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FM mode-locked, laser-diode-pumped $La_{1-x}Nd_xMgAl_{11}O_{19}$ laser

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We report the operation of a laser diode pumped $La_{1-x}Nd_xMgAl_{11}O_{19}$ laser mode locked by an electro-optic phase modulator. The repetition rate of the laser was 230 MHz, and the average output power was 50 mW, when pumped by a 500-mW broad-stripe laser diode. Transform-limited pulses of 14 ps duration were obtained. We have also demonstrated the FM operation of this laser, with bandwidths of up to 440 GHz being obtained.

There has recently been much interest in the active mode locking of laser diode pumped solid-state lasers to obtain pulse durations in the picosecond regime. Using frequency modulation (FM) mode locking with electro-optic phase modulators, researchers have obtained pulses as short as 12 ps (Nd:YAG)[1] and 9 ps (Nd:YLF[2] and Nd:glass[3]) at repetition rates in the region of 230 to 350 MHz. More recently, using a higher-frequency (1 GHz) electro-optic phase modulator,[4] 9-ps pulses have been reported from a Nd:YLF laser operating at 1.3 μm. In this paper we report the use of FM mode-locking techniques to produce pulses as short as 14 ps from a laser diode pumped $La_{1-x}Nd_xMgAl_{11}O_{19}$ (LNA) laser.

Longitudinal pumping of the LNA laser has been reported previously by several authors, who used krypton ion lasers,[5] $Ti:Al_2O_3$ lasers,[6] and laser diodes.[7,8] The broad absorption band of LNA around 800 nm makes this material particularly suitable for laser-diode pumping with commercially available laser diodes. The fact that the absorption band is broad (~15 nm FWHM[6]) also means that stringent wavelength control of the pump source by temperature tuning is unnecessary.

Of particular importance in the performance of mode-locked lasers is the fluorescent linewidth of the laser medium. The fluorescence spectrum of LNA shows two main peaks, one at 1054 nm and one at 1082 nm. Each of these wavelengths is interesting for specific applications. The 1082-nm wavelength coincides with the wavelength of the helium atom on the 2 ^3S–2 ^3P transition and can be used for optical pumping of helium.[8] Furthermore the 1054-nm peak coincides with the wavelength of Nd:phosphate glass lasers, and so a short-pulse LNA laser would be an interesting candidate for the seeding of Nd:glass amplifier chains. The linewidths of these two peaks are 1.19×10^{12} Hz (at 1054 nm) and 1.99×10^{12} Hz (at 1082 nm). The experiment in this paper concentrates exclusively on the peak at 1054 nm. For this peak, the fluorescence linewidth is ~8 times larger than the corresponding (1064 nm) transition in Nd:YAG, so one would expect the LNA laser to support shorter pulses (in principle as short as a few hundreds of femtoseconds) than the Nd:YAG laser. To our knowledge, the only previous report of the mode-locked operation of a LNA laser was that of Demchouk *et al*,[9] who used a saturable dye to mode lock passively a flashlamp-pumped system. The shortest pulse duration was 10 ps. The fluorescence linewidth of LNA is less than that of Nd:glass, which is 5300 GHz. We have previously obtained 9-ps mode-locked pulses from a laser-diode-pumped Nd:glass laser.[3] However, LNA has several material properties that make it an interesting alternative to Nd:glass. In particular, LNA's thermal properties are markedly superior. Two of the main problems associated with the Nd:glass laser are its low thermal conductivity (~0.6 W/m/K), which can lead to thermal lensing and thermally induced birefringence, and its low melting point (~550 °C). We have previously found that this latter factor severely restricts the output power available from laser diode pumped Nd:glass lasers.[3,10,11] LNA has a melting point comparable to that of Nd:YAG (~1800 °C) and a thermal conductivity an order of magnitude greater than that of Nd:glass, so we do not envisage thermal problems in

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this laser. We have pumped the LNA laser with a $Ti:Al_2O_3$ laser operating at approximately 800 nm at pump powers significantly in excess of 1 W without meeting any deleterious thermal effects.

The experimental apparatus used is shown in Fig. 1. The pump source was a broad single-stripe 500-mW laser diode (STC LQ-P-05). Its emitting area was 40 μm × 1 μm. The laser diode was held on a copper mount, and its wavelength was temperature tuned to 802 nm with a Peltier cooler. The maximum absorption in the laser medium was ~80%. The diode beam was collimated with a compound lens with a numerical aperture of 0.6 and a focal length of 6.5 mm. The beam was then passed through an anamorphic prism beam expander (magnification 6×) to circularize the beam. The beam was finally focused with a 3.2-cm focal length lens. All the collimating and focusing optics were antireflection coated at the laser diode wavelength. The pump beam was focused through the rear mirror of a standard three-mirror astigmatically compensated cavity.[12] This mirror, which had a radius of curvature of 20 mm, was highly transmitting (>90%) at the pump wavelength and highly reflecting (>99.9%) at the lasing wavelength (1054 nm). The cavity was completed by a 150-mm radius of curvature turning mirror (reflectivity at 1054 nm > 99.9%) and a 10° wedged output coupler with a reflectivity of 98.3%. The active medium was a 5-mm-diameter, 5-mm-length rod of LNA with polished ends cut normal to the *c* axis, mounted at the focus of the cavity at Brewster's angle (the refractive index of LNA is 1.8). This meant that the laser propagation was not parallel to the *c* axis. In this sample of $La_{1-x}Nd_xMgAl_{11}O_{19}$, the value of x was 0.09, corresponding to a Nd atomic density of $3.02 \times 10^{20}\ cm^{-3}$.

Without the modulator in the cavity, the lasing threshold was 51 mW of absorbed pump power, and the slope efficiency significantly above threshold was ~27% with respect to absorbed power. This low slope efficiency is attributed to poor overlap of the pump beam with the LNA laser mode over the rod length. In additional experiments, pumping with a $Ti:Al_2O_3$ laser has yielded slope efficiencies of approximately 50%. When the modulator was placed in the cavity, the threshold increased to ~80 mW. The passive insertion loss of the phase modulator has previously been estimated as being 3%,[3] so the cavity losses (excluding modulator and output coupler losses) were estimated at 3.4%. This is rather higher than might be expected, and the reason for this is not clear. The maximum output power obtained with the modulator in the cavity was 50 mW.

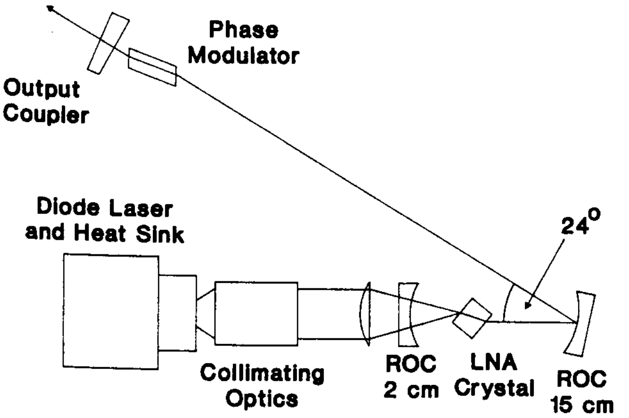

Fig. 1. Schematic diagram of the FM mode-locked LNA laser. ROC, radius of curvature.

The phase modulator used was a Brewster-angled $LiNbO_3$ crystal of dimensions 24 mm × 6 mm × 6 mm. Its operation has been described elsewhere[3] and will be summarized here. The electric field (between 0.5 W and 1.5 W at 230 MHz) was applied transverse to the modulator, using the largest electro-optic coefficient, r_{33}. The rf power was inductively coupled into an *LC* circuit containing the crystal by means of a search coil connected directly to the rf power amplifier. The phase retardation of the device was measured by observing the Bessel-amplitude sidebands imposed on a He–Ne laser ($\lambda = 632.8$ nm) and was found to be 0.3 rad at 1 W and 0.6 rad at 1.5 W. When the inverse dependence of phase retardation on wavelength was used, the retardation at 1.054 μm was estimated to be 0.4 rad at 1.5 W.

The laser was easily mode locked by adjusting the laser cavity length to match the 230-MHz resonance frequency of the phase modulator. The mode-locked output was monitored accurately with a standard, nonbackground free autocorrelation technique. The moving prism used in the autocorrelator was scanned at a rate of several hertz, and the autocorrelator had a total scan range of 98 ps. A typical autocorrelation trace of the mode-locked output is shown in Fig. 2. The duration of the autocorrelation is 20 ps (FWHM), which, if we assume a Gaussian temporal profile, corresponds to an optical pulse duration of 14 ps (FWHM). The maximum average output power of the mode-locked laser was 50 mW, i.e., the same output power as the maximum power of the free-running laser. The peak power of the mode-locked pulses was thus 15.5 W. The optical spectrum of the laser output was monitored by an 1800 lines/mm diffraction-grating spectrometer. The mode-locked spectrum corresponding to the autocorrelation trace in Fig. 2 had an optical bandwidth (FWHM) of 29.8

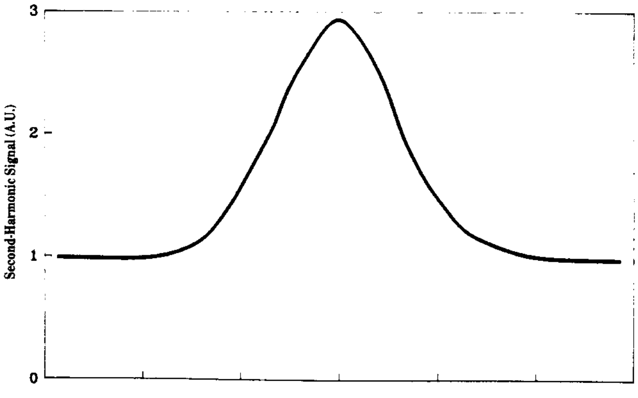

Fig. 2. Typical autocorrelation trace. Scale: 14 ps/division.

GHz, yielding a time–bandwidth product of 0.42. This is very close to the transform-limited value for a Gaussian pulse (0.44), although it is smaller than expected from the theory of FM mode locking (0.63, Ref. 13).

Along with the FM mode-locked performance of the laser, we have also investigated its FM operation.[14] In this mode of operation, when the frequency of the modulator is significantly detuned (tens of kilohertz) from the optimum mode-locking frequency, the laser output is constant in time, but the instantaneous frequency sweeps sinusoidally over a broad frequency range during each period of the modulator frequency. The maximum FM bandwidth observed was 440 GHz. A typical FM spectrum of FWHM 250 GHz is shown in Fig. 3. It is possible that the FM laser output could be compressed with a dispersive delay line to produce subpicosecond pulses directly.[15] The observed FM bandwidth is smaller than the fluorescence linewidth of LNA ($\sim 1.19 \times 10^{12}$ Hz). The reason for this is thought to be the cavity configuration used in our experiment, where there are two Brewster surfaces in the cavity and where the active medium is a significant distance away from the cavity end mirrors. This configuration has previously been shown to restrict the FM bandwidth available from a Nd:YAG laser.[16] It has also been shown theoretically[14] that the FM bandwidth should be inversely proportional to the detuning from the optimum mode-locking frequency. Figure 4, in which the measured FM bandwidth is plotted against frequency detuning, shows that the experiments qualitatively agree with this theory.

To compare the results obtained from the FM mode-locked laser with theory, we have calculated the pulse duration predicted by the well-known Kuizenga–Siegman theory.[13] In this theory, the predicted steady-state FM mode-locked pulse duration is given by

$$\tau = \frac{(2 \ln 2)^{1/2}}{\pi} \left(\frac{2g_0}{\delta}\right)^{1/4} \frac{1}{(f_m \Delta f)^{1/2}}, \qquad (1)$$

where g_0 is the saturated amplitude gain ($g_0 \sim 0.042$, calculated with $g_0 \sim 0.5 ln[1/(1 - L)]$, where L consists of all the cavity losses), δ is the single-pass phase retardation, f_m is the modulation frequency, and Δf is the fluorescence linewidth of the laser medium. Inserting the relevant parameters yields a value of $\tau = 15.3$ ps, in good agreement with our experimental result. Other authors working on laser-diode-pumped actively mode-locked Nd:YAG,[1] Nd:YLF,[2] and Nd:glass[17] lasers have reported reduced pulse durations from those predicted by the Kuizenga–Siegman theory. It has been suggested that this may be because of some nonlinear effect, such as self-phase modulation, occurring in the laser medium. We have observed no significant variation in pulse duration with pump power, and this result, combined with the good agreement between experiment and theory, leads us to believe that no nonlinear effects are occurring in our laser.

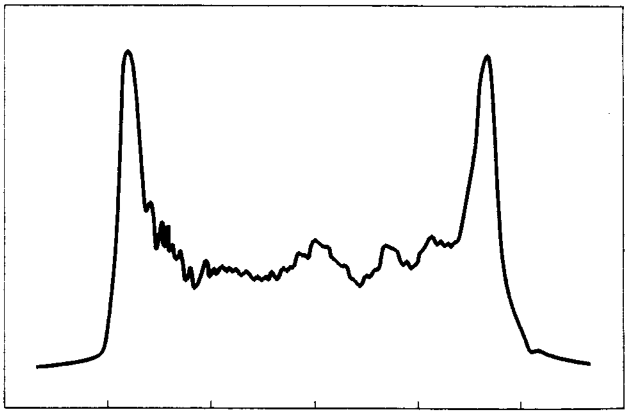

Fig. 3. Typical FM optical spectrum. Scale: 74 GHz/div.

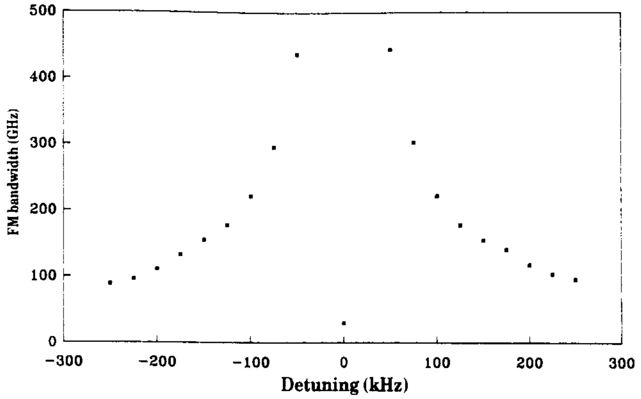

Fig. 4. Variation of FM bandwidth with frequency detuning. The FM mode-locked bandwidth of 29.8 GHz is also shown. For detunings smaller than 50 kHz, forced relaxation oscillations were observed.

In conclusion, we have reported the FM mode-locked operation of a laser diode pumped LNA laser, obtaining pulses as short as 14 ps. The average output power was 50 mW, and the pulses were transform limited. We note that, because of its good thermal properties (high melting point, high thermal conductivity), this laser material should be readily scalable to significantly higher powers. Furthermore, because of its broad fluorescence linewidth, shorter pulses than those obtained to date should be achievable with this laser. One means of doing this would be to use active mode locking in a different cavity configuration, where the gain medium is adjacent to the cavity rear mirror. This setup yields a much broader free-running linewidth[16,18] because of spatial hole burning and facilitates the generation of shorter mode-locked pulses.

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