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Optics Communications 259 (2006) 812–815
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

Diode-pumped, chirped-pulse Yb:S-FAP regenerative amplifier for laser-Compton X-ray generation

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Received 16 September 2004; received in revised form 15 September 2005; accepted 21 September 2005

Abstract

We present a diode-pumped, chirped-pulse Yb:S-FAP regenerative amplifier. This regenerative amplifier was developed as a first amplifier in an all-solid-state Yb:S-FAP laser system for laser-Compton X-ray generation. The amplifier delivers pulse energies above 24 mJ at a repetition rate of 50 Hz. Pulse compression reduces pulse widths to approximately 2.0 ps.
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PACS: 42.55.Xi; 42.55.Rz; 42.65.Re

Keywords: Diode pumped; Regenerative amplifier; Yb:S-FAP

Short-pulse X-ray generation from laser-Compton scattering between relativistic electrons and ultra-high-intensity laser pulses (laser-Compton X-ray generation) represents a promising light source for the study of light–matter interaction, for medical and biomedical applications such as structural analysis of human protein substances, and for various industrial imaging applications. We have demonstrated the femtosecond X-ray generation through laser Compton-scattering using a terawatt Ti:Sapphire laser with pulse energies around 100 mJ [1]. Practical application of such X-ray sources requires laser pulse energies of up to 0.5 J to produce the requisite 10^6 photons/pulse with the repetition rates of several-tens hertz and the pulse widths of below few picoseconds. Ti:Sapphire is an excellent material for generating high-intensity laser pulses due to its large gain bandwidth and thermal properties. However, the requirements of large-scale pump lasers make it difficult to build a compact, cost-effective Ti:Sapphire laser system with pulse energies above 100 mJ and repetition rates of several-tens hertz. Therefore, we plan to develop an all-solid-state, chirped-pulse amplification laser system containing a diode-pumped regenerative amplifier, a preamplifier and a main amplifier with Yb-doped materials to obtain the pulse energy more than 0.5 J at the pulse repetition rates of several-tens hertz.

Due to their promising laser characteristics, Yb-doped materials have recently attracted a great interest in relation to the development of diode-pumped all-solid-state lasers. The small quantum defects of Yb-doped materials result in lower thermal loading and reduce thermal problems. Additionally, the long fluorescence lifetime (1–2 ms) of Yb-doped materials offers the advantage of greater energy storage in a gain medium in high-energy ultra-short amplification, while their broad gain bandwidth make it possible to generate and amplify ultra-short laser pulses. Several diode-pumped

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doi:10.1016/j.optcom.2005.09.048

regenerative amplifiers with Yb-doped materials have been reported [2–5]. Unfortunately, the pulse energies reported in these studies have been limited to less than a few millijoules in the regenerative amplifiers. The lower pulse energies are attributable to the lower laser gain and the very high saturation fluence of the Yb-materials. Kawanaka et al. [6] successfully increased laser gain while reducing saturation fluence using cryogenically cooled Yb:YLF in their diode-pumped regenerative amplifier, obtaining a maximum pulse energy of 30.1 mJ.

Like other Yb-doped materials, Yb:$Sr_5(PO_4)_3$ (Yb:S-FAP) has a long fluorescence lifetime and a large stimulated-emission cross-section [7]. Furthermore, its low-pump saturation intensity is a great advantage in diode pumping, reducing the brightness required of laser-diodes. These advantageous properties make it possible to easily obtain high laser gain in a diode-pumped scheme [8]. The spectral bandwidth also supports pulse widths of a few picoseconds [9].

In our design of the laser system, the amplified energies from the preamplifier and the main amplifier are above 100 mJ and 1 J, respectively. Above 10 mJ of the amplified energy in the regenerative amplifier is also required in our laser system. We chose Yb:S-FAP as amplification laser materials because high laser gain cannot be accomplished at room temperatures in use of other Yb-doped materials.

In this paper, we present a diode-pumped, chirped-pulse Yb:S-FAP regenerative amplifier that delivers pulse energies above 24 mJ at a repetition rate of 50 Hz. This Yb:S-FAP regenerative amplifier was developed as a first amplifier in an all-solid-state, chirped-pulse Yb:S-FAP laser system for laser-Compton X-ray generation.

Fig. 1 is a schematic diagram of the diode-pumped Yb:S-FAP regenerative amplifier. The seed pulses are generated by a diode-pumped Yb:glass mode-locked oscillator (High-Q Laser) operating at 79.33 MHz, 1/36 of the 2856 MHz RF frequency of an S-band linear accelerator used to obtain relativistic electrons in the laser-Compton X-ray generation system. The oscillator produces 200 fs pulses of 6 nm bandwidth and 100 mW average output power. The seed pulses from the oscillator are stretched to about 800 ps in an Offner-type pulse stretcher. The grating (Jovin–Yvon) in the stretcher has 1740 grooves per mm. The pulses from the stretcher are injected into the cavity of the Yb:S-FAP regenerative amplifier, which incorporates a z-folded cavity and a water-cooled Yb:S-FAP crystal (Scientific Materials) of $3.5 \times 3.5 \times 22$ mm in size. The crystal is end-pumped with a pumping unit, which consists of a stacked-array of InGaAs diode lasers (Hamamatsu Photonics) operating at 900 nm; a lens duct; and an aspheric lens set. The pump light in the lens duct exit (measuring 2.5×2.5 mm) is image-relayed to the end face of the crystal. The diode stack is capable of producing a maximum pulse energy of 900 mJ at a repetition rate of 50 Hz. The pulse width of the pump light was adjusted to 1.3 ms. We have measured the effective focal length of the thermal lens generated in the Yb:S-FAP crystal based on the displacement of the focal beam waists of a He–Ne reference laser beam with a lens [10]. In this experiment, we have used another diode stack with higher pulse energy of 1.3 J. The focal length of the thermal lens was estimated to be −2.6 m for absorbed pump power of about 46 W. The negative focal lengths may be attributed to the negative dn/dT values for fluorides [11]. Based on this result, we designed a dynamically stable resonator for the regenerative amplifier, consisting of two concave mirrors, one of 2-m radius of curvature and the other of 5-m radius of curvature.

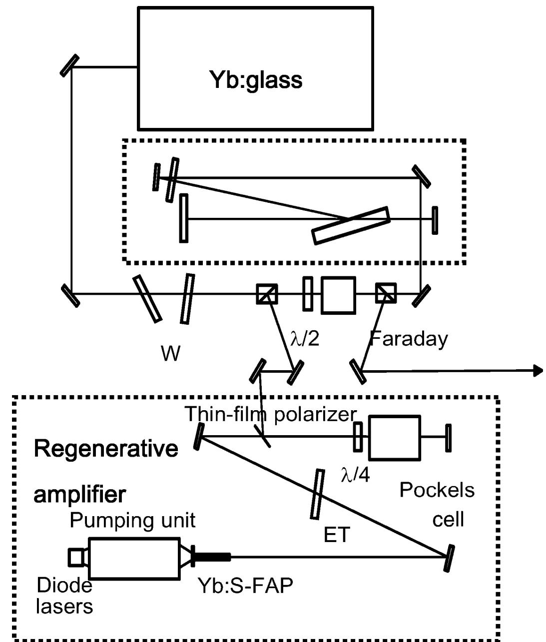

Fig. 1. Schematic diagram of a diode-pumped Yb:S-FAP regenerative amplifier: WP, waveplates, ET, solid etalon.

Since pulse duration is limited by the final bandwidth of amplified laser pulses, we must compensate for gain narrowing to obtain a pulse width below a few ps after compression. The gain narrowing in the amplifiers was overcome by both of reshaping the input spectrum and through regenerative pulse shaping [12]. We reshaped the output spectrum from the mode-locked oscillator by introducing two half-wave plates between the oscillator and the pulse stretcher. In this configuration, the spectrum is easily modified by varying the incident angle to the optical axis of the wave plates, a low-cost method that offers high-flexibility. We also used a solid etalon as a wavelength filter in the regenerative amplifier for the regenerative pulse shaping. Fig. 2 shows the spectra of the amplified pulses with and without compensation for gain narrowing. The spectral bandwidth of the amplified pulses was expanded by virtue of the compensation for gain narrowing in the regenerative amplifier although the spectrum was split into three peaks.

Fig. 3 shows the amplified pulse energy and the pulse build-up time as a function of absorbed pump energy at a pulse repetition rate of 50 Hz. An amplified pulse-energy above 24 mJ was obtained at a repetition rate of 50 Hz for

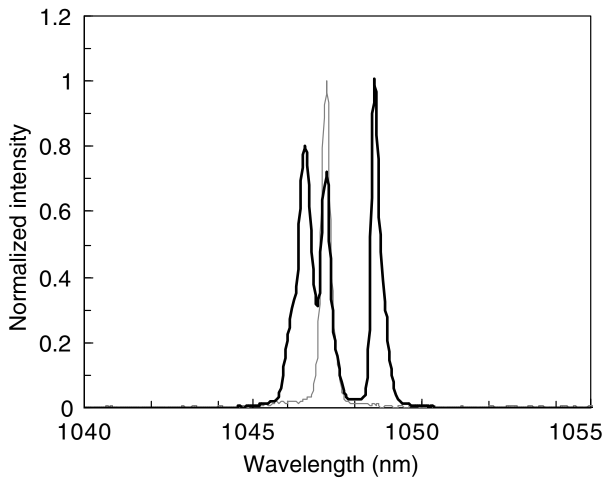

Fig. 2. Spectra of the amplified pulses with (thicker line) and without (thinner line) compensation for gain narrowing.

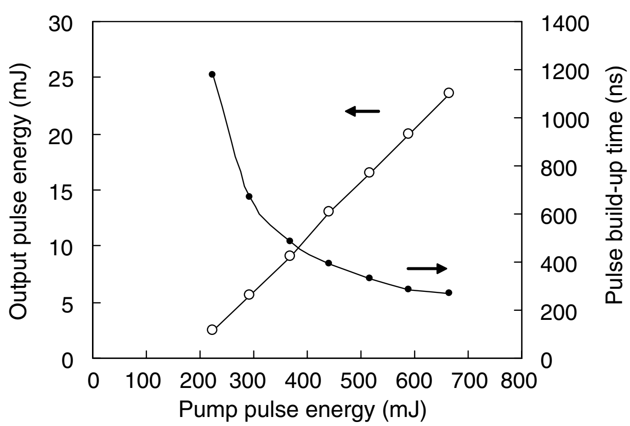

Fig. 3. Amplified pulse energy (open circles) and pulse build-up time (filled circles) as a function of absorbed pump pulse energy.

a pump energy of 665 mJ. The amplified energy increases linearly with absorbed pump energy, indicating that adequate compensation for gain narrowing prevents self-focusing induction. The number of round trips was 28. The lower extraction efficiency is due to a very low beam overlap efficiency of about 14% and insertion loss attributable to a solid etalon in the laser cavity.

The beam quality of the amplified pulses was evaluated with an 8-bit CCD camera (Pulnix, TM-745E) and a Shack–Hartmann-type wavefront sensor (AOA, Wave-Scope). Fig. 4(a) shows the near-field beam profile of the amplified pulses measured with a CCD camera. We obtained a TEM_{00}-like beam profile and a spot size at the far field almost equal to that for the diffraction-limited beam. Fig. 4(b) shows the point spread function calculated from the measured profile of the optical path difference (OPD). The OPD profile of the amplified pulse was measured with a wavefront sensor. Wavefront distortion was below 0.03λ rms, and we obtained a high Strehl-ratio [13,14] of 0.93, confirming that our regenerative amplifier was capable of producing a high-quality beam.

We tried pulse compression for regenerative amplified pulses with a parallel-grating pair. The gratings in the compressor have 1740 grooves per mm. The throughput of the compressor was about 50%. Fig. 5 shows a measured single-shot autocorrelation along with the transform-limited autocorrelation calculated from the measured compressed spectrum. The autocorrelation width was approximately 2.8 ps. The pulse width of the compressed pulses was estimated to be about 2.0 ps using the ratio between the calculated pulse width and the autocorrelation width for the transform-limited pulse. We have suspected that the pulse width longer than that for transform-limited pulses may be due to the higher-order dispersion errors introduced by the longer Yb:S-FAP crystal firstly. However, the residual fourth-order dispersion error broadened the pulse width only less than 100 fs in our calculation. We are unable to identify the causes of the longer pulse width at present.

We developed a diode-pumped, chirped-pulse Yb:S-FAP regenerative amplifier as a first amplifier in an all-solid-state Yb:S-FAP laser system for laser-Compton X-ray generation. The Yb:S-FAP regenerative amplifier delivered the pulse energies above 24 mJ at a repetition rate of 50 Hz. Our measurements of wavefront distortion for the amplified pulses confirmed that it was possible to

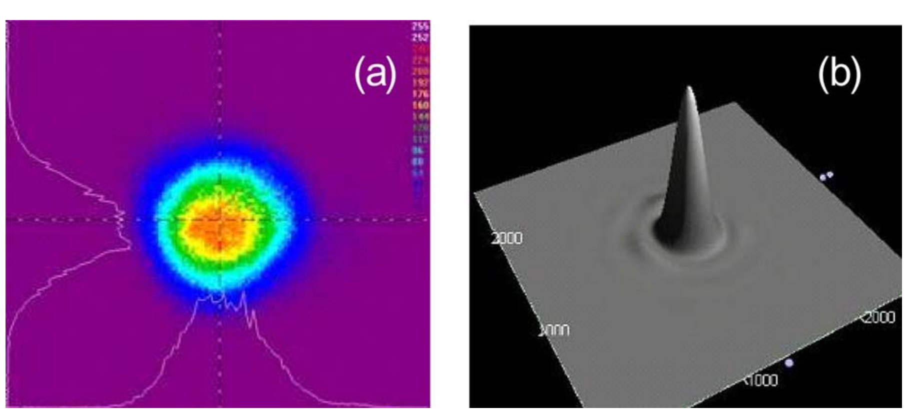

Fig. 4. (a) Near-field beam profile and (b) point spread function for amplified pulses.

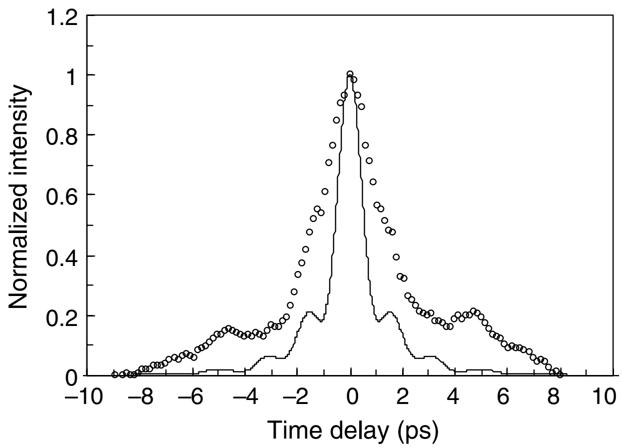

Fig. 5. Measured and calculated single-shot autocorrelation. The open circles represent the measured autocorrelation. The solid line is the Fourier-transform-limited autocorrelation.

obtain a high quality beam. We compensated for gain narrowing using waveplates to reshape the input spectrum and regenerative pulse shaping with a solid etalon, thereby expanding the spectral bandwidth of the amplified pulses. After compression, the pulse width was estimated to be about 2.0 ps.

Acknowledgements

The authors thank M.S. Bowers, E. Honea, and D. Jander of Aculight Corporation for their invaluable discussions and their support. This work is performed under the management of a Technological Research Association, the Femtosecond Technology Research Association supported by New Energy and Industrial Technology Development Organization.

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