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Yb:KGd$(WO_4)_2$ chirped-pulse regenerative amplifiers

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Abstract

Two Yb^{3+}-doped KGd$(WO_4)_2$ chirped-pulse regenerative amplifiers, one under direct diode pumping and the other under pulsed Ti:sapphire laser pumping, are demonstrated. A slope efficiency as great as 43% is achieved from the free-running bare cavity of the diode-pumped amplifier, and 72% from that of the Ti:sapphire-pumped. When injected, the diode-pumped amplifier produces 44 μJ, 390 fs pulses at 1 kHz, and the Ti:sapphire-pumped amplifier produces 16 mJ, 1 ps pulses at 1 Hz, following compression. © 2002 Elsevier Science B.V. All rights reserved.

1. Introduction

Today applications requiring amplified subpicosecond pulses mainly rely on Ti:sapphire-based laser systems, which are complicated, expensive, and bulky. Therefore, the enthusiasm for these systems in real-world applications, such as surgery and micromachining, has been limited. The fast development of laser diodes in the past decade has made ultrafast lasers more attractive for real-world applications because they guarantee a more compact, cost-efficient, and reliable laser system. The size, cost, and complexity can be further reduced by using direct diode pumping. Direct diode pumping can be employed in both fiber and open-cavity lasers. Recently a diode-pumped all-fiber, chirped-pulse amplification (CPA) system has been demonstrated [1,2]. It generates femtosecond pulses with up to 1.2 mJ pulse energy at an above-kHz repetition rate. Such a laser system is very compact and can be a great ultrafast laser system for real-world applications. However, because of the long fiber length needed, the undesirable cumulative nonlinear effects often limit the output energy and the compressibility of pulses. Therefore, for applications which require above-mJ pulse energy and/or clean pulses, an open-cavity system is preferable.

For direct diode pumping with an open cavity, the gain media used are chromium- (Cr-), neodymium- (Nd-), or ytterbium- (Yb-) doped

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materials because their absorption spectra include the wavelengths of commercially available diodes. Several diode-pumped CPA laser systems based on these materials have been demonstrated [3–9]. Among these materials, Yb-doped materials have the greatest potential to generate high energy, high repetition rate femtosecond pulses. Although the emission spectra of Yb-doped materials are not as broad as those of Cr-doped materials, many of them are still broad enough to support subpicosecond pulses. Furthermore, the energy-storage capabilities of Cr-doped materials are often limited by their relatively short upper-state lifetime and the availability of high power diodes at their pump wavelengths. On the other hand, compared to Nd-doped materials, Yb-doped materials have a longer lifetime and a broader emission spectrum. In addition, the simple electronic structure of the Yb^{3+} ion precludes undesired processes such as excited-state absorption, up conversion, and concentration quenching, and its low quantum defect results in low heat generation, which makes a highly efficient, high power laser possible.

Previously, we have demonstrated a diode-pumped Yb:glass regenerative amplifier which produces 1 mJ, 200 fs pulses [9]. The repetition rate, however, is limited by thermal effects to 150 Hz. In this paper, two chirped-pulse regenerative amplifiers based on Yb^{3+}-doped $KGd(WO_4)_2$ (Yb:KGW) are presented. Although Yb:KGW has a shorter upper-state lifetime, it has much greater absorption and emission cross-sections and a thermal conductivity three fold that of Yb:glass. We first demonstrate an Yb:KGW regenerative amplifier pumped by two low-power diodes, then a second Yb:KGW amplifier pumped by a flash-lamp-pumped Ti:sapphire laser, used to simulate high power diodes. The factors that limit the performances of both amplifiers are also discussed.

2. Diode-pumped Yb:KGW regenerative amplifier

In this section, we present what is, to the best of our knowledge, the first Yb:KGW kHz regenerative amplifier. The schematic diagram is shown in Fig. 1. The 5-at.% Yb^{3+}-doped KGW crystal is 4.1-mm long and cut at Brewster angle for signals with E||a polarization. For the E||a signals, the greatest absorption peak is at 981 nm; however, the second highest absorption peak (at 934 nm) has a much broader bandwidth [10,11]. Because we did not have a mirror coating capable of transmitting 980 nm while efficiently reflecting the Yb:KGW lasing wavelengths, and because the 934-nm absorption peak has a bandwidth greater than 20 nm, we chose 940-nm diodes to pump our Yb:KGW laser for their easy availability. Other advantages of pumping at 940 nm includes: (1) no need for accurate temperature (wavelength) control, and reduced bandwidth requirement, of the diodes because of the broad absorption bandwidth, (2) relaxed coating requirement of pump-through mirrors because of the greater separation of the pump and lasing wavelengths.

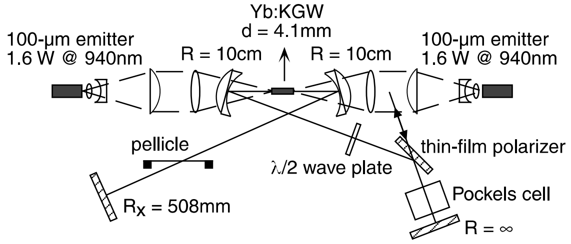

Fig. 1. Schematic diagram of the directly diode-pumped Yb:KGW regenerative amplifier.

The Yb:KGW crystal is mounted on an uncooled copper mount and cw end-pumped by two 1.6 W, 100 μm single-stripe laser diodes at 940 nm with a spectral bandwidth of ~3 nm FWHM. The light of one of our diodes is focused to a beam diameter of 120 μm × 30 μm ($1/e^2$ intensity) with 1.25 W reaching the crystal. The light of the other diode is focused to a beam diameter of 110 μm × 30 μm ($1/e^2$ intensity) with 1.35 W reaching the crystal. The output power and lasing wavelength

Table 1
Output power and lasing wavelength vs. output coupler's (OC's) transmission

OC's transmission	1%	2%	5%	18%
Output power (mW)	525	680	600	435
Lasing wavelength (nm)	1050	1047	1037	1028

vs. transmission of output coupler is shown in Table 1, obtained by using a preliminary cw cavity consisting of two spherical and two plane mirrors in a standard *x* configuration. Please note that the lasing wavelength decreases as the output coupler's transmission increases. This is due to the quasi-three-level characteristics of Yb^{3+}-doped materials. In steady-state, the greater the cavity loss, the shorter the lasing wavelength. As much as 680 mW from the cw Yb:KGW laser is obtained with a 2% output coupler, resulting in an optical-to-optical total efficiency of more than 25%. The cw output power vs. absorbed pump power shows a slope efficiency of 43%.

To make the cw laser into a regenerative amplifier, a thin-film polarizer (TFP) and a KD^*P Pockels cell are inserted into the cavity for pulse injection and extraction. The spontaneously developed wavelength of our Q-switched Yb:KGW laser is around 1022 nm. However, the working window of our TFP is from ~1040 to ~1070 nm with Brewster angle incidence. At 1022 nm, although the reflection of our TFP is almost 100% for s polarization, the transmission of p polarization is less than 50%. Based on the transmission measurement, we know that with a larger incident angle, the transmission curve shifts toward shorter wavelengths. By the same token, the loss on the uncoated side of the polarizer would increase. To properly align the TFP at the Q-switched spontaneous lasing wavelength, we first make the cw cavity lase at a wavelength as close to the Q-switched wavelength as possible by using a high transmission (18%) output coupler (as per Table 1). We then put the TFP inside the cavity and rotate it to minimize the p-wave transmission loss by maximizing the output power. Next, we configure the TFP for s-wave reflection within the cavity by adding a half-wave plate because the p-wave transmission has a greater round-trip loss. This allows us to achieve lower cavity loss and higher transmission for the light going in and out of the cavity around the Q-switched wavelength, without purchasing costly customized TFPs. We also set the Pockels cell at a static quarter wave for zero voltage to avoid using another wave plate.

The next problem that needs to be solved is the mismatch between the injected and the Q-switched spontaneous lasing wavelengths. The injected pulses originate from a directly diode-pumped Yb:glass saturable-absorber (SESAM) mode-locked oscillator [12]. The 200 fs mode-locked pulses are then stretched to approximately 0.8 ns, by a standard all-reflective single-grating stretcher, before being injected. The shortest central wavelength with stable operation available from our Yb:glass oscillator is around 1037 nm. For Yb^{3+}-doped materials, it is desirable to inject at a longer wavelength than the Q-switched spontaneous lasing wavelength in order to reduce the gain-narrowing effect and obtain a broader bandwidth [9]. However, in our case, the injected signal is too weak at that wavelength. Although the injected signal builds up in the amplifier, it is not strong enough to completely deplete the stored energy before the spontaneous emission signal builds up. Therefore, a pellicle is used in the cavity to suppress the spontaneous buildup by adding spectral loss.

Because our pump beam is highly elliptical, we have a multi-mode output beam. By adding an aperture inside the cavity and replacing one of the end mirrors with a cylindrical mirror, we are able to obtain a better mode and maintain a single stable build-up trace. The measured M^2 values of the amplified beam are 1.3 in the tangential plane and 1.0 in the sagittal plane. Fig. 2 shows the average output power and pulse energy vs. the repetition rate of the amplified pulses before compression. The highest repetition rate is limited by the speed of the Pockels cell driver to 2 kHz.

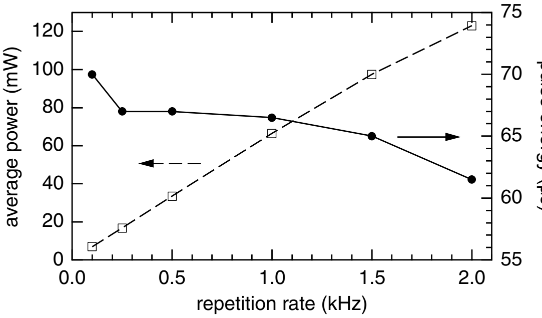

Fig. 2. Average output power and pulse energy vs. repetition rate from the diode-pumped Yb:KGW regenerative amplifier before compression.

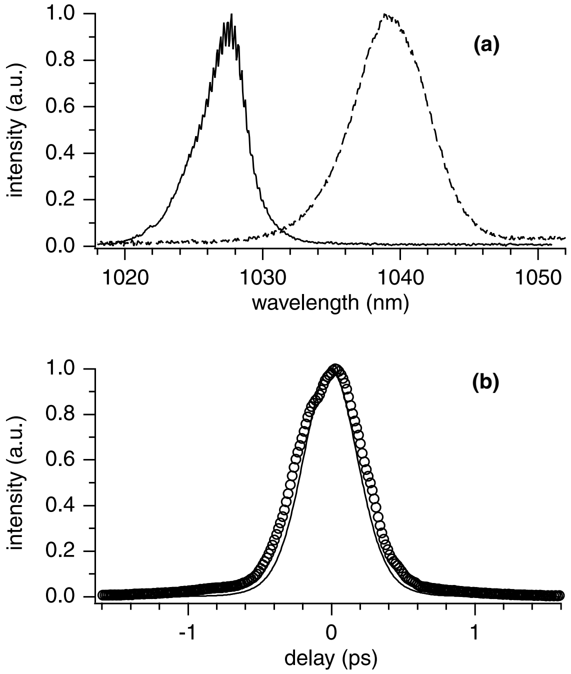

Fig. 3. (a) Injected (dashed curve) and amplified (solid curve) spectra of the diode-pumped Yb:KGW amplifier; (b) measured single-shot autocorrelation trace (circles), and autocorrelation trace (solid curve) calculated with the amplified spectrum in (a), assuming no chirp.

Fig. 3(a) shows the injected and amplified spectra and (b) shows the measured and calculated autocorrelation traces of the compressed pulses. The FWHM of the measured autocorrelation trace is ~550 fs, approximately 1.2 times the FWHM obtained from the calculated autocorrelation trace. Assuming Gaussian pulses, the measured trace corresponds to a 390 fs pulse width. After compression, 44 μJ pulse energy at 1 kHz is obtained.

The pulse energy of our diode-pumped Yb:KGW regenerative amplifier is limited by the generation of stimulated Raman scattering. The results we have shown above are actually obtained by dumping the cavity one roundtrip before the peak of the buildup trace. If the pulses are dumped at or after the peak of the buildup trace, stimulated Raman scattering is evident. Observation of Raman conversion in the cavity has previously been reported from a Yb:KGW Q-switched laser [13]. Fig. 4 shows the spectra of the pulses dumped at the peak of the buildup trace at both the fundamental and Raman wavelengths. The Raman shift is about 900 cm^{-1}. To further increase the pulse energy, the Raman threshold must be increased. This can be achieved by employing a shorter crystal with a higher doping concentration and/or a cavity with a larger mode, together with a higher pumping level. In the following section, we will demonstrate a millijoule Yb:KGW large-mode regenerative amplifier without generation of stimulated Raman scattering.

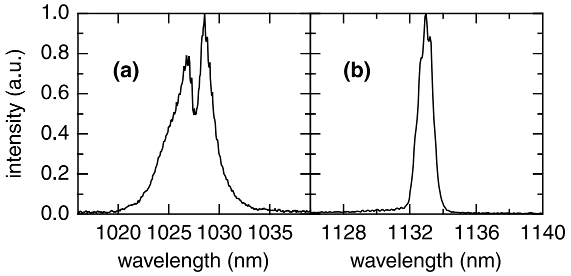

Fig. 4. (a) Fundamental and (b) Raman spectra of the amplified pulses dumped at the peak of the buildup trace.

3. Ti:sapphire-pumped Yb:KGW regenerative amplifier

In this section, we present a millijoule Yb:KGW regenerative amplifier. The schematic diagram is shown in Fig. 5. It is pumped by a flashlamp-pumped Ti:sapphire laser, which is used to simulate high power diodes. This Ti:sapphire laser produces ~150 μs pulses with a repetition rate limited by the power supply to 1 Hz. A 10 μm thick pellicle is placed inside the cavity for wavelength tuning. The output pulse energy depends on the lasing wavelength, and the maximum pulse

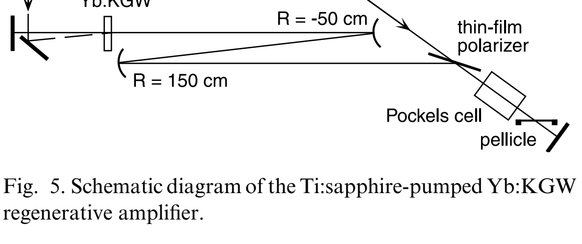

Fig. 5. Schematic diagram of the Ti:sapphire-pumped Yb:KGW regenerative amplifier.

energy achievable at 920 nm is about 2 J. We use the same Yb:KGW crystal that is used for the diode-pumped amplifier in the previous section. The crystal, mounted on an aluminum mount without active cooling, is oriented at Brewster angle for the vertical polarization, which is also the polarization parallel to the *a* crystal axis. First, a short cavity (~35 cm long) is constructed, which consists of only two plane mirrors. The optimal pump wavelength for maximum laser efficiency is found at 934 nm by turning the pellicle in the Ti:sapphire pump laser. The output pulse energy vs. absorbed pump pulse energy shows a slope efficiency of 72% with an 18% output coupler. The output beam is then used to align the rest of the cavity optics needed for the regenerative amplifier.

The large-mode regenerative amplifier includes a telescope to expand the beam in the Pockels cell and TFP to avoid damaging nonlinear effects. By changing the distance between the two telescope curved mirrors, the beam size in the crystal can be increased to as large as 1.5 mm in diameter. A broadband TFP with a working window of ~200 nm, from 900 to 1100 nm, is used in this amplifier, though at the cost of a greater loss than the near-Brewster TFP used in the diode-pumped Yb:KGW amplifier. As in the diode-pumped amplifier, the TFP is configured for s-wave reflection within the cavity to minimize the associated cavity loss, and the Pockels cell is set at a static quarter wave for zero voltage to avoid using a quarter-wave plate. No half-wave plate is needed here because the crystal is oriented at Brewster angle for the vertical polarization.

For the Ti:sapphire-pumped Yb:KGW amplifier, we use the same oscillator, stretcher, and compressor that are used for the diode-pumped Yb:KGW amplifier. Therefore, to assure successful injection, in addition to tuning the oscillator to the shortest wavelength available, it is necessary to insert a pellicle in the cavity to suppress the spontaneous buildup as in the diode-pumped amplifier, because the injected signal is too weak at the Q-switched spontaneous lasing wavelength. Since the Ti:sapphire-pumped Yb:KGW laser has a greater laser gain, a greater spectral loss has to be introduced. In fact, the pellicle is oriented in a way that the signal polarization is perpendicular to the pellicle's incident plane (s-polarized) to obtain sufficient loss at the Q-switched wavelength. Each time the pump energy is increased, the pellicle has to be adjusted to suppress the spontaneous buildup at wavelengths where the seed signal is too weak, while maximizing the amplified pulse energy. However, the loss at the signal wavelength usually increases with the loss at the Q-switched wavelength. Therefore, with a pump pulse energy greater than ~430 mJ, the amplified output energy no longer increases with the pump energy; in fact, it may begin to decrease. With 430 mJ pump energy, 25 mJ amplified pulse energy is obtained before compression. No stimulated Raman scattering is observed at this energy level. To further increase the amplified pulse energy, an oscillator with an output wavelength close to the Q-switched spontaneous lasing wavelength and/or a greater injected pulse energy must be employed. A pellicle can then be used for improving the amplified bandwidth [14] instead of for suppressing the spontaneous Q-switched signal.

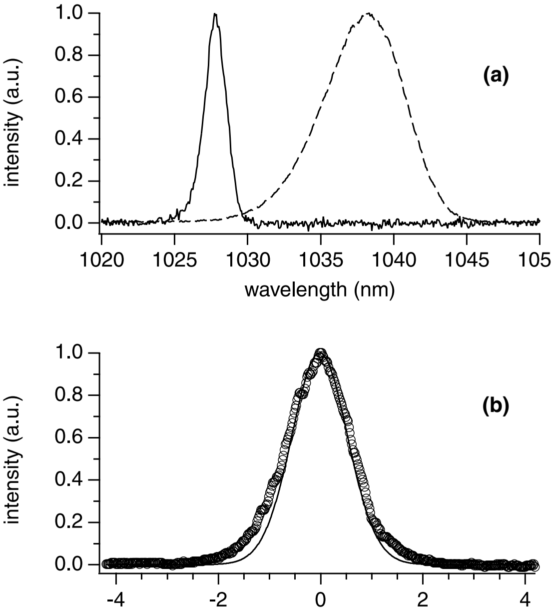

Fig. 6. (a) Injected (dashed curve) and amplified (solid curve) spectra of the Ti:sapphire-pumped Yb:KGW amplifier; (b) measured single-shot autocorrelation trace (circles), and autocorrelation trace (solid curve) calculated with the amplified spectrum in (a), assuming no chirp.

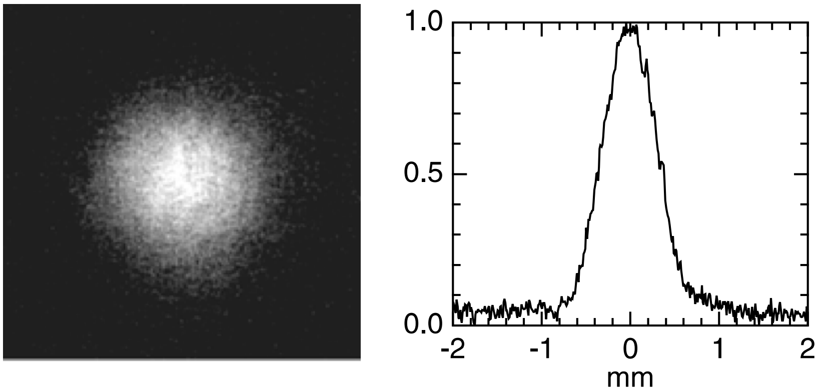

Fig. 7. Spatial profile and line out of the output from the Ti:sapphire-pumped Yb:KGW regenerative amplifier.

Fig. 6(a) shows the injected and amplified spectra and (b) shows the measured and calculated autocorrelation traces of the compressed pulses. The gain-narrowing effect is more severe in the Ti:sapphire-pumped Yb:KGW amplifier than in the diode-pumped amplifier, resulting in a longer pulse. The FWHM of the measured autocorrelation trace is ~1.44 ps, approximately 1.12 times the FWHM obtained from the calculated autocorrelation trace. Assuming Gaussian pulses, the measured trace corresponds to a 1 ps pulse width. The output beam quality from this large-mode regenerative amplifier appears good, as shown in Fig. 7. After compression, 16 mJ pulse energy at 1 Hz is obtained.

4. Conclusions

In conclusion, we have demonstrated two Yb:KGW regenerative amplifiers, one under direct diode pumping and the other under pulsed Ti:sapphire laser pumping. The diode-pumped Yb:KGW amplifier generates 44 μJ, 390 fs output pulses following compression at 1 kHz. The repetition rate is limited to 2 kHz by the Pockels cell driver. The pulse energy is limited by the generation of stimulated Raman scattering. To demonstrate greater pulse energy is achievable without Raman conversion, a second Yb:KGW amplifier with a large-mode cavity is built, pumped by a flashlamp-pumped Ti:sapphire laser, used to simulate high power diodes. This amplifier generates 16 mJ, 1 ps pulses at 1 Hz following compression. By increasing the cavity beam size, the Raman threshold is successfully increased and no Raman generation is observed in the Ti:sapphire-pumped amplifier. It should also be possible to increase the Raman threshold by using a shorter crystal with a higher doping concentration. The repetition rate of the Ti:sapphire-pumped amplifier is limited by the pump laser to 1 Hz. A much higher repetition rate should be attainable if high power diodes are used for pumping. To obtain a pulse energy greater than 16 mJ, injected pulses must have a wavelength close to the Yb:KGW Q-switched spontaneous lasing wavelength. Average power and pulse energy may also be increased by actively cooling the Yb:KGW crystal.

Acknowledgements

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