylindrical optics was only slightly less than that of the multimode cavity, whereas the mode quality was greatly improved. When the Yb:glass was pumped with 28-ms pulses at 20 Hz (0.56 duty cycle), an average output power greater than 4 W was obtained from both cavities by use of a 5% output coupler.

To make a regenerative amplifier we inserted a half-wave plate, a thin-film polarizer (TFP), and a Pockels cell into the cavity. We configured the TFP for *s*-wave reflection within the cavity, rather than the typical *p*-wave transmission, to reduce the losses. We set the Pockels cell at quarter-wave for zero voltage to avoid having to use an additional wave plate. Because the combination of thermal birefringence and polarization-sensitive optics, such as TFP's, resulted in higher cavity losses, the free-running output power of the regenerative amplifier showed more-obvious thermal effects than did that of the bare cavity at higher average pump powers. The amplifier was seeded with pulses that originated from a directly diode-pumped Yb:glass mode-locked oscillator.⁵ The oscillator was pumped at 964 nm by two InGaAs–GaAs laser diodes with a 30- μm stripe and a total power of 1.2 W and mode locked by use of a prism pair and a semiconductor saturable-absorber mirror in the cavity. The 200-fs (FWHM) mode-locked pulses were stretched

to approximately 0.8 ns by a standard all-reflective single-grating stretcher before they were injected. The stretched pulses were then switched into the regenerative amplifier by the Pockels cell and the TFP and amplified inside the cavity until the inversion was depleted. Because of the quasi-three-level characteristics of Yb:glass, the gain spectrum became redshifted as the inversion was depleted. By tuning the central wavelength of the injection pulses from the mode-locked oscillator, we were able to maximize the bandwidth of the amplified spectrum. Figure 3 shows the amplified bandwidth and peak wavelength as a function of the injection pulses' central wavelength. Figure 4(a) shows the injected and the amplified spectra. We intentionally redshifted the injection spectrum with respect to the amplifier's *Q*-switching spectrum and clipped it in the stretcher to obtain a broader amplified bandwidth, as discussed above. The measured and the calculated autocorrelation traces of the compressed pulses are shown in Fig. 4(b). The FWHM of the measured autocorrelation trace is ~ 290 fs. Assuming Gaussian pulses, the measured trace corresponds to a 200-fs pulse width, approximately 1.1 times the Fourier-transform-limited value. Using 2-ms-long pump pulses, we obtained 1-mJ pulse energy after compression at as much as 150 Hz, with the amplitude fluctuation of

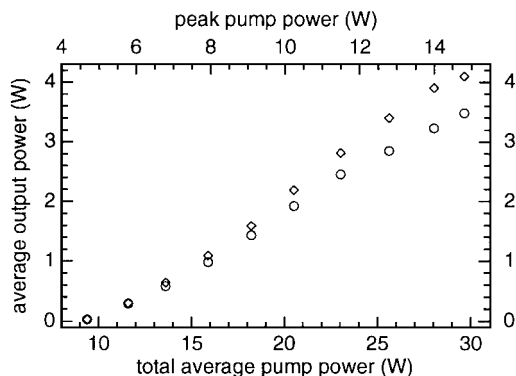


Fig. 2. Comparison of the output performances of the free-running bare cavities with 25-ms-duration 20-Hz pump pulses. Diamonds, cavity without cylindrical optics; circles, cavity with cylindrical optics.

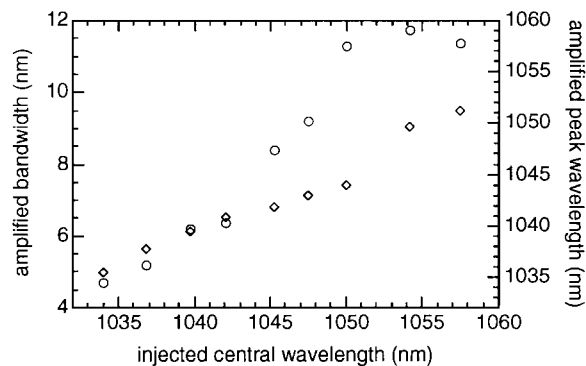


Fig. 3. Amplified bandwidth (circles) and amplified peak wavelength (diamonds) as a function of the injection pulses' central wavelength.

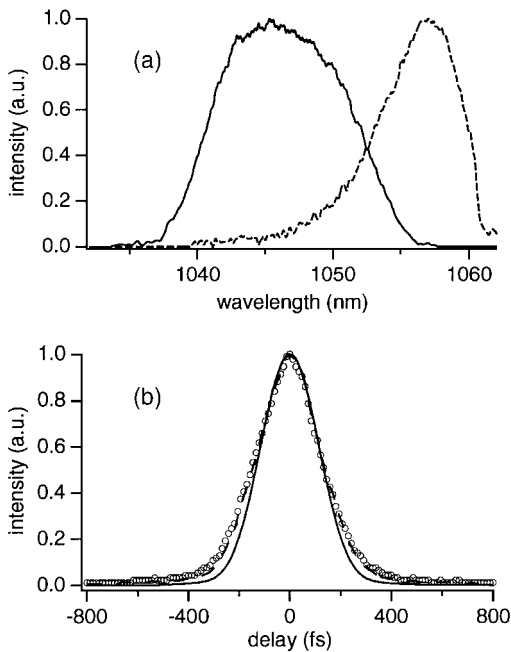


Fig. 4. (a) Injected (dashed curve) and amplified (solid curve) spectra. (b) Measured single-shot autocorrelation trace (circles), measured autocorrelation trace averaged over 100 shots (dashed curve), and autocorrelation trace (solid curve) calculated with the amplified spectrum in (a), and assuming no chirp.

the amplified pulses estimated to be less than 5%. Further improvement in the amplified bandwidth can be achieved by use of regenerative spectral shaping.¹⁰

In conclusion, we have demonstrated a compact cost-effective directly diode-pumped chirped-pulse amplification Yb:glass regenerative amplifier with millijoule, subpicosecond pulses. A novel pumping scheme was introduced so that there would be good mode matching between the pump and the lasing beams, and cylindrical optics were used to generate an elliptical TEM₀₀-like mode. From the bare cavity we obtained 4-W free-running average output power, using a 0.56 pump duty cycle. When the amplifier was injected, we obtained 1-mJ 200-fs (FWHM) pulses with less than 5%

amplitude fluctuation after compression by use of 2-ms pump pulses and a repetition rate as great as 150 Hz.

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