Hybrid mode locking of a flash-lamp-pumped $Ti:Al_2O_3$ laser

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We demonstrate an all-solid-state hybrid mode-locking technique for flash-lamp-pumped solid-state lasers. The combination of active acousto-optic modulation and fast saturable-absorber action from a low-temperature multiple quantum well allows strong pulse shaping to be achieved during the rapid pulse energy buildup from the flash-lamp pumping. Pulse durations as short as 4.5 ps have been generated. The high-energy storage available from $Ti:Al_2O_3$ allows this new mode-locking technique to produce pulses with peak powers of >4 MW at a 10-Hz repetition rate directly from a single laser.

Nearly all mode-locked $Ti:Al_2O_3$ lasers to date have been cw mode-locked systems with relatively low pulse energies. Short pulse energies in the range of microjoules to millijoules can be generated by regenerative and multipass amplifier systems. Although these techniques achieve excellent performance, they are relatively costly and complex. Simple, affordable sources of wavelength-tunable, picosecond, high-power laser pulses are relevant to applications such as frequency doubling, optical parametric oscillators, materials processing, laser surgery, and picosecond ultrafast nonlinear spectroscopy. In this Letter we demonstrate a high-performance, all-solid-state, mode-locked flash-lamp-pumped $Ti:Al_2O_3$ laser by combining active acousto-optic modulation and fast saturable-absorber action from a low-temperature multiple quantum well. The flash-lamp-pumped $Ti:Al_2O_3$ laser is a simple, economical, high-peak-power laser source that can be an attractive alternative to conventional oscillator–amplifier approaches. In addition, the development of new techniques for mode locking flash-lamp-pumped lasers can be generalized to a broad class of new solid-state laser materials currently being developed.

Mode locking transient flash-lamp-pumped systems is challenging because unlike with cw lasers the pulse energy grows rapidly in time. Although mode locking has been extensively studied for lamp-pumped Nd:glass and Nd:YLF lasers,[1] relatively few investigations of mode locking have been performed in tunable flash-lamp-pumped solid-state media. Picosecond operation of an alexandrite laser was attained with saturable absorption and an external cavity.[2] Mode locking in flash-lamp-pumped $Ti:Al_2O_3$ with saturable absorber dyes[3–5] and intracavity second-harmonic generation[6] has been demonstrated, resulting in long pulse durations of ≥ 25 ps.

To address the problem of mode locking in flash-lamp-pumped lasers, we used a combination of active and passive mode locking with a low-temperature multiple-quantum-well antiresonant Fabry–Perot saturable absorber to achieve optimum pulse shortening during the rapid pulse buildup time. The laser cavity, shown schematically in Fig. 1, incorporates a 15-cm-long, 8-mm-diameter, $Ti:Al_2O_3$ laser rod pumped by two close-coupled flash lamps driven with 15-μs electrical pulses of up to 12 kV. Operating multimode with a simple planar resonator (not shown) generates pulse energies as high as 1 J at a 10-Hz repetition rate. The high small-signal gain of up to 5 per pass permits a wide range of cavity designs to be implemented. An intracavity telescope that consist of two antireflection-coated lenses was used to achieve the mode control necessary for stable saturable absorber mode locking and to scale the beam waist sizes to control energy extraction and saturable absorption. Unequal focal length lenses (2.5:1) detuned from confocal separation allow a relatively large waist (1.5-mm $1/e^2$ radius) to be formed on the semiconductor saturable

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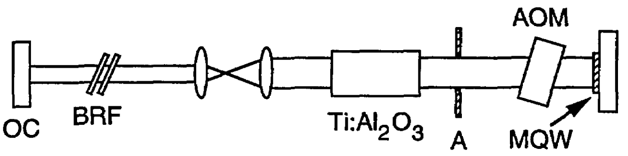

Fig. 1. Schematic of the flash-lamp-pumped mode-locked oscillator. OC, output coupler; BRF, birefringent filter; A, aperture; AOM, acousto-optic modulator; MQW, multiple quantum well.

absorber, while the smaller waist resulting at the output coupler (0.5 mm) remains sufficiently large to avoid damage. The optimal output coupler has 14% transmission.

Short-pulse formation during the rapid pulse buildup time is achieved by a hybrid mode-locking technique. Active mode locking rapidly shortens pulses that are long compared with the modulation period, whereas fast saturable-absorber mode locking provides a pulse-shortening velocity that increases inversely with the pulse duration. In this experiment we used a Brewster-cut fused-silica acousto-optic modulator driven with 5 W of rf power at a resonance frequency of ~52 MHz. Subnanosecond pulses are generated within the first few oscillations at the onset of lasing. When this device was used as the only mode-locking element, the minimum pulse duration that could be generated was 100 ps.

To reduce the pulse duration further, we employed an antiresonant semiconductor Fabry–Perot saturable absorber (A-FPSA).[7,8] The A-FPSA was previously demonstrated for mode locking cw lasers including Nd:YAG, Nd:YLF, and Cr:LiSAF.[9] In this Letter we extend the use of the A-FPSA to transient lamp-pumped lasers. The saturable absorber was a low-temperature (~300 °C) molecular-beam-epitaxy-grown AlGaAs–GaAs multiple-quantum-well structure with 38 periods of 10-nm-thick GaAs quantum wells and $Al_{0.3}Ga_{0.7}As$ barriers. The low-temperature multiple-quantum-well structure was grown on top of an $Al_{0.3}Ga_{0.7}As$/AlAs dielectric mirror stack grown on a GaAs substrate at normal growth temperature. The excitonic resonance occurs at ~840 nm. An antiresonant Fabry–Perot structure is formed by the uncoated front surface of the low-temperature multiple quantum well (nominal reflectivity of ~30%) and the highly reflecting mirror stack. This antiresonant design allows the effective cross section of the absorber to be decreased. In addition, the low-temperature growth allows the recovery time of the absorber to be controlled. Thus, in principle, the saturable-absorber characteristics may be explicitly designed to achieve optimum mode-locked performance.[8] The overall small-signal reflectivity of the A-FPSA was nominally 60% at 825 nm. Pump–probe measurements indicate that in response to an incident fluence of 200 $\mu J/cm^2$, a differential reflectivity of 15% results and decays with a time constant of 12 ps.

Because of the high gain and long pump pulse duration associated with flash-lamp pumping, the laser output consists of relaxation oscillation spikes. At our typical operating pump energy of ~120 J or 1.2 times threshold, the output consists of two relaxation oscillation spikes separated by ~2.5 μs containing ~15 and ~25 pulses, respectively. The formation of mode-locked pulses within the relaxation spikes can be studied with fast (< 1-ns response time) photodiodes to monitor simultaneously the intensity of the pulse train and its second harmonic generated in a phase-matched $LiIO_3$ crystal. The visualization of these signals on a single-shot basis is facilitated by electronically inverting and delaying the harmonic trace relative to that of the fundamental by one half the cavity round-trip time and then displaying the sum on an oscilloscope.

The amplitude of the photodiode signal from the pulse train is a measure of the integrated intensity or the total energy of the pulse. The amplitude of the second-harmonic signal is a measure of the square of the intensity times the pulse duration. Thus, if the second-harmonic signal is normalized to the fundamental signal, then it is inversely proportional to the pulse duration. A typical trace depicting the pulse train produced when active modulation alone is used is shown in Fig. 2(a). Within the first few cavity oscillations pulses of a few hundred picoseconds duration are formed. Throughout the entire pulse train, however, the pulse duration decreases by a factor of

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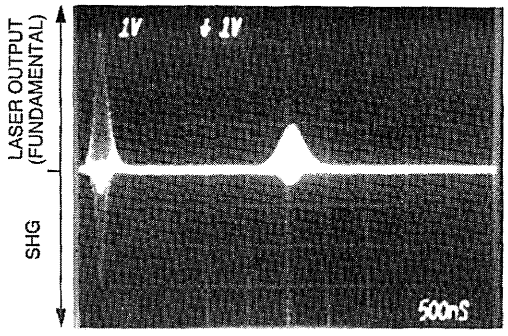
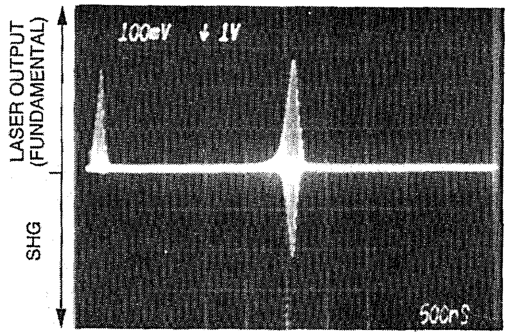


(a)

ACTIVE AND PASSIVE MODULATION



(b)

Fig. 2. Photodiode trace of output from the laser (positive going) and its second harmonic (negative going) for (a) active mode locking only and (b) hybrid active–passive mode locking. Comparison of the relative amplitudes of these signals allows a real-time diagnostic of mode locking performance.

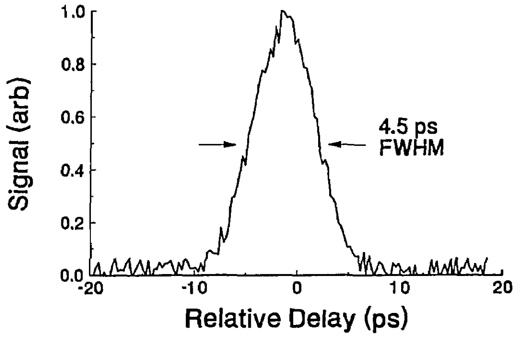


Fig. 3. Slow-scan autocorrelation of average mode-locked pulse duration in the second relaxation spike. The pulse duration is 4.5 ps, assuming a sech^2 temporal profile.

less than 3 as deduced from the relative amplitude of the fundamental and second harmonic. In contrast, Fig. 2(b) demonstrates the strong pulse shaping that results from the combined action of active and passive mode locking. Pulses in the second relaxation spike typically are shorter than those in the first by a factor of ~20. Additionally, the shift of the peak in the second-harmonic trace to later times relative to the peak in the fundamental indicates that strong pulse shaping continues to occur throughout the second relaxation spike.

To register the second harmonic, a standard (multiple-shot) noncollinear autocorrelation was performed with a photodiode and boxcar integrator. When the integrator was triggered after the first relaxation spike, the average mode-locked autocorrelation within the second relaxation spike (Fig. 3) was found to have a FWHM of 6.9 ps, corresponding to a pulse duration of 4.5 ps (assuming a sech^2 pulse). The wavelength was 824 nm and the time-integrated spectral bandwidth was 0.8 nm, giving a time–bandwidth product of 1.6. The entire pulse train contains 800 μJ of energy, corresponding to ~20 μJ per mode-locked pulse. With an intracavity two-plate birefringent filter the laser can be tuned from 820 nm to 835 nm with a maximum pulse duration of 7.5 ps.

The pulse energy, duration, and limited tunability demonstrated with this laser are superior to those of previous flash-lamp-pumped $\mathrm{Ti{:}Al_2O_3}$ systems; however, performance can be significantly improved. Although the pulse duration is limited by the relaxation time of the saturable absorber, one may increase the pulse energy by scaling the mode size in the resonator, and electro-optically cavity dumping single pulses. Pulse energy may be increased by scaling the mode size in the resonator, and single pulses can be extracted by electro-optic cavity dumping. Using these techniques, we believe that it should be possible to generate picosecond pulse durations in the millijoule energy range. The tuning range of the laser also could be increased by use of a broadband A-FPSA design.[10] It also should be noted that the hybrid mode-locking concepts demonstrated can be extended to other nonlinearities that are of inherently broad bandwidth, such as Kerr rotation of elliptical polarization, self-focusing, and carrier-induced index changes.

In conclusion, we have demonstrated a new all-solid-state technique for mode locking flash-lamp-pumped lasers. The combined pulse-shaping mechanisms of active and passive mode locking used in conjunction with the high gain and high energy storage supplied by flash-lamp pumping makes possible the development of a simple, cost-effective source of high-peak-power optical pulses.

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