Ultrafast semiconductor laser-diode-seeded Cr:LiSAF regenerative amplifier system

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An ultrafast, hybrid mode-locked semiconductor laser-diode system has been used to seed a flash-lamp-pumped Cr:LiSAF regenerative amplifier system, producing subpicosecond pulses with millijoule output pulse energy. This system has the potential to eliminate argon-ion-pumped-based, ultrafast laser systems. © 1997 Optical Society of America

Key words: Regenerative amplification, mode-locked diode laser, injection seeding.

1. Introduction

Compact and efficient sources of ultrashort, high-power optical pulses play an important role in novel technologies such as x-ray generation for photolithography,[1,2] high-spatial-resolution medical imaging,[3,4] advanced rf photoinjectors[5] and high-speed measurement and characterization systems.[6] In this paper we present experimental results of an ultrafast, mode-locked semiconductor laser-diode system that is used as an injection seed source for a flash-lamp-pumped Cr:LiSAF regenerative amplifier system. The combined laser system produces optical pulses of ~1 ps in duration with pulse energies of 1.5 mJ. The system we describe in this paper has the potential to replace large frame-ion-laser-pumped, ultrafast oscillators as seed sources for high-power ultrafast laser systems.

In the past high-power ultrafast optical pulses were generated by the employment of a low-power master oscillator, such as a mode-locked solid-state or dye-laser oscillator, with subsequent amplification. High pulse energies, of the order of millijoules, were produced by incorporating amplifying schemes based on either multiple single-pass amplifiers,[7–9] a single multipass amplifier[10,11] or regenerative amplification.[12,13] These laser systems have assisted in pioneering many new advances in ultrafast science; however, for commercial applications, these laser systems are hindered by the necessity of large frame-ion lasers for excitation of a mode-locked master oscillator. Here, we investigate the potential for utilizing a hybrid mode-locked external-cavity semiconductor laser as the injection seed source for a high-power ultrafast regenerative amplifier system. Although there has been considerable effort to develop compact, high-power laser sources,[14–18] the goal of our study is to determine if compact mode-locked diode laser sources possess the required injection characteristics to be viable sources for high-power regenerative amplifiers.

2. Experimental Method

The experimental configuration is illustrated in Figs. 1 and 2 and consists of an external-cavity hybrid mode-locked semiconductor laser,[19] a pulse stretcher for chirped-pulse amplification,[20] a gated semiconductor traveling-wave optical amplifier, a flash-lamp-pumped linear-cavity Cr:LiSAF regenerative amplifier,[21] a pulse compressor, and associated diagnostics. Ultrashort optical pulses are generated from a hybrid mode-locked external-cavity semiconductor laser-diode system. The system utilized in this experiment generates optical pulses with temporal durations of 760 fs with pulse energies of the order of 30–35 pJ. The laser oscillator consists of a GaAs/AlGaAs semiconductor traveling-wave optical amplifier in an external cavity with a GaAs/AlGaAs multiple-quantum-well rear reflector that serves as a saturable absorber. The saturable absorber is antireflection coated with a proton-implantation processing step to reduce the absorber recovery time.

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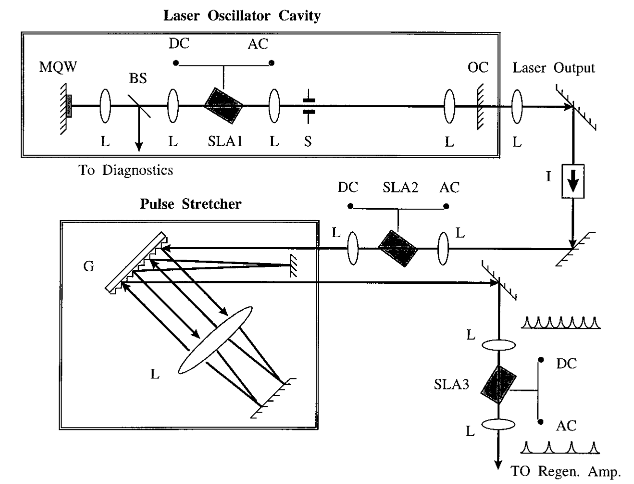

Fig. 1. Schematic of the experimental setup of the external cavity mode-locked semiconductor laser system: MQW, multiple-quantum-well saturable absorber mirror; L, lens; BS, beam splitter; SLA, semiconductor laser amplifier; S, slit; OC, output coupler; I, optical isolator; G, diffraction grating.

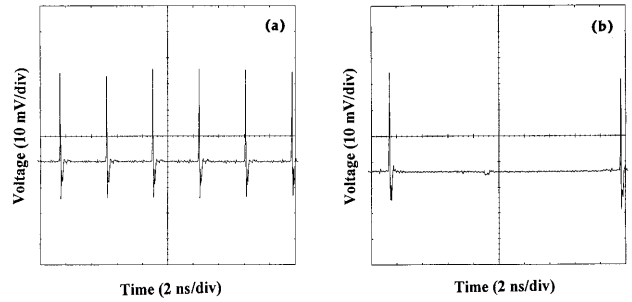

Fig. 3. Oscilloscope trace of the output mode-locked diode laser pulse train (a) before prepulse selection of the traveling-wave amplifier and (b) after the traveling-wave amplifier pulse selector.

Imaging of the output facet of the semiconductor optical amplifier onto the saturable absorber is sufficient to obtain the necessary photon density to initiate passive mode locking when the external cavity is biased appropriately. The external-cavity diode laser is excited with both dc currents (~150 mA) and ~0.5 W of rf power at a frequency of 274 MHz, corresponding to the longitudinal mode spacing of the external cavity, to achieve hybrid mode locking. The generated mode-locked optical pulses are highly chirped owing to the mode-locking dynamics associated with gain saturation, depletion, and saturable absorption.[22] The generated optical pulses then pass through an optical isolator and are injected into a second semiconductor traveling-wave optical amplifier to increase the optical pulse energy to ~75 pJ. Before injection into the regenerative amplifier, the pulses are stretched to 120 ps with a standard grating pulse stretcher. This pulse-stretching step, in conjunction with pulse amplification, is performed to avoid the occurrence of nonlinear optical effects.

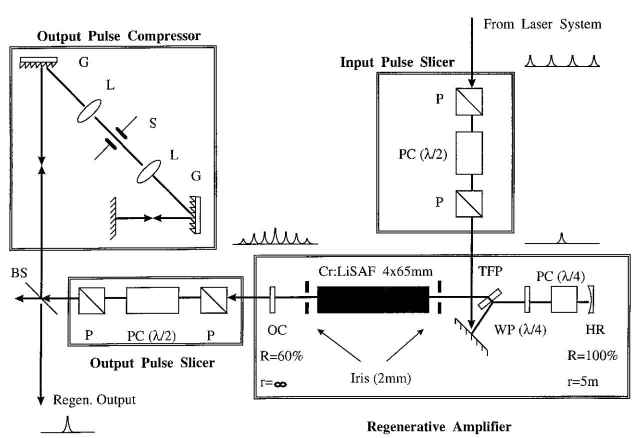

Fig. 2. Schematic of the regenerative amplifier system: OC, output coupler; P, polarizer; PC, Pockels cell; TFP, thin-film polarizer; WP, wave plate; HR, high-reflection mirror.

For optimized pulse amplification, a single pulse must be selected from the pulse train generated from the mode-locked laser-diode system. The repetition rate of the laser-diode system is 274 MHz, corresponding to a pulse-to-pulse spacing of 3.65 ns, making the pulse selection process difficult if commercially available Pockels cells and corresponding pulse drivers are employed to select single pulses from the pulse train. To overcome this difficulty, we inject the mode-locked pulse train into another semiconductor optical amplifier. By appropriately pulse-biasing this device, we realize a fast gating device. In these experiments a 3-ns FWHM electrical pulse synchronized to the rf driving signal at 274 MHz was employed to select or gate out every tenth pulse from the pulse train. This initial pulse slicing was performed before the main regenerative amplifier pulse slicing to reduce the laser-diode system repetition rate, achieving compatibility with the regenerative amplifier system pulse slicer.

Note that the optical pulses are also amplified in this process. This helps to compensate for the diffractive losses encountered in the pulse stretcher. The optical pulses are amplified to an output saturation pulse energy of ~75 pJ. No appreciable temporal or spectral distortion is observed on the amplified output pulses.

In Figs. 3 (a) and (b) sampling oscilloscope traces are displayed, illustrating the optical pulse train before and after the semiconductor optical amplifier/pulse slicer. The contrast provided by the semiconductor optical gate was measured to be greater than −23 dB. Owing to the hybrid mode-locked nature of the laser-diode system, we can employ direct electrical triggering of the regenerative amplifier pulse slicer, avoiding the use of a fast photodetector to provide triggering pulses. The final pulse selection is performed with a standard Pockels cell and injected into the regenerative amplifier, which consists of a linear-cavity configuration and a pulse slicer placed at the output coupler of the regenerative amplifier system.[21] The single-selected pulse is then directed into a pulse compressor and diagnostics.

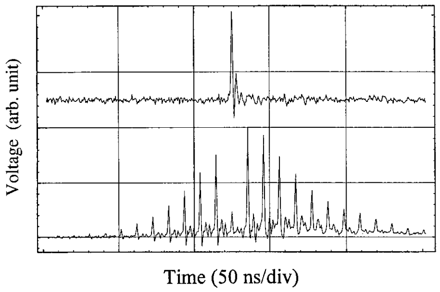

Fig. 4. Oscilloscope traces of the regenerative amplifier output: top, single-selected output-amplified pulse; bottom, the rejected amplified-output pulse train.

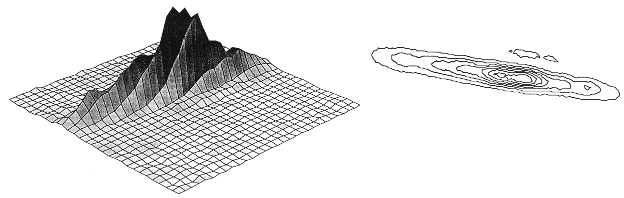

Fig. 5. Transverse-mode profiles of the injected diode laser beam: right-hand side, surface plot; left-hand side, contour plot.

The amplified single pulse, along with the rejected pulse train, is shown in Fig. 4. These results were obtained by injecting ~20–40-pJ pulses from the laser-diode system into the regenerative amplifier. The large depth of modulation, illustrated in Fig. 3 (bottom), demonstrates that sufficient injection of the semiconductor optical pulse has been accomplished, whereas Fig. 3 (top) illustrates the large contrast obtained from the tandem Pockels cell gate. An analysis of the rejected pulse train shows that approximately 55 round trips are required for the injected pulse to reach maximum gain. The single-selected pulse energy was measured to be 1.5 mJ, representing a gain of over 30 million. Note that the temporal pulse duration in this case was that of the stretched optical pulse and was measured to be 120 ps. This would necessitate a time–bandwidth product that is ~250 times the transform limit.

An additional concern regarding the use of semiconductor diode lasers as injection seed sources to the regenerative amplifier system is the optical transverse-mode mismatch between the mode-locked diode laser and the regenerative amplifier cavity. It is well known that semiconductor diode lasers possess a large degree of asymmetry and astigmatism in the transverse-mode profile of an output optical beam. The semiconductor optical amplifier devices employed in these experiments are without exception and possess an elliptical output transverse-optical beam cross section with an ellipticity ratio of approximately 7:1. The main resulting detriment owing to the mismatch in the transverse-mode profiles is a reduction in the coupling efficiency between the mode-locked semiconductor laser-diode system and the regenerative amplifier. This reduction in the coupling efficiency results in a required increase of the injected optical power. Despite the cavity-mode mismatch problem, the regenerative amplifier acts as a spatial filter and produces a clean TEM_{00} transverse-mode profile output beam. To demonstrate this quantitatively, Figs. 5 and 6 show the transverse-mode profiles of the mode-locked semiconductor diode laser and the output of the regenerative amplifier, respectively, as measured with an optical beam profiler. The salient feature, as demonstrated by the figure, is the production of a clean TEM_{00} output beam from the regenerative amplifier when the injected optical beam possesses a large degree of transverse ellipticity, e.g., 7:1. In these experiments no effort was employed to circularize the beam or eliminate beam astigmatism to demonstrate the robustness of the mode-locked diode laser and regenerative amplifier system. However, simple, commercially available circularizing and astigmatic correction optics are available for diode lasers. The incorporation of these devices would optimize the mode match between the two laser systems and result in a larger injection-coupling efficiency.

To demonstrate the overall temporal performance of the combined mode-locked diode laser and regenerative amplifier, we measured the minimum possible pulse width generated directly from the hybrid mode-locked external-cavity semiconductor diode laser system. Again, the laser-diode system does not produce transform-limited pulses directly but produces pulses that are highly chirped owing to the mode-locking dynamics of gain saturation, depletion, and saturable absorption. To assess the temporal performance of the mode-locked diode laser system, we direct the output pulse train into a dual-grating dispersion compensator to compensate for chirp impressed on the pulses during the mode-locking process. This allows us to optimize the mode-locked diode laser system's performance for maximum linear chirp, which minimizes the pulse width after the pulses are compressed. Second-order autocorrelation traces were obtained from the mode-locked semiconductor diode laser when the system was configured for minimum pulse duration. In these experiments the optical pulses are directed from the laser-diode master oscillator–power amplifier into a grating stretcher and then into a dual-grating dispersion compensator with an internal 1:1 telescope. This was done to compensate for the dispersive effects owing to mode-locking and the pulse stretcher. This procedure allows one to optimize the performance of

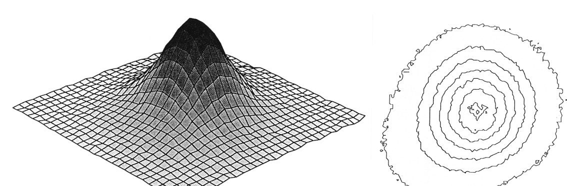

Fig. 6. Transverse-mode profiles of the regenerative amplifier output beam: right-hand side, surface plot; left-hand side, contour plot.

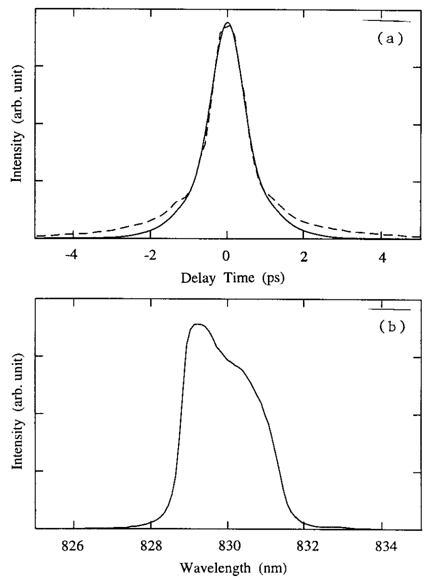

Fig. 7. Characteristics of the mode-locked semiconductor laser-diode system: (a) second-order autocorrelation trace (solid curve) and autocorrelation trace computed with cubic phase chirp (dotted curve), (b) optical spectrum of the optimized mode-locked semiconductor laser-diode system.

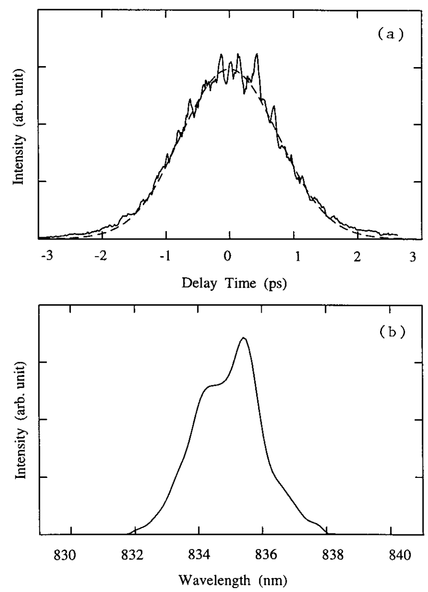

Fig. 8. Characteristics of the regenerative amplifier output: (a) second-order autocorrelation trace (solid curve) and autocorrelation trace computed with quadratic phase chirp (dotted curve), (b) optical spectrum.

the laser-diode system, i.e., minimize the generated pulse width, as the pulses propagate through the stretcher and compressor. Once the configuration is finally optimized, the pulses are directed out of the stretcher into the regenerative amplifier and subsequently into the pulse compressor. Note that the inclusion of the 1:1 telescope does not appreciably effect the system performance because of (1) the double-pass geometry employed, which eliminates limitations caused by lateral spectral walkoff, and (2) the small amount of spectral bandwidth contained within the generated mode-locked laser pulses, which eliminates potential bandwidth reduction from diaphragmation from the telescope.[23]

Figures 7(a) and 7(b) show the second-order autocorrelation trace and the corresponding optical spectrum of the dispersion-compensated mode-locked laser-diode system, respectively. Owing to the non-Gaussian or nonhyperbolic secant-squared envelope of the spectral intensity, a Fourier analysis was performed to determine the quality of the optical pulses generated from the mode-locked diode laser system. The second-order or intensity autocorrelation was computed by generating the electric-field spectrum from the measured intensity spectrum and then generating the temporal electric field with Fourier transformation techniques. The resulting electric field can then be used to generate a temporal intensity profile. From this generated temporal intensity profile, we can obtain the intensity autocorrelation function.

The results of the analysis, along with the experimentally measured second-order autocorrelation trace and optical intensity spectrum, are shown in Figs. 5(a) and 5(b). In our analysis, we predict an autocorrelation trace with a FWHM of 0.74 ps and a corresponding intensity pulse width of 0.511 ps compared with the measured autocorrelation FWHM of 1.15 ps. The computed intensity pulse width, along with the measured spectral intensity, yields a time–bandwidth product of 0.54. Owing to the smaller theoretical autocorrelation FWHM, and because the chirp impressed on laser-diode mode-locked pulses is nonlinear,[24] the theoretical analysis was modified to include cubic phase distortion. Quadratic phase distortion was ignored because the major contributions of this chirp were eliminated by the dual-grating dispersion compensator. The resulting analysis yields a deconvolved pulse width of 0.756 ps with a time–bandwidth product of 0.80. The residual cubic phase that provided the best fit was $\sim 20\ \text{ps}^3$ and is shown in Fig. 5(a) along with the measured intensity autocorrelation.

Figure 8 shows the second-order autocorrelation trace and corresponding optical spectrum obtained after the pulses pass through the regenerative amplifier and compressor system. The autocorrelation trace shows a FWHM of 1.7 ps. A Fourier analysis of the experimentally measured intensity spectrum yields an autocorrelation FWHM of 0.625 ps and a corresponding intensity pulse width of 0.45 ps. The nonoptimized recompressed autocorrelation trace suggests the existence of additional residual chirp that has not been compensated. Additionally, the shape of the autocorrelation trace suggests that the additional pulse-width broadening is associated with a residual uncompensated quadratic phase. The compressor was aligned and positioned for maximal compression to compensate for the pulse stretcher and the chirp impressed on optical pulse during mode locking. Additional pulse broadening occurs owing to the large group-velocity dispersion associated with the large number of round trips within the regenerative amplifier cavity, which contains the laser amplifier rod and the Pockels cell. To account for the pulse-width broadening, we incorporated an additional quadratic phase distortion into the Fourier analysis. With the addition of a phase distortion of ~7 ps,[2] the numerically generated autocorrelation trace yields a FWHM of 1.8 ps and a corresponding intensity pulse width of 1.32 ps, providing a good match compared with the experimentally generated autocorrelation. To verify this we calculated the amount of pulse-width broadening that would be expected for pulse propagation within the regenerative amplifier cavity. Considering the number of round trips, the total optical path length associated with the LiSAF regenerative amplifier rod is 7.15 m with an additional 2.2 m of KDP for the Pockels cell. By use of known refractive indices for both materials, we calculated the additional pulse broadening for each optical element. For the LiSAF regenerative amplifier rod, we obtained an additional 0.489 ps of pulse broadening associated with group-velocity dispersion for a given optical bandwidth of 2.34 nm. The potassium dihydrogen phosphate Pockels cell contributes an additional 0.34 ps of pulse broadening, giving a total additional pulse broadening of 0.829 ps. Considering the theoretically obtained pulse width of 0.451 ps and taking into account the additional pulse broadening yields a final pulse width of 1.28 ps. This final result is in excellent agreement with the extracted pulse width of 1.32 ps as obtained with Fourier analysis, which included the incorporation of a quadratic phase.

One important application of a compact, high-power ultrafast laser system is for time-resolved studies of nonlinear phenomena, as well as other ultrafast spectroscopic studies. An extremely useful tool for these studies is an ultrafast supercontinuum probe.[25] This light source is an ultrashort optical pulse with an extremely broad spectral content. The broad spectral content is generated by the nonlinear processes of self-phase modulation and parametric mixing[26] and typically requires not only an ultrashort optical pulse but a pulse with significant energy to induce the nonlinear phenomena. Careful consideration of the output-pulse characteristics suggests that the mode-locked diode-laser-seeded regenerative amplifier system is able to generate such a supercontinuum pulse. To test this concept, we focused the amplified and compressed output optical pulses by a 15-cm singlet lens into a 2-cm cell of H_2O. Water was chosen as the continuum-generating element simply because of its availability and the fact that the Raman vibrational frequencies are located at approximately 3000 cm^{-1}, eliminating any difficulty in analysis of the generated spectra. The resultant continuum pulse was subsequently spatially dispersed by passing the amplified optical pulses through a prism and then recording the resulting spatially dispersed spectrum on color photographic film to obtain a measure of the spectral width of the generated continuum pulse. This particular method of diagnosing the spectral extent was chosen because of the complexity of measuring single-shot spectra covering a range from 300 nm to 1.7 μm. Performing a detailed analysis of the visible portion of the generated continuum pulse and recognizing that in theoretical analyses we predict a symmetrically generated spectral intensity from self-phase modulation processes, we can deduce that amplified pulses produced a broadband supercontinuum pulse spanning from below 400 nm to over 1660 nm.

3. Conclusions

In conclusion, we have demonstrated the first experiments, to our knowledge, of a femtosecond diode laser system seeding a flash-lamp-pumped Cr:LiSAF regenerative amplifier system, producing subpicosecond optical pulses with millijoule pulse energies. The resultant output shows that minimal temporal and spectral distortion occurs during the stretching, amplification, and subsequent recompression of the amplified optical pulses. In addition, the optical pulses were used to generate a broadband continuum pulse spanning from less than 400 nm to greater than 1.6 μm, which is useful for a variety of ultrafast spectroscopic applications. We believe that this laser system has the potential to replace ion-laser-based, ultrafast, high-power laser systems, because of its small size and excellent wall-plug efficiency.

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