Self-starting additive-pulse mode locking of a Nd:LMA laser

M. W. Phillips, J. R. M. Barr, D. W. Hughes, and D. C. Hanna

Optoelectronics Research Centre, Southampton University, Southampton SO9 5NH, UK

Z. Chang, C. N. Danson, and C. B. Edwards

Central Laser Facility, Rutherford Appleton Laboratory, Didcot OX11 0QX, UK

Received July 6, 1992

A Ti:sapphire-pumped Nd:LMA laser has been passively mode locked by using additive-pulse mode locking, which generates 600-fs-duration pulses at 1.054 μm. The wavelength, pulse duration, and long-term stability of the laser make it eminently suitable as a front-end oscillator of a high-power, chirped-pulse amplifier experiment based on 1.053-μm amplification in Nd:phosphate glass.

In recent years, additive-pulse mode locking (APM) has become recognized as a reliable scheme for generating ultrashort pulses in a variety of laser materials, including Nd^{3+}-doped hosts.[1-5] In the cases of Nd:YAG (Ref. 2) and Nd:YLF,[4] it has generated the shortest mode-locked pulse durations obtained so far in these lasers (1.7 and 1.5 ps, respectively). In this Letter we report the APM performance of Nd:LMA ($La_{1-x}Nd_xMgAl_{11}O_{19}$). Continuous-wave operation of this laser material has been reported previously by several authors.[6,7] Mode-locked operation has also been reported. 10-ps pulses have been observed by using dyes to passively mode lock a flash-lamp-pumped Nd:LMA laser,[8] and 14-ps pulses have been generated from a laser-diode-pumped, frequency-modulated Nd:LMA laser.[9] The APM Nd:LMA laser is being assessed as a potential front end for a 50-TW chirped-pulse amplification Nd:glass laser currently under development at the Rutherford Appleton Laboratory.[10] The facility currently uses an APM Nd:YLF laser operating at 1.053 μm, which generates mode-locked pulses of 2-ps duration.[11] An improved generator is required that operates at a wavelength compatible with the amplifier chain and that generates subpicosecond pulses. Nd:LMA meets these criteria, operating at 1.054 μm with a gain bandwidth of 1.3 THz and being capable of supporting 350-fs-duration pulses. Furthermore this laser material offers absorption peaks between 790 and 806 nm, suitable for optical pumping with high-power AlGaAs laser diodes.

In addition to Nd:LMA, another candidate to be used as the seed for the system described above is clearly the APM laser-diode-pumped Nd:glass laser. We have previously obtained pulses as short as 650 fs from this laser.[12] However, one major advantage of Nd:LMA over Nd:glass is its ability to be scaled to significantly higher output powers by increasing the pump powers used. We have previously found with Nd:glass that melting of the active medium produces the most stringent limitation on laser output power. In particular, for a 4% wt.-doped sample of Schott LG760 phosphate glass, the glass melts at a pump power of just over 1 W.

A schematic of the APM Nd:LMA laser configuration is shown in Fig. 1. The gain medium in the primary laser cavity was a plane–Brewster Nd:LMA rod (supplied by Roditi[13]) of 10-mm length and 4-mm diameter. The rod had a 15% dopant concentration of Nd^{3+} and was cut with the crystal c axis perpendicular to the plane surface. The plane surface had a dielectric coating with a transmission $T = 95\%$ at the pump wavelength of 790 nm and a reflectivity $R = 99.5\%$ at the laser wavelength of 1.054 μm. Although Nd:LMA is diode pumpable, a high-power laser diode with suitable emission wavelength was not available at the time of the experiment. Instead, the rod was end pumped at powers of as much as 2 W from a cw Ti:sapphire laser. An off-axis highly reflecting (HR) mirror with a 15-cm radius of curvature (ROC) (angle of incidence 15°) was used to stabilize the laser resonator and to compensate for astigmatism in the Nd:LMA rod. A pair of Brewster-angled SF10 prisms separated by 1.4 m was inserted into the resonator to compensate for net positive dispersion in the coupled-cavity scheme. The primary cavity had a 15% output coupling mirror. The total cavity length was 1.9 m.

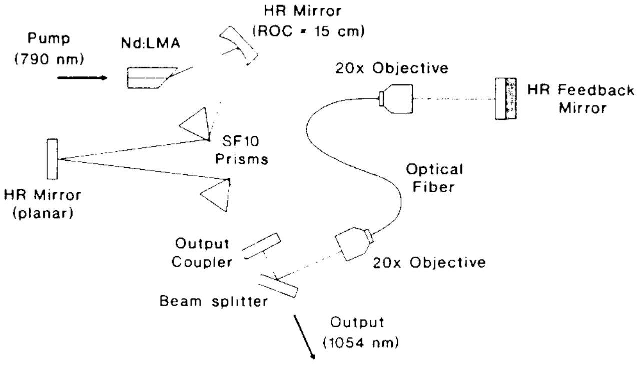

Fig. 1. APM laser configuration.

0146-9592/92/201453-03$5.00/0

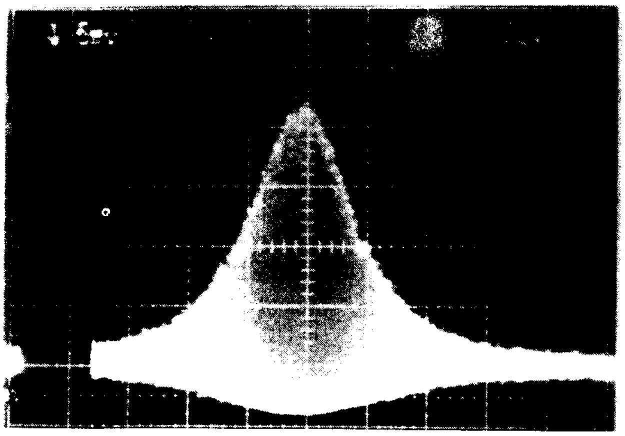

Fig. 2. Interferometric autocorrelation trace of the mode-locked pulse train. Each unit of the graticule corresponds to 430 fs of delay between the autocorrelator arms. The pulses are free of frequency chirp and have a 600-fs duration (assuming a Gaussian intensity profile).

One problem noted with Nd:LMA was thermally induced beam degradation, which we attribute primarily to thermal lensing. It was found that good beam quality and output power from the primary cavity could be achieved only if the laser mode and pump mode were approximately matched in size in the gain medium. If the laser mode was larger than the pump mode, then many transverse modes were observed. In the absence of thermal lensing, this arrangement normally results in reliable selection of the fundamental transverse mode of the laser cavity. At present, it is difficult to make a quantifiable estimate of the thermal lensing effects based on the material parameters of LMA since dn/dT (the refractive-index change with temperature) and the photoelastic constants are either poorly known or unknown. However, by direct comparison, under the conditions used in this experiment, Nd:YLF and LG760 (Nd:phosphate Schott glass) show negligible thermal effects, whereas in Nd:LMA thermal lensing is significant. Nevertheless, by ensuring a good mode overlap in the Nd:LMA rod (both the laser mode and pump spot sizes were estimated to be 25 μm) and by adjusting the cavity focusing to compensate for the thermal lensing in the rod, we could obtain output powers in excess of 350 mW in a TEM$_{00}$ spatial mode from the primary laser cavity for 1.8 W of incident pump power. This pump power was subsequently used for characterization of the APM laser performance. The threshold pump power for oscillation in the primary laser cavity was 300 mW.

A 90% reflectivity beam splitter was used to direct a portion of the laser output into an external coupled cavity. The coupled cavity contained 80 cm of non-polarization-preserving fiber supporting a single transverse mode at 1.054 μm (numerical aperture 0.11, core diameter 6.7 μm). Light was coupled into and out of the fiber by using standard 20× microscope objectives, with typical launch efficiencies in excess of 45%. A 3-mm-thick silica disk was index matched between each objective window and the fiber end by using paraffin as the index-matching liquid. This improved the launch efficiency and eliminated spurious backreflections from the fiber, which are detrimental to APM operation.[11] The thickness of the disk was chosen to match the working distance of the microscope objective, which reduced the risk of pulse dropout due to thermal degradation of the index-matching liquid. A planar high-reflectivity mirror provided feedback at the far end of the fiber. This mirror was mounted on a piezoelectric stack to allow interferometric cavity-length matching. The relative phase of the two cavities was locked by stabilizing the average intensity of the primary laser by using the technique of Mitschke and Mollenauer.[15] The coupled cavity length was matched to that of the primary laser cavity.

APM operation was observed above a threshold power level corresponding to 80 mW of laser light launched into the fiber. With 1.8 W of pump power, 150 mW of laser power was launched into the fiber, and 50 mW of usable output power was available after the beam splitter. Stable pulsing at the cavity round-trip frequency of 80 MHz was obtained by carefully adjusting the phase offset between the two cavities. The mode-locked pulse profile and optical spectrum were monitored with a real-time autocorrelator and a grating spectrometer, respectively. Figure 2 shows an interferometric autocorrelation trace of the laser output, which indicates clearly the expected 8:1 contrast ratio between pulse and background. The trace shows a pulse of 600- or 550-fs duration when we assume a Gaussian temporal profile or a hyperbolic-secant temporal profile, respectively. Numerical fits to the autocorrelation traces indicated that the pulses possessed wings and deviated from both a Gaussian shape and a sech^2 shape below 20% of the peak height. However, the high fringe visibility out into the wings of the trace suggests that the pulses were not significantly chirped. The corresponding optical spectrum is shown in Fig. 3, which indicates a laser bandwidth of 750 GHz centered at 1.054 μm. The pulse time–bandwidth product was 0.45 and 0.41 for Gaussian and sech^2 pulses, respectively. The trace in Fig. 3 also shows narrow features in the optical spectrum, which were unstable in time. These were

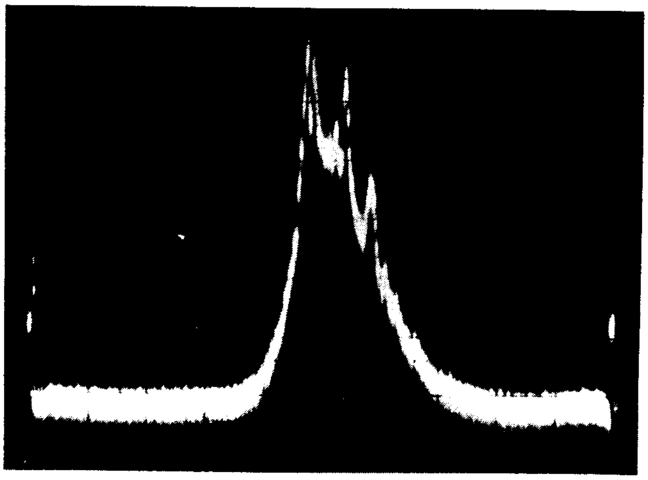

Fig. 3. Optical spectrum of the mode-locked laser. The full frequency scan is 5.6 THz with a resolution of 20 GHz. The bandwidth (FWHM) of the laser is 750 GHz.

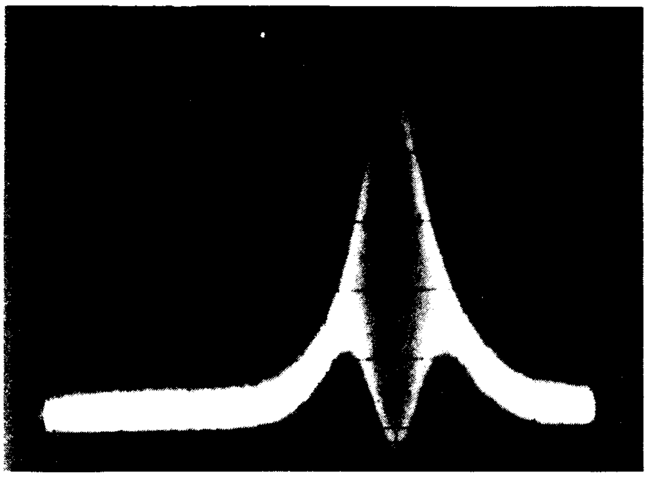

Fig. 4. Autocorrelation of the laser output in the absence of intracavity dispersion compensation. Each graticule unit corresponds to 1.7 ps of differential delay in the autocorrelator arms. The pulses are heavily chirped with a pulse duration of 1.5 ps.

attributed to the presence of an intermittent cw background to the pulses. These narrow features, in addition to the overall asymmetry of the optical spectrum, indicate that the pulses were not totally transform limited. In contrast, an autocorrelation of the return pulses from the control cavity showed significant frequency chirping, consistent with the APM mechanism.

The short-term pulse amplitude stability of the laser was monitored with a fast photodiode, which indicated <1% fluctuation in peak power over a 10-ms period. The long-term stability was also good with continuous mode locking for periods of as much as several hours, with no indication of relaxation oscillations.

To obtain subpicosecond output pulses from this system, it was important to compensate for intracavity dispersion. As an example, Fig. 4 shows an autocorrelation of the laser output with the dispersive prism pair removed from the cavity. In this case, the pulse duration was ~1.5 ps and the pulses were heavily chirped (indicated by a lack of fringe visibility in the wings of the trace). The pulses were approximately twice bandwidth limited with a spectral bandwidth of 700 GHz.

By shortening the fiber length to 60 cm in the coupled cavity, it was possible to reduce the pulse duration in the dispersion-compensated laser to 550 fs (assuming a Gaussian temporal profile). However, the optical spectrum of these pulses exhibited a stable narrow feature, which indicated a constant cw background that could not be eliminated by appropriate phase offset between the primary and external cavities. This is most likely due to the increase in APM threshold power level as a result of shortening the fiber length. By improving the power characteristics of the laser and the launch efficiency into the fiber it should be possible to operate further above threshold for shorter fiber lengths, and thereby obtain pulse durations approaching the 350-fs limit imposed by the gain bandwidth of Nd:LMA, in the absence of a cw background.

In conclusion, we have demonstrated additive-pulse mode locking in a Ti:sapphire-pumped Nd:LMA laser operating at 1.054 μm, generating near-bandwidth-limited pulses (assuming a Gaussian profile) of 600-fs duration. The pulses show <1% amplitude noise with continuous mode-locked operation for periods of several hours. These results indicate that the Nd:LMA laser, when diode pumped, will be an ideal source for seeding high-power chirped-pulse amplification systems based on amplification in Nd:phosphate glass.

The authors thank Stuart Butterworth of the Optoelectronics Research Centre, Southampton University, for constructing the real-time autocorrelator and performing the analysis of the interferometric autocorrelation traces. This research was supported in part by funding from the Science and Engineering Research Council, UK, through the Optoelectronics Research Centre.

Z. Chang is a visiting scientist from the Xian Institute of Optics and Precision Mechanics, Xian, China.

References

1. L. Y. Liu, J. M. Huxley, E. P. Ippen, and H. A. Haus, Opt. Lett. **15**, 553 (1990).
2. J. Goodberlet, J. Jacobson, J. G. Fujimoto, P. A. Schultz, and T. Y. Fan, Opt. Lett. **15**, 504 (1990).
3. J. M. Liu and J. K. Chee, Opt. Lett. **15**, 685 (1990).
4. G. P. A. Malcolm, P. F. Curley, and A. I. Ferguson, Opt. Lett. **15**, 1303 (1990).
5. F. Krausz, C. Spielmann, T. Brabec, E. Wintner, and A. J. Schmidt, Opt. Lett. **15**, 1082 (1990).
6. L. D. Schearer, M. Leduc, D. Vivien, A.-M. Lejus, and J. Thery, IEEE J. Quantum Electron. **QE-22**, 713 (1986).
7. T. Y. Fan and M. R. Kokta, IEEE J. Quantum Electron. **25**, 1845 (1989).
8. M. I. Demchouk, V. P. Mikhailov, A. K. Gilev, A. M. Zabaznov, and A. P. Shkadarevich, Opt. Commun. **55**, 33 (1985).
9. D. W. Hughes, A. A. Majdabadi, J. R. M. Barr, and D. C. Hanna, "FM mode-locked, laser-diode-pumped $La_{1-x}Nd_xMgAl_{11}O_{19}$ laser," submitted to Appl. Opt.
10. Z. Chang, C. N. Danson, M. D. Dooley, C. B. Edwards, M. H. R. Hutchinson, I. P. Mercer, M. R. G. Miller, Z. Najmudin, C. E. Ollman, D. A. Pepler, R. A. Smith, P. F. Taday, W. T. Toner, and T. R. Winstone, "Ultrashort pulse operation of the Vulcan Nd:glass laser facility using chirped pulse amplification," in *CLF Annual Report 1992* (Central Laser Facility, Rutherford Appleton Laboratory, Didcot, UK, 1992).
11. Z. Chang, C. N. Danson, C. B. Edwards, M. H. R. Hutchinson, I. P. Mercer, and M. R. G. Miller, "An ultra-short pulse diode pumped Nd:YLF oscillator operating at 1053 nm," in *CLF Annual Report 1992* (Central Laser Facility, Rutherford Appleton Laboratory, Didcot, UK, 1992).
12. D. W. Hughes, J. R. M. Barr, M. W. Phillips, and D. C. Hanna, IEEE J. Quantum Electron. **28**, 1010 (1992).
13. Roditi International Corp. Ltd., Carrington House, 130 Regent Street, London W1R 6BR, UK.
14. H. A. Haus and E. P. Ippen, Opt. Lett. **16**, 1331 (1991).
15. F. M. Mitschke and L. F. Mollenauer, IEEE J. Quantum Electron. **QE-22**, 2242 (1986).