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High power gain-switched diode laser master oscillator and amplifier

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A tapered-stripe, traveling-wave semiconductor optical amplifier was seeded with 3.3 mW of gain-switched diode laser light to obtain over 200 mW average power with pulse widths≈105 ps full width at half-maximum (FWHM) and a pulse repetition rate of 499 MHz corresponding to a peak power of 3.8 W. Shorter pulse widths were obtained when the amplifier was driven with less current at the expense of reduced output power. Pulse widths as short as 31 ps FWHM and an average power of 98 mW corresponding to a peak power of 6.3 W were obtained when a different, lower power seed laser was used. © *1995 American Institute of Physics.*

It is advantageous to optically pump the laser-driven spin-polarized electron source[1] at the Continuous Electron Beam Acceleration Facility (CEBAF) with short-pulse laser light having a pulse repetition rate equal to one third of the 1497 MHz resonant frequency of the superconducting radio-frequency accelerator cavities.[2] Such a laser system will provide electron beam delivery to one of three nuclear physics experiment halls; multiplexing of the optical pulses will provide electron beam delivery to three halls and allow independent variation of electron beam current to each hall. A pulsed laser system eliminates the need to chop a dc electron beam and enhances the lifetime of the spin-polarized electron source photocathode because the laser light illuminates the photocathode only a fraction of the time. Other applications, such as blue-light generation and free-space optical communication, also benefit from the use of a short pulse, high repetition rate, high average power laser light source.

Gain-switched diode lasers are simple, compact, and reliable sources of short pulse, high repetition rate laser light.[3] The primary advantage of gain switching over the mode locking technique is that the pulse repetition rate is determined solely by the diode laser electrical drive frequency. It is a simple matter to adjust the gain-switching frequency and to lock this frequency to an external frequency of interest. Gain-switched diode lasers are inherently stable devices requiring no intracavity elements; pulse stability is dependent only upon the stability of the electrical drive circuitry.[4] It is true that mode locked diode laser systems can produce shorter optical pulse widths, however, for many applications, the 10–100 ps pulse widths obtainable with gain switching are adequate. As for the CEBAF application, optical pulse widths less than ≈20 ps will produce electron bunches that are dominated by space charge effects and as a consequence, the electron beam will experience emittance growth incompatible with the accelerator injector requirements. The most serious disadvantage of gain switching is that the average output power from a gain-switched diode laser is low, typically less than 10 mW.

Semiconductor optical amplifiers can be used to amplify low power seed laser light.[5] Previous work with pulsed seed lasers and optical amplifiers has relied on the technique of mode locking to obtain short pulse, high peak power laser light.[6] In work reported here, a semiconductor optical amplifier was seeded with gain-switched diode laser light to obtain over 200 mW average power with pulse widths≈105 ps FWHM and a pulse repetition rate of 499 MHz corresponding to peak power of 3.8 W. Shorter pulse widths (≈85 ps FWHM) were obtained at lower amplifier drive currents at the expense of lower average output power. Pulse widths as short as 31 ps FWHM and an average power of 98 mW, corresponding to a peak power of 6.3 W, were obtained when a different, lower power seed laser was used.

A schematic of the apparatus is shown in Fig. 1. The seed laser was gain switched in the usual way;[7] short electrical pulses were combined with a dc bias current using a bias-tee network, and then applied to the cathode of a predominantly single-mode diode laser (two seed lasers were tested; SDL 5410-C and Mitsubishi ML-2701). Short electrical pulses (≈60 ps FWHM) were obtained with 1 W of amplified sinusoidal input delivered to a comb generator (HP 33004 A). A 47 Ω resistor in series with the diode laser provides impedance matching to minimize optical pulse broadening that might result from electrical reflection between the diode laser and the bias-tee network. The shortest optical pulses were obtained when the diode laser was biased within a narrow range of dc currents near the diode laser threshold current.[8]

The output of the gain-switched seed laser was colli-

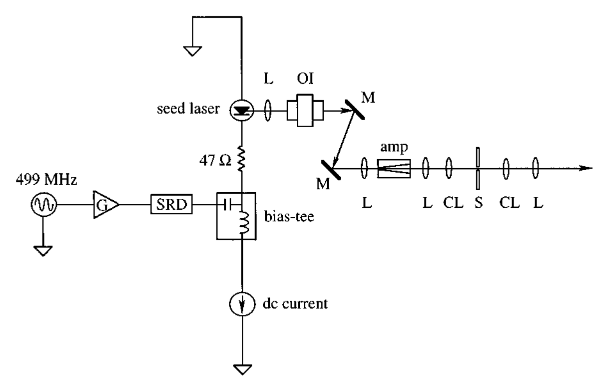

FIG. 1. A schematic diagram of the gain-switched diode laser master oscillator and semiconductor optical amplifier. M, mirror; L, lens; CL, cylindrical lens; S, slit; OI, optical isolator; SRD, step recovery diode/comb generator; G, electrical amplifier.

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mated with a 4.5 mm focal length lens and passed through an optical isolator. The seed laser beam was then focused into the GaAlAs tapered-stripe, traveling-wave semiconductor optical amplifier[9] using a 6.5 mm focal length lens. The semiconductor optical amplifier was 2.5 mm long, 5 μm wide at the input facet and 130 μm wide at the output facet. Both facets of the amplifier were antireflection coated. The amplified output was collimated and shaped with spherical and cylindrical lenses as shown in Fig. 1 to obtain a nearly circular beam ~3 mm in diameter ($1/e^2$ beam width). Amplified spontaneous emission (ASE)[10] that originates from within the amplifier was filtered from the output using a single axis spatial filter (i.e., slit). The optics used to collimate, shape, and spatially filter the output of the semiconductor amplifier were those of the SDL 8630 external-cavity tunable diode laser. Temporal characteristics of the seed laser beam and the amplified output were monitored with, (1) a fast photodiode (Opto-Electronics Model PD50; 35 ps rise time) and a sampling oscilloscope with a fast sampling-heat plug-in (Tektronix S-4; 25 ps rise time) and, (2) an autocorrelator (Femtochrome FR-103XL).

Seeded-amplifier output power was measured as a function of amplifier drive current [Fig. 2(a)]. An open-heat sink SDL 5410-C laser was used as the gain-switched seed laser. Gain-switched seed laser electrical drive conditions were chosen to yield clean, narrow optical pulse widths with very little secondary temporal pulse excitation. (A slight afterpulse could be seen trailing ≈130 ps behind the main pulse. The amplitude of the afterpulse was ~5% that of the main pulse.) The wavelength of the seed laser light was 852 nm and the average output power was 5.5 mW. Seed-laser beam steering mirrors with reflectivity less than 100% and a narrow diameter optical isolator attenuated the input beam such that only 3.3 mW arrived at the amplifier. Noncollinear autocorrelation measurements using a $LiIO_3$ frequency-doubling crystal indicated that the seed laser pulse shape was Gaussian and the pulse width was ≈85 ps FWHM. Amplifier output was composed of pulsed output and amplified spontaneous emission, which can be thought of as unwanted dc noise on which the pulsed output rides. ASE values were measured by blocking the seed laser input beam. The pulsed output power plotted in Fig. 2 was determined by subtracting ASE values from total amplifier output power values. A maximum average pulsed power of 220 mW was obtained at an amplifier drive current of 1.25 A. The ASE contribution becomes increasingly large and pulsed power falls for higher amplifier currents.

Autocorrelator measurements were performed to determine the pulse shape and pulse width of the amplified output as a function of amplifier drive current [Fig. 2(b)]. For low amplifier drive currents, the amplified output pulse shapes were Gaussian and the pulse width was roughly that of the input seed laser (≈85 ps FWHM). For higher amplifier drive currents, the pulse width was observed to increase. This pulse-broadening behavior is believed to be related to the relatively long pulse width of the gain-switched seed laser input. The seed-laser input pulses have a free-space pulse length of 25 mm FWHM, a value roughly two times the effective optical path length of the optical amplifier ($L_{2\mathrm{eff}}$

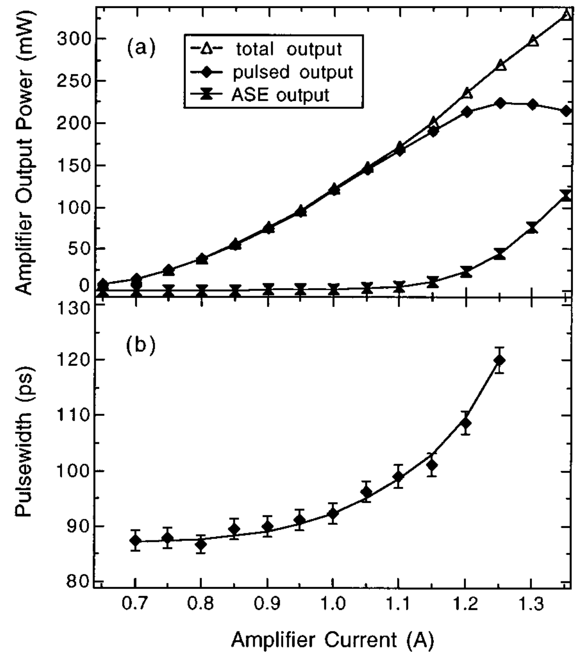

FIG. 2. (a) Amplifier output power and (b) pulse width as a function of amplifier drive current. The smooth lines between data points are added to the plots to aid the eye in determining trends and do not represent theoretical curve fits to the data.

$= L \cdot n \approx 13$ mm). It is possible that amplifier gain was depleted by the leading edge of the long input pulse, causing reduced amplification at pulse center and subsequent pulse broadening. A slight pulse shape asymmetry can be seen at high amplifier drive currents, consistent with the above hypothesis.

Seeded-amplifier output power was also measured as a function of gain-switched seed laser input power (Fig. 3). The amplifier drive current (1.15 A) was chosen to yield amplified output containing only 5% contamination from amplified spontaneous emission (with 3.3 mW input). Once again, seed laser conditions were chosen to yield narrow pulse widths and secondary temporal pulses were minimized. Then, the input power into the optical amplifier was attenuated using neutral density filters inserted into the beam. For low input powers, pulsed amplified output power was ob-

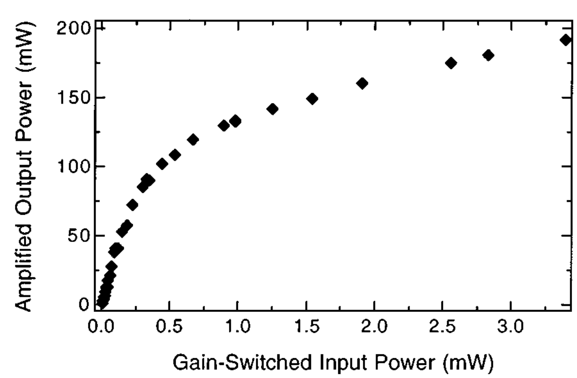

FIG. 3. Amplifier output power as a function of gain-switched diode laser input power.

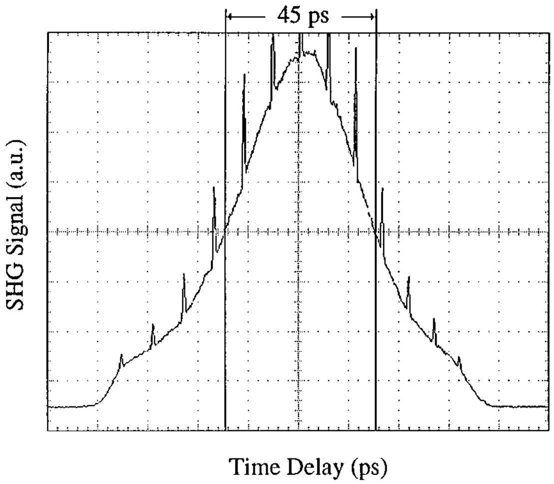

FIG. 4. Autocorrelation trace of amplified output using a gain-switched Mitsubishi ML-2701 seed laser. The pulse shape is nearly Gaussian and the FWHM of the trace is ~45 ps which corresponds to a real pulse width of 31 ps.

served to increase sharply with increasing input power. Beyond input powers of ≈0.25 mW, amplifier gain began to saturate and the rate of increase was lower. For 3.3 mW of gain-switched seed laser input power, nearly 200 mW average output power was obtained. The data suggest even higher output powers would be obtainable with higher input powers.

A Mitsubishi ML-2701 laser was also used as a gain-switched seed laser for the optical amplifier. Approximately 1 mW of average output power was obtained from this seed laser with ~0.7 mW delivered to the optical amplifier. The wavelength of the output was 858 nm. Optimized seed laser electrical drive conditions yield clean, narrow optical pulse widths without any indication of secondary temporal pulse excitation. The maximum pulsed-output power obtained from the amplifier was 98 mW at an amplifier drive current of 1.25 A. An autocorrelation trace of the amplified output obtained under these conditions is shown in Fig. 4. The pulse shape is symmetric and nearly Gaussian with a FWHM of the 45 ps indicating a true pulse width of 31 ps (45 ps ×0.707), corresponding to a peak power of 6.3 W. Contrary to results obtained with the higher power SDL 5410-C seed laser, the amplified output pulse widths did not increase with increasing amplifier drive current. The Mitsubishi ML-2701 seed-laser pulses have a free-space pulse length of 9 mm, which is less than the effective optical path length of the optical amplifier. Perhaps pulse broadening occurs only when the free-space optical pulse length of the input pulse becomes comparable to the effective path length of the optical amplifier. The narrow spikes on the autocorrelation trace indicate excitation of more than one longitudinal mode. The spikes are separated by roughly 8 ps, the roundtrip time of the laser cavity. Spikes were also evident on autocorrelation traces obtained with the SDL 5410-C seed laser however, the spike spacing is roughly 18 ps. The longer roundtrip time and associated photon lifetime of the SDL 5410-C laser, may explain why the gain-switched pulse widths of the SDL 5410-C laser were longer than the Mitsubishi ML-2701 laser.

In conclusion, a very simple and reliable means to obtain high average power, short pulse, high repetition rate laser light has been demonstrated using a gain-switched diode laser master oscillator and a tapered-stripe, semiconductor optical amplifier. This scheme provides an alternative to more sophisticated systems that rely on mode locking techniques. Stable output power and pulse widths were obtained over a period of days, requiring only minor and infrequent adjustment of the seed-laser beam alignment mirrors. Future work will be devoted to increasing the output power of the system by boosting the seed-laser input power and coupling efficiency into the optical amplifier and/or by using two optical amplifiers in series. Also, the wavelength tunability range of the system will be investigated through active heating/cooling of the seed laser and optical amplifier.

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