Techniques for Increasing Output Power From Mode-Locked Semiconductor Lasers

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Abstract

Mode-locked semiconductor lasers have drawn considerable attention as compact, reliable, and relatively inexpensive sources of short optical pulses. Advances in the design of such lasers have resulted in vast improvements in pulsewidth and noise performance, at a very wide range of repetition rates. An attractive application for these lasers would be to serve as alternatives for large benchtop laser systems such as dye lasers and solid-state lasers. However, mode-locked semiconductor lasers have not yet approached the performance of such systems in terms of output power. Different techniques for overcoming the problem of low output power from mode-locked semiconductor lasers will be discussed. Flared and arrayed lasers have been used successfully to increase the pulse saturation energy limit by increasing the gain cross section. Further improvements have been achieved by use of the MOPA configuration, which utilizes a flared semiconductor amplifier stage to amplify pulses to energies of 120 pJ and peak powers of nearly 30W.

Keywords: laser diode, pulsed laser, mode-locked, high-power, MOPA, flared waveguide, tapered waveguide, laser array

I. Introduction

Because of their compactness, reliability, efficiency, and relative low cost, mode-locked semiconductor lasers are attractive sources of short optical pulses. Such pulse sources are of interest for use in physics measurements, for instrumentation systems, and for telecommunications applications. Femtosecond pulsewidths have been achieved^{1,2}, which is feasible due to the multi-terahertz optical gain bandwidths available from semiconductor media. With proper design, mode-locked diode lasers have very low amplitude and timing jitter levels compared to other types of pulsed lasers. Femtosecond rms timing jitter levels have been achieved, limited largely by phase noise in the driving electrical sources³. Terahertz repetition rates have been demonstrated⁴, and devices are available over a wide range of wavelengths by utilizing semiconductor bandgap engineering.

Typically, semiconductor lasers emit much less average power under mode-locked operation than they do under cw conditions. This is fundamentally due to pulse broadening effects in semiconductor amplifiers arising from gain saturation due to carrier depletion during the amplification process. This pulse distortion becomes particularly severe when the pulse energies approach the saturation energy,

$$E_{\text{sat}} = \frac{h\nu A}{\Gamma dg/dn}$$

where A is the active region cross section, $h\nu$ the photon energy, Γ the confinement factor, and dg/dn the differential gain. In passively (saturable absorber) mode-locked lasers, as the laser is driven to higher pulse energies, this broadening counteracts the pulse shortening process in the saturable absorber or gain modulator, which may result in poor quality pulses or in the cessation of mode-locked operation altogether. The saturation energy limit is about 2 pJ for a typical single-mode laser, which, depending on the repetition rate, results in mode-locked average powers far below the laser's cw power capability. For example, at a repetition rate of 1 GHz, this results in an internal average power of 2 mW within the laser, which may represent less than only 1 mW output power after output coupling losses.

An attractive application for these lasers would be to serve as alternatives for large benchtop laser systems such as dye lasers and solid-state lasers. However, mode-locked semiconductor lasers have not yet approached the performance of such systems in terms of output power. In this paper we will discuss various techniques for overcoming the problem of relatively low output power. This will first include a brief discussion of pulse formation and amplification in diode laser amplifiers and saturable absorbers. Then we will describe the use of laser arrays⁵, flared waveguide amplifier lasers⁶, and master oscillator power amplifier (MOPA) lasers⁷ to achieve increased pulse energies and higher output powers. Average powers of 300 mW with peak powers of nearly 30 W have now been obtained from a mode-locked MOPA laser.

II. Modeling of Pulse Propagation in Laser Amplifiers

Because the optical pulses generated in mode-locked lasers are typically short compared to the transit time through

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the devices, the usual spatially-averaged rate equations for the carrier and photon populations are inappropriate for this problem. The usual method for this analysis is to model the device as many short segments while also separately accounting for the forward and reverse propagating photon densities². The spatial and temporal resolution of the variation in photon and carrier densities is determined by the length and transit time in the segments used for the calculation. Helkey⁸ greatly improved the computational efficiency of the calculation by using an exponential basis function to model the gain in each segment, as opposed to the linear relation that had been previously used. Because this models the gain in each device segment much more accurately, and also because the carrier density spatial variation is slow compared to that of the photon density, an amplifier may be modeled with much fewer gain segments, each separated by free space segments which do not require computation. A fine segment spacing is used as necessary for resolution of the spatial variation in the optical field, but computation of the carrier density is done only in the few gain segments.

Agrawal and Olsson⁹ have derived parametrized rate equations that are particularly useful for the analysis of semiconductor laser amplifiers. Their parametrization allows the characterization of a gain segment in terms of only the input pulse energy normalized to the saturation energy and also the unsaturated gain. These rate equations are as follows:

$$P_{out}(\tau) = P_{in}(\tau) \exp[h(\tau)]$$

$$\frac{dh(\tau)}{d\tau} = -\frac{P_{in}(\tau)}{E_{sat}} [\exp[h(\tau)] - 1]$$

where h is the logarithm of the exponential gain function, P_{in} is the input power, E_{sat} is the saturation energy, $h\nu$ is the photon energy, A the mode cross-sectional area, Γ the confinement factor, and dg/dn is the differential gain. τ is the time measured in the reference frame moving with the optical pulse. Internal waveguide loss is neglected, which is valid if the gain is much higher than this loss. Gain recovery is also neglected in these particular equations, which is valid when the optical pulsewidth is much shorter than the carrier lifetime, which is almost always the case.

An analytical solution for the instantaneous gain $G(\tau) \equiv \exp[h(\tau)]$ is⁹:

$$G(\tau) = \frac{G_0}{G_0 - (G_0 - 1)\exp(-U_{in}(\tau)/E_{sat})}$$

$$U_{in}(\tau) = \int_{-\infty}^{\tau} P_{in}(\tau') d\tau'$$

where U_{in} is the energy input up to time τ , and G_0 is the unsaturated gain. This forms the basis for the elegant logarithmic gain equation approximation used by Helkey⁸ to estimate the changes in instantaneous gain for the numerical analysis:

$$U_{in}(\tau) \approx P_{in} \Delta\tau$$

$$\Delta h = \log [G(t)] - \log [G_0] = -\log [G_0 - (G_0 - 1)\exp(-P_{in}/E_{sat})]$$

which estimates the gain well without having to explicitly compute higher order derivatives.

Modeling of Saturable Absorbers.

This model applies well also to saturable absorbers, with the only modification being a reduction of the saturation energy parameter by σ , defined as the ratio of gain-to-absorber saturation energies. The saturation energy is typically lower in a saturable absorber segment because it operates at lower carrier density than in the gain segment. This causes the differential gain (or loss) in the absorber to be higher due to the sublinearity of the gain vs. carrier density characteristic. It has been

Figure 1. Calculated unidirectional propagation through a uniform laser gain and absorber segment for varied input pulse energy normalized to E_{sat} at the gain segment input. $G_0 = 130$, $G_{\text{abs}} = 0.04$, and $\sigma = 3$.

shown theoretically that the absorber must saturate at lower energies than in the amplifier for passive mode-locking to take place¹⁰. Higher ratios of σ also result in enhanced pulse shortening per pass in the absorber¹¹. This can be understood intuitively by considering that pulse shortening in a saturable absorber occurs because the pulse edges (or just the leading edge in the case of a slowly recovering absorber) are attenuated more than the peak of the pulse. Better shortening results when the difference in attenuation between the pulse edges and pulse peak is greater, or equivalently, when the reduction of loss per number of absorbed photons is higher. Of course, this occurs when the differential gain is higher in the absorber, corresponding to higher values of σ .

Pulse Shaping in Mode-Locked Lasers.

To gain intuition into the pulse formation process in a mode-locked laser, it is helpful to consider the case of unidirectional pulse propagation through a laser gain and absorber segment cascade. What results is a combination of amplification and pulse broadening in the amplifier and pulse shortening in the absorber. Higher values of σ result in more efficient steepening of the pulse leading edge by improving the contrast between absorption of the leading pulse edge and saturation of the absorption during peak of the pulse. (The trailing edge is not affected because the absorption does not recover significantly on the timescale of the pulsewidth.)

At increasing pulse energies gain saturation causes pulse broadening in the amplifier resulting from the pulse edges being amplified more than the peak. This process eventually overwhelms the pulse sharpening that occurs from the saturable absorber, preventing mode-locking at higher pulse energies. In addition, the net energy gain through the entire device must be sufficient to overcome the other losses in coupling to an external cavity. Figure 1 shows pulse shaping and energy gain for unidirectional propagation through a uniform amplifier plotted vs. $E_{\text{in}}/E_{\text{sat}}$ at the amplifier input. The parameters used are $G_0 = 130$, an unsaturated absorption of 0.04, a σ of 3, and an input pulsewidth of 3 ps. At $E_{\text{in}} \sim E_{\text{sat}}$, the net pulse shaping leads to overall pulse broadening through the device, at which point mode-locked generation of pulses ceases.

III. Arrayed Diode Lasers For High-Power Applications⁵

Much research has been devoted towards arraying diode lasers to emit high output powers into a diffraction-limited beam. Such a source would be attractive for applications such as free space communication, laser radars, and optical harmonic generation. Some initial attempts at developing such a source involved fabrication of multiple fundamental mode waveguides

in close proximity on the wafer^{12,13}. The use of such laser arrays results in higher output powers, but such arrays tend to emit in multi-lobed far-field patterns. This makes their incorporation into external cavities with high coupling efficiencies difficult. Fiber nonlinearities were employed to produce bursts of multiple subpicosecond pulses from such an array¹⁴. Resonant-optical-waveguide (ROW) diode array lasers have recently demonstrated in-phase (single main-lobed) diffraction-limited operation at multi-Watt total output powers¹⁵. Such arrays are therefore good candidates for high power semiconductor laser mode-locking in external cavities. In this paper, we report on the first mode-locked operation of such devices, with external cavity coupling efficiencies comparable to that typically obtained using single-element lasers. Mode-locking without multiple pulsations is achieved with increased output power proportional to the number of array elements.

The use of segmented lasers for external cavity mode-locking has been demonstrated to result in improved performance and operational flexibility. Multi-segment lasers allow for the separation of the functions of DC gain, gain modulation, and saturable absorption within a single device. This results in shorter pulses and suppression of the secondary pulsations seeded by reflections from the AR coated facet at the interface between the laser and the external cavity^{16,17}. To demonstrate analogous benefits with arrayed lasers, 2-segment ROW devices were fabricated by etching the p-contact layer and metallization, resulting in lasers with electrically isolated absorbing sections of both 25 and 50 μm lengths at the output facet, with the balance of the device used as a DC gain segment. The lasers were 1000 μm long overall, and the electrical isolation between segments was typically 70 Ω . To allow separate contacting of the device segments in the p-side down mounting configuration, an electrically insulating diamond heat spreader is used between the laser and the copper heatsink. This diamond heat spreader has a patterned solder metallization to match the device's segmented contact design.

External Cavity Performance of ROW laser

The experiments employed 20-element arrays with a lasing wavelength of 850 nm. Half-wave Al_2O_3 coatings were evaporated onto both diode facets to increase the catastrophic facet damage output power limit. The facet used to couple to the external cavity was then additionally antireflection coated with a reactively sputtered anti-reflective quarter-wave SiN_xO_y layer (index~1.83). Such coatings reproducibly reduce laser facet reflectivities to less than 0.1%¹⁸.

The ROW arrays are coupled to an external air cavity using three intra-cavity lenses, as shown in Figure 2. An AR-coated GRINROD lens is used at the laser because of its high collection efficiency and numerical aperture. The cylindrical lens is used to compensate for astigmatism in the laser emission. The beam is focused onto the external cavity mirror using an achromatic doublet. This doublet is used because the non-circular beam profile fills most of the lens and would be subject to the off-axis aberrations characteristic of a singlet lens, which are compensated in an achromat.

Figure 2 shows the light vs. current dependence of an array laser with and without feedback from the external cavity. The coupling reduces the threshold current from 570 to 330 mA, which is virtually the same as the threshold before AR-coating. This suggests that the round trip cavity coupling efficiency is approximately 30%. The output beam is collimated by a GRINROD and cylindrical lens with a similar collection efficiency. The ROW array's external cavity coupling compares well with what is typically achieved using single element lasers².

Figure 2. Diagram of the external cavity mode-locked ROW array laser and light vs. current characteristics with and without external cavity coupling. The external cavity feedback reduces the threshold to the level before antireflection coating of the laser facet.

Passive Mode-Locking of ROW Arrays

The multi-segment devices were coupled to a similar external cavity as described above of approximately 19 cm length, corresponding to a repetition rate of 775 MHz. Passive mode-locking was initiated by reverse-biasing (typically -0.5 to -1.0V) the short laser section and forward-biasing the gain section above threshold. Measurements on single-stripe devices have shown that such short reverse-biased sections act as intra-waveguide saturable absorbers with fast (~ 15 ps) recovery times and lower saturation energies than the forward-biased gain segments due to the sublinearity of the differential gain vs. carrier density characteristic¹⁰. Essentially functioning as a waveguide photodetector, such an absorber also provides a useful source of electrical signals that are synchronized with the pulse output of the passively mode-locked laser. The absorber electrical output was amplified and used to trigger the time base of the sampling oscilloscope, providing a low-jitter measurement as in the actively mode-locked case where the modulation source itself was used as the trigger signal. Such a measurement results in pulsewidths of 23 ps, which is the impulse response of the measurement system. Autocorrelation measurements show that the pulses generated are of 9-10 ps autocorrelation width, corresponding to pulsewidths of 6-7 ps using a deconvolution factor of 1.55 (appropriate for hyperbolic secant squared pulses). Figure 3 shows the autocorrelation of the shortest pulses measured thus far, with an autocorrelation width of 8.6 ps corresponding to a pulsewidth of 5.6 ps. These pulses were obtained at an average power of 13.4 mW, corresponding to peak powers of over 3 W. The measurement also shows good suppression of the trailing pulses that occur from reflections from the AR coated laser facet. A maximum pulse energy of 21.9 pJ is obtained at 800 mA gain bias current. This corresponds to a 104 pJ pulse energy in the laser itself, in reasonable agreement with the calculated value of saturation energy. This demonstrates the effectiveness of increasing the saturation energy of the laser by increasing the mode cross-sectional area in an arrayed structure.

Hybrid Mode-Locking of ROW Arrays

For certain applications it is necessary to synchronize the optical pulse output with an external electrical signal. We therefore investigated hybrid mode-locking as a technique to combine the strong pulse-shortening effect of the saturable absorber with external gain modulation. Electrical pulses were injected into the gain segment of the laser along with the DC forward bias, with the short absorber section reverse-biased as in the passively mode-locked case. When the modulation frequency was tuned to match the round trip time of the laser, short pulses with characteristics similar to that of the passively mode-locked case were generated, with pulsewidths less than 6.5 ps as measured by autocorrelation. This is due to the fact that the saturable absorption is the dominant pulse-shaping mechanism in this configuration. Figure 3 shows the sampling oscilloscope measurement of pulses generated in this manner, with the time base triggered by the rf modulation source. The oscilloscope displays the pulsewidth to be 23 ps which again is the impulse response limit of the measurement, indicating that the pulses are short and have low timing jitter with respect to the drive signal.

Figure 3. Autocorrelation of pulses obtained from a passively mode-locked ROW array laser, and a sampling oscilloscope trace of pulses from a hybridly mode-locked ROW array laser, indicating that the pulses are short and have low timing jitter with respect to the drive signal.

Flared Waveguide Mode-locked Lasers⁷

Flared waveguides have previously been used in amplifiers for CW sources^{19,20}. A compound laser using a flared broad area amplifier has been actively mode-locked²⁰. In our integrated device, the flared waveguide expands the optical mode from a narrow region which constrains lasing to a single lateral optical mode, to a wider multimode region for higher power. Because the pulse saturation energy is proportional to A , this energy may be enhanced by many times in the flared region of the laser. A typical device is approximately 600 μm long, and is pumped in two electrically-isolated segments. Such multi-segmented designs are used to integrate the functions of DC gain, gain modulation, and saturable absorption within a single device. The short ($\sim 60 \mu\text{m}$) mode-locker segment on the right is reverse-biased to function as an intra-waveguide saturable absorber. The laser waveguide expands from single-mode width ($\sim 2.5 \mu\text{m}$) in the mode-locker to 7.5 μm width in the amplifier over a 150 μm long flared section, resulting in higher saturation energies in the amplifier compared to that in the mode-locker. This is analogous to mode-locked dye laser designs, where the beam in the saturable absorber dye jet is typically focused to a smaller spot size than in the gain jet.

The difference in mode cross section between the gain and saturable absorber segments impacts directly on σ , the ratio of gain to absorber segment saturation energies¹¹. σ is a key factor for pulse shaping performance in mode-locked lasers. In a conventional (uniform waveguide) laser, the forward-biased gain segment typically operates at approximately three times higher saturation energy than in the short absorbing section used for saturable absorption. This is due to the saturation energy being inversely proportional to the differential gain, which has a sublinear characteristic vs. carrier density. In a flared waveguide laser, the mode expansion in the gain segment further enhances σ , resulting in improved pulse shaping performance.

To study pulse shaping in flared amplifier-absorber structures it is necessary to consider roundtrip propagation because the effect of the flare on gain saturation is very different in the forward and reverse directions. Figure 4 shows the case of roundtrip pulse propagation through a gain-absorber cascade with $G_0 = 17$, an unsaturated absorption of 0.2, a σ of 3, and an input pulsewidth of 3 ps. The results are qualitatively similar to the previous example, as the device parameters have been adjusted to give similar values of effective roundtrip unsaturated absorption and gain. The calculation for a structure with a flare ratio of 3 with the same parameters for direct comparison is shown in Figure 5. The important difference between

Figure 4. Calculated round trip pulse propagation in a uniform laser gain and absorber segment for varied input pulse energy normalized to E_{sat} at the gain segment input. $G_0 = 17$, $G_{abs} = 0.02$, and $\sigma = 3$.

the flared and uniform device characteristics is that the net saturated gain for the flared devices is much higher, and is peaked in better alignment with the regime of optimal pulse shortening. For example, for an energy gain requirement of 10 (to compensate external cavity coupling and other losses), the flared gain structure reaches this degree of saturation at nearly three times higher pulse energy compared to the uniform device, and results in enhanced values of maximum net pulse shaping due to reduced pulse broadening contribution from the gain.

The flare in the amplifier could also be formed in the reverse direction, such that the waveguide is wider towards the absorber. The mode area expansion in the absorber causes the absorber saturation energy to increase, resulting in a degradation of σ by the flare factor. Figure 6 shows the calculated characteristics of this configuration for a flare ratio of 3, with same parameters in the previous example but with $\sigma=1$. The saturation in the gain segment is much more severe with this flare geometry, and there is a degradation in net pulse shortening due to reduced σ . This is the opposite of the situation in the devices with the flare towards the gain segment, where the effect of the flare is exploited to enhance σ , resulting in improved mode-locking characteristics.

Experiments were performed on uniform, flared gain, and flared absorber geometry devices, all fabricated on the same wafer. The active region consisted of three 8 nm $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ quantum wells separated by 10 nm GaAs barriers, with $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ separate confinement regions on a GaAs substrate. The lasers were prepared using the impurity-induced disordering process¹⁹, which allows the definition of non-uniform waveguide geometries. Two-segment lasers were coupled to any external cavity using a lens and a high-reflectivity dielectric mirror, with an antireflection coating (<1%) applied on the facet used for coupling to the cavity. The longitudinal mode spacing of this laser is determined by the length of the external cavity rather than by the cleaved device length, and thus may be adjusted mechanically. This is done to adjust the mode-locked repetition frequencies so that they fall within the range of common microwave sources and instrumentation. Passively mode-locked operation was initiated by reverse-biasing the short ($\sim 70\mu\text{m}$) absorber section while biasing the gain section above threshold. Diodes of 500-600 μm overall cleaved lengths were used, with an single-mode active region width of 2.5 μm . The flared devices have linear tapers from 2.5 μm to 7.5 μm over a 150 μm distance. The lengths used for the single-mode waveguide in the gain section were 80 and 100 μm , both resulting in single lateral mode operation.

Figure 5. Calculated round trip pulse propagation in a flared laser gain and absorber segment for varied input pulse energy normalized to E_{sat} in the single mode part of the gain. $G_0 = 17$, $G_{abs} = 0.02$, and $\sigma = 3$, with a flare ratio of 3.

Figure 6. Calculated round trip pulse propagation in a flared laser gain and absorber segment for varied input pulse energy normalized to E_{sat} in the single mode part of the gain. $G_0 = 17$, $G_{\text{abs}} = 0.02$, and $\sigma = 1$, with a flare ratio of 3.

Autocorrelation measurements of the pulses obtained from the three device types are shown in Figure 7. Pulses of 3.5 ps duration and 1.8 pJ pulse energy were obtained from the uniform waveguide laser. The flared absorber devices yielded higher pulse energies (4.1 pJ) due to the increased absorber bleaching energy, but with a broadening of pulsewidth (4.2 ps) because of the degradation in σ for this geometry. Due to the enhancement of both amplifier saturation energy and σ , the best results were achieved using the flared gain section devices, with pulse energies of 6.8 pJ and over 2 W peak power, simultaneously with an improvement in pulsewidth (3.3 ps). This demonstrates the effectiveness of the flared gain geometry in enhancing mode-locking characteristics, as the operation of mode-locked lasers at higher powers is usually accompanied by broadened pulsewidths.

This technique could be extended to even higher output energies by flaring to even broader amplifying regions. Such devices may require junction-side down mounting to improve heat dissipation and allow operation at higher bias currents, as the mode-locked devices operate with the gain stage biased to strong saturation. To our knowledge, the peak powers of over 2 W that were obtained from the flared gain section mode-locked laser are the highest peak powers obtained directly from single stripe mode-locked diode lasers. With the further improvements that may be obtained with larger flaring ratios, this is a very promising technique for generating high mode-locked output powers using a relatively simple diode laser apparatus. This approach is also important for constructing sources of sufficient power to saturate broad-area amplifiers used for post-amplification.

IV. Mode-Locking of Master Oscillator Power Amplifiers (MOPAs)⁷

Although flared waveguides increase the pulse shaping performance and amplifier saturation energies in mode-locked lasers, this saturation energy still places an upper limit on pulse energies under mode-locked operation. Additional benefits are realized with the use of a post-amplification stage. This provides the advantage of allowing the mode-locked master oscillator to be independently optimized (at lower pulse energies) from the power amplification stage. Such an amplifier may be operated at higher saturation levels than inside the mode-locked laser since the broadening effects of gain saturation are

Figure 7. Diagrams of uniform, flared absorber, and flared gain mode-locked lasers, and measured autocorrelations of pulse performance from such devices. The flared gain geometry results in increased pulse energy and reduced pulsewidth.

more tolerable in single-pass post-amplification than they are in the mode-locked oscillator, where pulse evolution occurs over many round trips. The saturation energy of a flared single-pass amplifier can be made relatively large at the output end of the amplifier. By expanding the gain cross-section area along the length of the amplifier, as the amplified power grows, a more uniform power density and degree of gain saturation is maintained throughout a flared amplifier.

Pulse Amplification in Highly Saturated Single Pass Amplifiers.

The power amplification stage in a MOPA may be operated in a much more highly saturated regime than in the mode-locked laser. The pulse broadening effects of gain saturation are much less of a problem in a single-pass post-amplification stage, as opposed to the mode-locked laser, where pulse evolution occurs over many round trips. A flared broad-area amplifier is very effective for amplifying pulses to very high energies. Figure 8 shows the calculations of pulse broadening and energy gain for an amplifier with a flare ratio of 32 and a uniform amplifier, this time with $G_0 = 1000$. The results are plotted vs. the normalized output energy so the pulse energies being generated can be readily observed. The pulse broadening in the flared amplifier is ~ 1.1 at levels of high saturation, which will not generally be a problem for most applications.

A schematic diagram of the mode-locked MOPA is shown in Figure 9. The use of a 6 cm long external cavity results in a mode-locked pulse repetition rate of 2.5 GHz. The amplifier employs a strained InGaAs quantum well active region, and has a $4\text{ }\mu\text{m}$ wide single-mode input waveguide which expands within the device to $130\text{ }\mu\text{m}$ width at the output facet. The amplifier is mounted p-side down on a copper heatsink for CW operation, and both the input and output facets of the amplifier are AR-coated. Two AR-coated lenses are used to image the output of the master oscillator onto the input aperture of the flared amplifier, and an optical Faraday isolator is inserted between the lenses to prevent injection of back-emitted ASE from the amplifier into the master oscillator. This isolator includes a half-wave plate at the output for polarization matching to the amplifier. The cylindrical lens in the output collimator compensates for astigmatism in the amplifier output that results because the optical mode inside the amplifier expands laterally towards the output end via diffraction, while being index guided in the transverse direction. An aperture is used to select out the central lobe of the amplifier emission pattern.

The amplifier was biased at a current of 2.0 A throughout the measurements. Amplified spontaneous emission (ASE) noise is subtracted from the total output power in calculating the amplified output powers. Mode-locking of the master oscillator ceased when the back-emitted ASE from the amplifier was allowed to be injected into the laser. The injection of ASE from the amplifier into the saturable absorption segment of the laser interferes with the recovery of the absorption between pulses. An important implication of this phenomenon is that it may not be possible to monolithically integrate a mode-locked master oscillator with the amplifier unless an integrated isolator can be fabricated as well.

Using 9.1 mW average power from the mode-locked laser to saturate the amplifier, the residual ASE noise level was only 9 percent of the total output power. The highest amplified pulse energy was 118 pJ, corresponding to an internal pulse

Figure 8. Calculated pulse shaping and energy gain in uniform and flared (flare ratio = 32) single pass highly saturated amplifiers, plotted vs. output energy to emphasize the output pulse energies being generated.

energy in the amplifier of approximately 170 pJ. E_{sat} at the output end of the amplifier, where the gain cross section area is the largest, is approximately 120 pJ. This shows that it is feasible to generate pulses with energies higher than E_{sat} in a single-pass post-amplification stage, which is generally not practicable in the mode-locked laser itself because of the effects of gain saturation at such high pulse energies.

The autocorrelation of the highest energy pulses obtained is shown in Figure 9. The total average power in this case was 325 mW. Subtracting the ASE contribution of 29 mW, this corresponds to a peak power of 28.1 W. Although the amplified pulsed output comprises 91% of the total output power, the modulation depth is 99.9% due to the very low duty cycle of the pulsed output.

This is the first demonstration of a flared amplifier MOPA under mode-locked operation, resulting in record average

Figure 9. Diagram of mode-locked MOPA laser, and autocorrelations of pulses before and after amplification.

and peak mode-locked output powers without pulse compression. Although the amplifier saturation energy limits the pulse energy obtainable in the mode-locked laser, the MOPA configuration allows the generation of pulses with energies in excess of the saturation energy in a post-amplification stage. The high cw and peak powers obtainable from the mode-locked MOPA make it a viable all-semiconductor option for use as a replacement for much larger and more costly mode-locked laser systems.

V. Summary

The directions pursued for high-power mode-locked lasers mirror the approaches that have been pursued in the development of high-power diffraction-limited CW sources. The arrayed laser approach has been successful in increasing the pulse saturation energy in a lateral array mode with large cross sectional area. Flared waveguide lasers also expand the mode area and saturation energy in the widened section of the devices, and this type of laser also has the important advantage of increased gain-to-absorber saturation energy ratio when the absorber is integrated in the single-mode region of the device. For this reason, and also because of the relative difficulty in fabricating diffraction-limited laser arrays, the flared waveguide laser approach at the present appears to be the more promising of the two techniques. Such a laser is also well-suited to inject high-gain flared broad area amplifiers, providing an additional order of magnitude increase in pulse energy. This finally puts the mode-locked diode laser in the realm of large benchtop laser systems such as dye lasers and solid-state lasers in terms of average power and pulse energy. An important next step is to develop an integrated mode-locked MOPA laser, with the most formidable challenge perhaps being the need for optical isolation between the oscillator and amplifier sections of the device.

There are many important potential new applications for high power mode-locked diode lasers. A mode-locked flared broad area laser²¹ was used to generate frequency doubled blue light with nearly 10% efficiency²². The high peak power pulses generated from the mode-locked MOPA laser are suitable for high-efficiency harmonic generation²³. A mode-locked MOPA laser, using either a pulse compressor or a femtosecond pulsewidth master oscillator, may generate pulses with 100's of Watts peak power, and might be used to pump an optical parametric amplifier or oscillator. High power mode-locked semiconductor lasers may also serve as convenient, relatively low-cost and reliable sources for measurement techniques such as electro-optic sampling²⁴, whose proliferation thus far has been limited due to the requirement of a large and expensive

mode-locked laser system for the optical pulse stream. Generally speaking, the possibility of using high-power mode-locked semiconductor laser sources (especially an integrated mode-locked multi-Watt MOPA laser) to replace large benchtop lasers such as dye and solid-state lasers is an extremely attractive and exciting prospect. This work was supported by the United States Department of Energy under contract No. DE-AC04-94AL85000.

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